Grain Drying in Asia

Proceedings of an International Conference held at the FAO Regional Office for Asia and the Pacific, Bangkok, Thailand, 17–20 October 1995

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Cover: A low-cost portable grain dryer developed in Vietnam for small farmer households with access to electricity. See pp 308–313.

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Invited Paper

Welcome Remarks

Representatives of GASGA, ACIAR, AFHB, distinguished delegates, my colleagues in FAO, ladies and gentlemen:

It is my pleasure and privilege to welcome you all to the FAO Regional Office for Asia and the Pacific, on behalf of the Director-General of FAO and on my own behalf.

FAO is indeed privileged to be a partner with such distinguished institutions as the Australian Centre for International Agricultural Research (ACIAR), the ASEAN Food Handling Bureau (AFHB), and the Group for Assistance on Systems relating to Grain After-harvest (GASGA). This international conference has been made possible by their collaborative endeavour. The Regional Association for Post Production Technologies in Asia (REAPASIA), catalysed by the FAO Regional Office (RAP), has made a modest contribution towards sponsoring resource persons, as has the Agricultural Engineering Services of FAO Headquarters, using the TCDC/ECDC partnership program.

The preceding three decades and a half, although a period of unprecedented population growth, have seen substantial progress in efforts both to produce food and ensure access to food for all people. Over the past 30 years, the volume of agricultural production has doubled and world agricultural trade has increased threefold. The global per capita availability of food has increased from 2300 kilocalories (9600 kJ) per day in the early sixties to some 2700 kilocalories (11300 kJ) at present, despite an increase of over 2400 million people in the world's population.

Yet 800 million people in the world today go to bed hungry. As many as 192 million children under the age of five suffer from chronic or acute protein and energy deficiencies.

Current statistics for Asia and the Pacific region are depressing. The region houses two-thirds of the world's undernourished. One person in five does not have access to sufficient food energy to lead a healthy, active life. Nineteen (19) of this region's 27 developing countries which are members of FAO are low-income, food-deficit countries.

We must, however, not let such disheartening statistics contain our aspirations, because Asia and the Pacific region has also made real progress. This vast region, home to 70% of the world's developing population, is not uniformly food insecure. East Asia, including Southeast Asian countries, has made the most rapid improvement worldwide. In two decades, it has halved the numbers of undernourished people, reducing the percentage from 44 to 16 of the total population. South Asia has also made steady, though insufficient gains. It reduced the percentage of undernourished population by a third from 34 to 24%, but could not manage to bring down the absolute numbers of undernourished people, owing to population growth.

Apart from this record of significant achievements, FAO's study on Agriculture Towards 2010 (AT 2010) suggests that per capita cereal production and agricultural production in general, will continue to grow, though at a lower pace. Cereal self-sufficiency ratios are likely to be little changed at 97% in East Asia and fall slightly from 102 to 97% in South Asia. At these self-sufficiency levels, net cereals imports in 2010 are likely to rise by only 2 million tonnes to 22 million tonnes in East Asia; but may double to 1 million tonnes in South Asia.

This slight to moderate projected import expansion at the end of 20 years will, to an extent, be balanced because import capacity will continue to grow rapidly as in the past. The percentage of export earnings spent on food imports in the group of 26 developing countries in the region declined from 15 to 5% in the past two decades, and will undoubtedly decline further as export earnings expand.

Consequently, East Asia may see the percentage of population chronically undernourished falling from 16 to 6% and the numbers from 252 to 70 million. South Asia will also experience significant progress, though it will not be enough. The percentage of undernourished may be halved to 12%, with the number of undernourished people falling from 271 to 202 million.

Rice, as you know, is not only a staple food in many countries in Asia, it is a way of life. The expanding agricultural economies in some countries are focusing on the international market. Thailand is exporting more than 5 million tonnes of rice this year and Vietnam around 2 million tonnes. Drying is the first step in reducing quantitative and qualitative losses of grain after harvest. A combination of temperature and moisture control is optimal in minimising deterioration during the storage. Since the first is costly, then drying becomes the most cost-effective technique. Technologies are there for drying and storage of grains. Yet there have been relatively few successes in transferring efficient grain drying systems in this region. The scientists assembled here will evaluate the relevant technologies and also the obstacles to their adoption. Let me mention here the changed trade scenario after the Uruguay Agreement. Opportunities for export from Asia will be counterbalanced by international competition. To be an effective player in this competitive environment, quality of grain must be ensured.

Asian countries produce over 90% of the world's rice, over 85% of its wheat, and over 60% of coarse grains. Dramatic increases in production have not always been matched by similar improvements in postproduction handling. In the context of this conference, it is clear that grain drying is not simply a technical solution to a grain storage problem. If that were so, why is it that literally hundreds of grain dryers have been developed and yet farmers in many countries of the region continue to use the roadsides to dry their grains, under less than optimal conditions?

Technology has perhaps to be reorientated, from hardware solutions to software, knowledge-based solutions. More importantly, the frontier science and technology must be integrated with the local organic and experiential wisdom of farmers.

Adoption of technologies is not enough; the small farmers who till our soils must be empowered to own the technologies. Access to credit or private sector support for the additional resources required is essential for such empowerment.

Participants and observers in the drying conference will, no doubt, deliberate upon available and relevant technologies. What to my mind is critical is the producers' access to and ownership of your knowledge and expertise.

It is now my honour and privilege to declare this GASGA International Conference on Grain Drying in Asia, officially open.

A.Z.M. Obaidullah Khan
FAO Assistant Director General and Regional
Representative for Asia and the Pacific

Keynote Address

Mr A.Z.M. Obaidullah Khan, FAO Assistant Director General and Regional Representative for Asia and the Pacific; distinguished participants; ladies and gentlemen:

It is a privilege and pleasure for me to participate in this International Conference on Grain Drying in Asia and to present the keynote address to the distinguished scientists assembled here.

May I extend a warm welcome to all the distinguished participants, experts, and organisations present at this international conference. As has been mentioned by the FAO Regional Representative, Mr A.Z.M. Obaidullah Khan, this conference has been made possible by the collaboration of four international and regional bodies:

- The Australian Centre for International Agricultural Research (ACIAR);
- The ASEAN Food Handling Bureau (AFHB);
- The Group for Assistance on Systems relating to Grain After-harvest (GASGA); and
- The Food and Agriculture Organization, Regional Office for Asia and the Pacific.

This is a good example of mutual collaboration, where the comparative advantage of each agency has come to the forefront in ensuring a conference of technical excellence.

Never in the history of this region has grain drying taken on such critical importance, as Thailand and her neighbours strive to produce grains for the export markets of the world. In the case of rice, double and even triple cropping is now standard practice to obtain higher yields from the same land. The risk lies in the proximity of these harvests to the wet seasons in the countries involved, and the lack of comprehensive drying facilities to handle wet paddy. The danger of postproduction losses is increased by this intensive production and, in some cases, by the lack of incentives for the farmers to undertake drying procedures.

The socioeconomic environment in which the farmers are operating is as significant as the physical environment in determining whether these technologies are used. In addition, extension and promotion is vital to convince potential users of the value of these technologies before they can be fully transferred into popular use.

As I speak, one of the worst floods on record is causing record damage to Thailand's agricultural economy. A most serious situation exists, where provinces with at least 8 million rai [ca 6.25 rai = 1 ha] of cultivated land are flooded.

One million tonnes of rice may be lost from an estimate of 21 million tonnes this year. The only bright side of the picture is that prices for rice are expected to rise and that there will be no shortage of irrigation water for the second crop of rice. Last year's second crop planting was on about 4.1 million rai.

Animal feed production has been affected severely as a result of the damage to maize and soybeans, especially in Sukhothai and Phitsanulok. Maize production may now drop from 3.6 million tonnes, by over 200,000 tonnes. Prices of maize substitutes are increasing and broken rice has reached 7 Baht per kilo, a record price.

This GASGA International Conference on Grain Drying in Asia is very timely. A number of critical factors have been identified in earlier meetings on postharvest technologies. These factors include: the increased importance of the wet season crop in the total output of grains; the shift to more commercial cereal markets in tropical countries, with higher outputs entering the marketing chain; and a growth in the ability of trading countries to discriminate between qualities of grains.

At government level, there is a need to consider policy on the required infrastructure and framework for the farmers, processors, transporters, and marketers, to optimise the postharvest operations for grains.

Research goals in the postharvest sector have included identification of ways and means to protect grains in production, by reduction of postproduction losses. Also, positive technologies to meet the needs of producers and consumers have been sought by identifying critical control points in postharvest operations.

When researchers formulate their objectives they need to consider first the social, economic, political, and administrative framework surrounding the work, as well as the actual economic cost/benefit considerations. These points for consideration were put forward by earlier international seminars held by the same groups assembled here.

It should be clarified during the conference discussions whether the barriers to progress arise from the policy environment, from socioeconomic considerations, or are problems with technical solutions. All of us must redirect our energies to becoming involved in the reframing of policies which may be impeding implementation of sound postproduction practices.

This international conference is an important milestone in the history of postproduction technology. Thai scientists present are ready to participate to the full with international scientists gathered here, to ensure that a complete exchange of technical information takes place, with the goal of improving the quality of grain production in this and other countries, as well as improving international cooperation between the countries represented here.

May I now wish your deliberations every success.

Thank you.

Dr Narong Chomchalon
Regional Plant Production Officer
FAO
Bangkok

Remarks from Conference Sponsors

GASGA

Mr Chairman, ladies and gentlemen, dear friends and colleagues, at the opening of this international conference, I would like to say a few words about GASGA, the group whose acronym you have seen on the front page of the circulars sent to all participants.

GASGA, the Group for Assistance on Systems relating to Grain After-harvest, is a voluntary association of organisations concerned with donor operations on grain storage, handling, and processing in developing countries.

Those organisations have major involvement in most, if not all, of the following:

- provision of professional advice;
- conduct of field projects; and
- conduct of research and its application in relation to the problems of the postharvest sector of grain production.

The association is essentially technical; it is international in character, but informal and limited in membership, so that its deliberations can take place more readily.

The following organisations are the current members of GASGA:

ACIAR	Australian Centre for International Agricultural Research, Canberra, Australia;
CIRAD	Centre de Cooperation Internationale en Recherche Agronomique pour le Développement, Montpellier, France;
GTZ	Gesellschaft für Technische Zusammenarbeit, Eschborn, Germany;
FAO	Food and Agriculture Organization of the United Nations, Rome, Italy;
NRI	Natural Resources Institute, Chatham, U.K.

GASGA's main objective is to coordinate and disseminate information and advice on postharvest food-crop systems, especially of grains, in order to improve policies, procedures, and efficiency. For this purpose, position papers on basic issues are prepared, such as on mycotoxins, pesticides, and the importance of the postharvest sector for development. Also, executive seminars are organised, and a GASGA newsletter is produced.

The GASGA executive meets annually to review progress in its activities and to consider proposals for future work. In its meeting in Rome in 1994 it was unanimously agreed that grain drying in Asia was becoming crucial due to (a) the expanding agricultural economies of this region; (b) the development of a second harvest of paddy in countries where the rainy season is coming soon after, thus making difficult the traditional sun drying; (c) the cost of artificial drying which needs to be examined in the light of available and newly developed technologies; and (d) the privatisation trend evident in many places thus giving, in principle, more opportunities to producers and operators to benefit more directly from their investment and efforts.

We are therefore very pleased to see that this conference is now a reality, thanks to the support of many, but more particularly from the three organisers, the ASEAN Food Handling Bureau, ACIAR, and FAO, the last two of which, you will recall, are GASGA members.

I wish this conference every success.

J. Faure
CIRAD

ACIAR

FAO Regional Representative Mr Obaidullah Khan, distinguished guests, ladies and gentlemen:

In the past 20 years we have seen many successes in the improvement of grain productivity and quality in Asia; a fortunate legacy of the green revolution and peace. Communities have prospered as a result, and will continue to do so. Land, however, is a finite resource. We are almost at the limit of land area available for agriculture, and water, energy, and other natural resources are becoming scarce.

So precious was rice, my colleagues in the region have told me, that their parents would scold them if they left just one grain in their bowl! Teaching children to eat all of what they are given is an admirable means of reducing postharvest waste—and a great challenge in a television-programmed, consumption-orientated modern society. So too is maximising the quantity and quality of produce available for the plate.

Also here at FAO Headquarters in Bangkok, we yesterday celebrated World Food Day and FAO's 50th Anniversary with a symposium on the theme 'Food for All'. The symposium was honoured to be addressed by HRH Princess Maha Chakri Sirindhorn and other distinguished speakers.

Her Royal Highness noted that 'food for all' must be translated in 'nutrition for all'. Quality of food is as much a vital concern as is quantity. Food for all encompasses not only production, but also minimisation of postharvest losses and maximisation of storage life and grain quality.

Grain drying, along with other facets of postharvest technology will continue to play a primary role in garnering the harvest, especially if greenhouse gases and global warming make cropping and harvesting less predictable. Grain drying methods have been part of the technology and social revolution, a hand-in-hand partnership with the green revolution, which has been vital in achieving food for all.

In the coming decades, population growth, land and water availability, and community demand for chemical-free food will challenge our ingenuity further. This meeting sets the scene for directing and progressing one component: grain drying.

In welcoming you on behalf of ACIAR, I would also like to pay tribute to my predecessor in the ACIAR Postharvest Program, Dr Bruce Champ. Under his stewardship, the ACIAR postharvest technology research partnerships in the region have contributed significantly to grain drying options—options that are energy efficient, cost effective, and adaptable.

Modern sophisticated technology, on the one hand, and innovative low-technology alternatives, on the other, have both done much to reduce time and labour per unit yield.

The outcomes we seek—feeding people and livestock, and implementing grain drying technology—are matters of both individual effort and the synergy that comes from working together. What each of us gains from this meeting similarly relies on our individual and combined efforts. Over the next four days we will talk, listen, taste, and smell conference activities and Thai hospitality.

I believe that GASGA's initiative in organising this conference, and the strong participation in it, reflect HRH Princess Maha Chakri Sirindhorn's concluding comment at the symposium yesterday. The Princess said:

> The greatest advantage is the growing sense of regional and international partnership for development ... a new spirit of technical cooperation among developing countries has emerged. This

> stronger sense of empathy and cooperation will strengthen ... efforts to use our resources on a sounder and more sustainable practical basis. In this way, 'Food for All' can indeed become a realistic goal for everyone.

Mr Obaidullah Khan, distinguished participants, thank you for your attention. Enjoy the meeting.

G.I. Johnson
Coordinator
Postharvest Technology Program

AFHB

Mr Khan, Assistant Director General and FAO Regional Representative for Asia and the Pacific, representatives from GASGA, ACIAR, and FAO, ladies and gentlemen:

May I wish all of you a very good morning and a warm welcome to the GASGA International Conference on Grain Drying in Asia.

On behalf of the ASEAN Food Handling Bureau based in Kuala Lumpur, Malaysia, I would like to express our sincere thanks to everyone in this conference who has helped us in organising and in making this conference a success.

It is a privilege for the ASEAN Food Handling Bureau to be on the organising committee with GASGA, ACIAR and the FAO.

As you may be aware, the Bureau is in the process of taking on some new directions itself. These should become clearer by next year. However, we trust our pathways will continue to meet and we can still all work together using the skills which have been built up in the Bureau.

With this, I look forward to sharing and having more fellowship with all of you in the next four days in Bangkok and in this International Conference on Grain Drying in Asia.

Koh Siew Hua
Project Officer

INVITED PAPERS

Setting the Scene

Grain Quality Problems in Asia

Bienvenido O. Juliano*

Abstract

Maintenance of grain quality is the major consideration in postharvest handling of grains. Grain quality is influenced by variety, preharvest environment, and postharvest handling. Grain breeding programs concentrate on varietal improvement, whereas engineers improve postharvest processes to enhance grain quality. Major grain quality problems arise from lack of incentive to farmers, and are manifested in yellow rice, brokens, ageing and storage changes, variety mixing and mislabelling, and lack of screening methods to differentiate among rices with similar starch properties and among special rices for rice food products. High aflatoxin level from fungal growth is the major problem for maize and parboiled rice. Fissuring during drying is also a quality problem in maize.

Specific grain properties relevant in drying include moisture content (water activity) and both critical and equilibrium moisture contents, and hull or husk tightness. Delayed drying may result in stackburning of wet grain due to nonenzymic browning and microbial growth and mycotoxin production in maize and parboiled rice. Improper and over-drying may reduce head rice yield and aroma. Rice varieties differ in their critical moisture content (11–16%, below which they fissure readily) and in equilibrium moisture content. Further interdisciplinary research should accelerate the solution of quality problems related to postharvest handling of grain.

MILLED rice is the staple food in tropical Asia and is the major source of dietary energy and protein (Juliano 1993). The major nutrient of milled rice is starch (90% of dry matter) followed by protein (8% of dry matter). Rice is consumed mainly as boiled whole grain. Starch occurs as compound starch granules 3–9 μm in size and protein exists as two types of protein bodies 0.5–4 μm in size (Juliano 1985). Milled rice is classified by iodine-colorimetric assay for apparent amylose content (AC) into: waxy, 1–2% milled rice dry basis; very low, 5–10%; low, 10–20%; intermediate, 20–25%; and high, 25–33%. Final starch gelatinisation temperature (GT), wherein 90% of the starch granules swell irreversibly in hot water, is classified as low <70°C, intermediate 70–74°C, and high 74.5–80°C. The AC is the major influence on the texture of cooked rice, with waxy being the softest and most sticky, and high-AC low GT rices the most flaky (Juliano 1993). By contrast most nonwaxy maize varieties have high AC and intermediate GT starch.

Maintenance of grain quality is a major consideration in postharvest handling of grains. Grain quality is influenced by variety, preharvest environment, and postharvest handling (Juliano and Duff 1991a) (Table 1). Although variety is the principal factor contributing to grain quality, good postharvest handling can maintain or even improve it. In countries with marked variability in temperatures during the ripening periods, significant differences in grain quality have been reported within a variety. In tropical Asia, grain physiochemical properties of a variety are relatively constant.

Grain quality denotes different properties to various groups in the postharvest system. To the farmer, grain quality refers to quality of seed for planting and dry grain for consumption, with minimum moisture, microbial deterioration, and spoilage. The miller or trader looks for low moisture, grain size, shape, and translucency, variety integrity, and high total and head (wholegrain) milled rice yield. Market quality is mainly determined by physical properties and variety name, whereas cooking and eating quality is determined by physiochemical properties, particularly AC (Table 2).

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* Philippine Rice Research Institute—Los Baños, Pili Drive, University of the Philippines at Los Baños campus, 4031 College, Laguna, Philippines.

Table 1. Effects of environment, processing, and variety on grain quality at different steps in the postharvest system[a] (Juliano and Duff 1991a; Juliano 1993).

Postharvest process	Environment	Postharvest handling	Variety	Remarks
Harvesting	+	+	+	Growth duration; photoperiod; degree of ripeness; dormancy
Threshing	+	+	+	Threshability; shattering
Drying	+	+	+	Crack resistance
Stackburning	+	+	0	Yellowing
Mycotoxins	+	+	+	Hull/husk tightness
Storage/ageing	+	+	+	
Pests	+	+	+	Hull tightness, etc.
Dehulling	0	+	+	Hull tightness/content
Milling	+	+	+	Crack resistance
Marketing				
Size and shape	+	0	+	Genetically determined
Degree of milling (whiteness)	+	+	+	Depth of grooves
Head rice	+	+	+	Crack resistance
Translucency	+	+	+	
Aroma	+	+	+	
Pecky grains	+	+	+	Stink bug resistance
Foreign matter	+	+	0	
Shelf life	+	+	0	
Cooking and eating				
Amylose content	+	0	+	Vol. expansion; texture
Gelatinisation temperature	+	0	+	Cooking time; texture
Gel consistency	+	0	+	Cooked rice hardness
Texture of cooked rice	+	+	+	
Grain elongation	+	+	+	
Nutrition				
Protein content	+	+	+	
Vit. A content	+	+	+	Yellow maize
Oil quality	+	+	+	Unsaturated fatty acids
Seed	+	+	+	Viability: vigour

[a] + = Quality affected; 0 no effect.

Grain breeding programs concentrate on varietal improvement, whereas agricultural engineers look at postharvest processes to enhance grain quality. Grain quality factors important for table rice include grain size, shape, and translucency, colour, total and head milled rice yield, aroma, cooking and eating quality, and nutritional value. These are mainly varietal in nature, but are affected also by preharvest environment and postharvest handling.

Major Grain Quality Problems

Major grain quality problems arise from lack of incentive to farmers to grow better quality rice, and are manifested in yellow rice from stackburning of wet grain, brokens from grain fissuring during drying, ageing, and storage changes, variety mixing and mislabelling in the trade, lack of screening methods to differentiate among rices with similar starch properties, lack of screening methods for special rices for rice food products, and lower protein content in yield trials. High aflatoxin level from microbial growth on wet grain is the major problem for maize and parboiled rice.

Table 2. Rice-grain apparent amylose content (AC) type preferred in various Asian countries (Juliano and Duff 1991b; Juliano and Villareal 1993).

Waxy	Low AC	Intermediate AC	High AC
Laos	China (japonica)	Cambodia	Bangladesh
Thailand (north)	China-Taiwan (japonica, indica)	China[a] (japonica)	China (indica)
		India (Basmati)	India
	Japan	Indonesia	Pakistan
	Korea, South	Malaysia	Philippines
	Nepal	Myanmar	Sri Lanka
	Thailand (northeast)	Pakistan (Basmati)	Thailand (north, central, south)
		Philippines	
		Thailand (central)	
		Vietnam	

[a] Data from China National Rice Research Institute, Hangzhou.

Lack of incentives to farmers

Lack of incentives to the Filipino rice farmer to improve grain quality was reported by Umali and Duff (1990). Given the importance of quality characteristics for creating and stimulating demand, especially among the higher income urban sector, transmission of price and market signals and a greater degree of integration at the farm to wholesale market level will be necessary to improve the farmgate price and to provide incentive to farmers to produce better quality rice. Moreover, improvements in grain quality that do not lower yields will generally benefit all rice consumers by lowering the cost of better quality rice.

Problems related to drying

Drying may be considered as the initial step of ageing. Moisture content (water activity) is the most important criterion for rough rice quality (Roettger 1982; Unnevehr et al. 1992). The traditional photoperiod-sensitive rices have more synchronous flowering and the harvested grains have fewer immature and overdried grains than nonphotoperiod-sensitive rices (Juliano 1993). Dormancy prevents preharvest sprouting of grain (Juliano and Chang 1987). The level of the major aroma principle, 2-acetyl-l-pyrroline (Buttery et al. 1983), in the aromatic variety Hieri planted in 17–24 farmers' fields at Kubokawa, Kochi, Japan during 1993–95 was similar and ranged from 60–200% of the mean value (Fusliimi et al. 1996).

Delayed drying of harvested grain may result in grain deterioration and yellowing through stackburning caused by heating of the wet grain (>20% moisture) through microbial and grain respiration (Phillips et al. 1988, 1989). Yellowing can be simulated by heating grain at 60°C (Yap et al. 1990). Yellow discoloured grains result from a nonenzymic browning type reaction (NRI 1991) and all varieties are affected. The slight cream colouration of aged rice probably involves the same mechanism. Colourless precursor products are first formed before discolouration occurs (NRI 1991). Yellow grains are harder and more translucent than unaffected grains, indicating that mainly wet grains are affected. A prediction equation for stackburning has been calculated by Wrigley et al. (1994).

Protein of yellow rice has lower lysine content than protein of sound grain and had lower net protein utilisation and protein quality in growing rats (Eggum et al. 1984) (Table 3). However, moderately yellow rice does not produce major adverse effects when fed to rats and broiler chicks in nutritionally balanced diets (NRI 1991). Stackburning of maize of less than 12.5% moisture bagged in polypropylene in lieu of jute bags has been reported, nutritionally altering the maize and making it less suitable for milling for food (Tyler 1992). Yellow rice grain is more translucent and has higher head rice yield than white rice grain (Yap et al. 1990).

Aflatoxin produced by the fungus *Aspergillus flavus* is the major problem in maize because of the practice of delayed drying of the grain (Wicklow 1994). Aflatoxin results in liver disorders and cancer in poultry, pigs, cattle, and man. Surveys in Thailand indicated that aflatoxin contamination of maize was low at harvest and increased during storage (Siriacha et al. 1991). Ears were less contaminated by *A. flavus* and aflatoxin than were the grains. Most contamination started in grains that were damaged by shelling and were not dried properly. A 1990 survey in the Philippines showed that most stocks of the maize entering trade channels were positive for aflatoxin and the levels were higher than those observed on farms (Quitco 1991).

Table 3. Comparison of properties, and of energy and protein utilization in rats, of four yellow milled rices from stackburning of unthreshed panicles plus straw with those of three ordinary milled rices (Eggum et al. 1984; Juliano 1985).

Property (at 14% moisture)	Yellow rices	White rices
Crude protein (% N × 6.25)	7.4	8.7
Lysine (g/16 g N)	3.1	3.5
Amino acid score[a] (%)	56	64
Energy content (kJ/g)	15.4	15.4
Balance data in growing rats		
Digestible energy (% of intake)	96.0	96.6
True digestibility (% of N intake)	92.0	98.4
Biological value (% of absorbed N)	66.4	67.2
Net protein utilisation (% of N intake)	61.0	66.1
Protein quality[b] (%)	52	63

[a] Based on 5.5% lysine as 100% (WHO 1985).
[b] Based on amino acid score × TD/100 (FAO 1990).

Hull or husk tightness may be a factor, as *A. flavus* can readily inoculate the ripening grain. Incidence of aflatoxin in rice in India is higher with incidence of heavy rains (cyclones) during the harvesting season (Tulpule et al. 1982). During the 4-day soaking step of parboiling, sound grain soaked in *A. flavus*-inoculated water failed to have aflatoxin, suggesting that reported high aflatoxin levels in soaked grain results from contamination of the rice grains before soaking (Yap et al. 1987). All brown rices tested were susceptible and their bran colonised by *Aspergillus* spp. (Ilag and Juliano 1982). Seed viability is adversely affected by these problems.

Drying should consider the varietal differences in critical moisture content (11–16%) below which the grain fissures upon moisture adsorption (Juliano and Perez 1993) (Table 4). All rices are resistant to fissures at 16% moisture (Juliano et al. 1993). Rough rice is stressed by soaking 1–3 hr in 30°C water before dehulling and milling in a Kett micromill. The Japanese have taken advantage of this phenomenon and adjust moisture content of grain to 15% so that head rice during milling will be high and the milled rice will not fissure during the cold water soaking phase of cooking (Satake 1994), but proper storing of the 15%-moisture rice may be a problem. Above 75% relative humidity, equilibrium moisture content is higher in waxy and low-AC rough rices than in high-AC rough rice (Juliano 1964) (Table 5). Such differences are consistent with the negative correlation of equilibrium water content of brown rice steeped in water at 30°C water with AC (Kongseree and Juliano 1972; Antonio and Juliano 1973), and with the absence of chalky regions (Antonio and Juliano 1973). Among high-AC translucent milled rices, equilibrium water content is higher in low GT than in intermediate GT rices (IRRI 1980). Fissuring is also a major problem in maize drying, because of greater susceptibility of cracked grain to disease and pest infestation.

Low-temperature drying preserves the rice aroma principle, 2-acetyl- 1-pyrroline (Itani and Fusilini 1996). Hot-sand flash drying results in parboiling in the wet season, but only drying in the dry season, with improvement of grain translucency and milling quality.

Table 4. Critical moisture content[a] for fissures in rough rice of four rices differing in crack resistance; 1990 dry and wet seasons at Los Baños, Laguna, Philippines (Juliano and Perez 1993).

Variety or line name[a]	Critical moisture content[b] (% wet basis)	
	Dry season	Wet season
CP/SLO 17	<10	12
IR60	14	13
IR74	15	16
IR42	16	16

[a] CP/SLO 17 low AC high GT; IR60, IR74, and IR42 high AC low GT.
[b] Moisture content below which rough rice fissures significantly on soaking for 1-3 hr in 30°C water.

Table 5. Equilibrium moisture content at >75% relative humidity at 27.5°C by desorption and adsorption of four rough rices differing in starch properties (Juliano 1964).

Relative humidity (%)	Equilibrium moisture content (% wet basis)				
	Waxy low GT		Low AC low GT	High AC interm. GT	Standard error
	(Malagkit Sungsong)	(Taichung Glu. 46)	(Taichung 65)	(Peta)	
Desorption isotherm					
96.5	22.3	21.7	20.4	19.6	0.18**
84	16.3	16.4	15.8	15.8	0.13*
75	14.3	14.1	14.1	14.0	0.08ns
Adsorption isotherma					
75	13.3	13.2	13.0	12.8	0.07**
84	15.4	15.6	15.0	14.8	0.09**

[a] Starting at 5% moisture.

Ageing and storage changes

Physiochemical changes (ageing) occur in the grain during 3–4 months after harvest when stored above 15°C, resulting in higher total and head rice milling yield, greater volume expansion and water absorption during cooking, with less solids in cooking liquid, and a more flaky cooked rice (Juliano 1985, 1994). The milled rice also develops a slight cream colour. Aged rice has a price premium in tropical Asia, particularly for rice products, but ageing reduces the stickiness of japonica rice. Waxy rice also undergoes ageing, and freshly harvested rice is preferred for rice products. Thus, high temperature drying reduces the quality of Japanese waxy rice crackers (Saito et al. 1974). Storage also results in loss of the more volatile components of rice aroma and of vitamins in the grain, particularly vitamin A. Some ageing also occurs during grain drying and probably during grain desiccation in the field. Insect infestation also results in quantitative and quality losses of stored grain (Juliano 1985). Growth of *Tribolium castaneum* larvae is negatively correlated with AC of rice (Vohra et al. 1980).

The lipids (fat) of rice located in the spherosomes or fat globules begin to decrease after 6 months of storage, while the level of free fatty acids increases (Aibara et al. 1986). Oxidation of the unsaturated fatty acids into carbonyl compounds (aldehydes and ketones) contributes to the stale odour of stored rice, mainly due to hexanal (Juliano 1985). Shelf life of milled rice is shorter than that of rough rice due to fat rancidity.

Viability decreases during storage at ambient temperature, with varietal differences in mean viability periods (Juliano et al. 1990).

Variety mixing and mislabelling

Grain size and shape are mainly varietal characteristics. Variety mixing and mislabelling in the market is common, and variety name in the Philippines is used to denote particular variety types rather than the variety itself (Juliano et al. 1989). Some varieties also have variable translucency, such as IR64 (Perez et al. 1990). Thus, consumers have a variable concept on the grain quality of market samples labelled by specific variety names. Authentic samples are needed to validate data from consumer surveys. Unfortunately, routine variety identification of milled rice is not yet possible (Juliano 1995). With the approval of the GATT Uruguay Round trade agreement mislabelling of cheap imported rice as local rice is a problem being addressed in South Korea.

Texture evaluation of rices with similar starch properties

As many countries achieve self-sufficiency, grain quality has become an important breeding objective (Juliano and Duff 1991b). In the Philippines and most of tropical Asia, the physiochemical properties preferred are intermediate AC and intermediate GT (Juliano and Villareal 1993) (Table 2). This type has soft cooked rice, with some degree of stickiness. Thus in the Philippines, all varieties released recently have these properties of intermediate AC and GT (Juliano 1996). Current methods for evaluating cooked rice texture are not sensitive enough to differentiate among them. Alternative approaches being pursued are hardness distribution within the cooked grain (surface vs core) and effect of amylopectin staling on cooked-rice hardness. Collaboration among chemists involved in national breeding programs should accelerate the development of such methods, as the problem is now common to most national programs.

The Philippine Rice Research Institute (PhilRice) aims to achieve softer rices, similar to premium upland rices with 18–22% AC (Juliano and Villareal

1993), by slightly lowering its AC objective from 20–25% to 18–22%. The rice has to be of low GT (for 18–20% AC) and intermediate OT (for 20–22% AC) to have the desired soft texture of freshly cooked rice (Juliano 1996).

Screening methods for special rices

Rapid screening methods for special rices, such as waxy (glutinous) and nonwaxy rices ideal for use in local traditional rice products (Juliano and Hicks 1996), are also important to ensure that such rice types are not eliminated in the breeding program. The local production and availability of wet-milled and dried flour may reverse the trend of substituting maize starch and wheat flour for wet-milled rice in traditionally rice-based products, particularly rice noodles and steamed fermented cakes.

Nutritional value

The reduction of yield and protein content in yield trial plots at PhilRice and IRRI has been attributed to insufficient available nitrogen (N) during the reproductive stage: split application of N fertilizer close to flowering has been recommended (Cassman et al. 1995, unpublished data). Rice is the principal source of protein in the tropical Asian diet (Juliano 1993) and reduction of protein content from the mean value of 7.3% down to as low as 5% would reduce the available protein in Asian diets. Hence, protein level of milled rice should at least be maintained in the new varieties. The grain should also be free of mycotoxins that can cause human cancer. International efforts to improve the level of micronutrients, vitamin A, iron, and zinc in the cereal grain have been initiated, with rices tolerant of low levels of available iron and zinc in rice soils being studied (Bouis 1995). The feasibility of introducing carotenoid biosynthesis in rice endosperm is being explored (Rockefeller Foundation 1993).

Linoleic acid content of rice oil is negatively correlated with temperature during ripening of Japanese rice (Taira et al. 1980).

Need for Interdisciplinary Research

Since most of the problems discussed here involve more than one scientific discipline, the combined inputs of agricultural engineers, biologists, chemists, social scientists, and other scientists in relevant disciplines will accelerate the effective and efficient solving of research problems, considering the limited human and monetary resources available in the region. Regional collaboration should be encouraged inasmuch as the problems are common to the region.

References

Aibara, S., Ismail, I.A., Yamashita, H., Ohta, H., Sekiyama, F. and Morita, Y. 1986. Changes in rice bran lipids and free amino acids during storage. Agricultural and Biological Chemistry, 50, 665–673.

Antonio, A.A. and Juliano, B.O. 1973. Amylose content and puffed volume of parboiled rice. Journal of Food Science, 38, 915–916.

Bouis, H. 1995. Enrichment of food staples through plant breeding: a new strategy for fighting micronutrient malnutrition. SCN (UN SubCommittee on Nutrition) News, 12, 15–19.

Buttery, R.G., Ling, L.C., Juliano, B.O., and Tumbaugh, J.O. 1983. Cooked rice aroma and 2-acetyl-1-pyrroline. Journal of Agricultural and Food Chemistry, 31, 823–826.

Cassman, K.G., De Datta, S.K., Olk, D.C., Alcantara, J.M., Samson, M.I., Descalsota, J.P. and Dizon, M.A. 1995. Yield decline and nitrogen economy of long-term experiments on continuous, irrigated rice systems in the tropics. In: Lal, R., and Stewart, B. A., ed., Soil management: experimental basis for sustainability and environmental quality. Boca Raton, Florida, USA, Lewis/CRC Publishers, 181–222.

Eggum, B.O., Juliano, B.O., Villareal, C.P. and Perez, C.M. 1984. Effect of treatment on composition and protein and energy utilization of rice and mung bean by rats. Oualitas Plantarum Plant Foods for Human Nutrition, 34, 261–272.

FAO (Food and Agriculture Organization of the United Nations) 1990. Protein quality evaluation: report of a Joint FAO/WHOJUNU Expert Consultation, Bethesda, Maryland, USA, 4–8 December 1989. Rome, Italy, FAO, 66 p.

Fushimi, T., Itani, T., Kohyama, N. and Sekiya, K. 1996. Variation of 2-acetyl-1-pyrroline concentration of the aromatic rice (cv. Hieri) cultivated at Kubokawa-area in Kochi prefecture. In: Proceedings of the 2nd Asian Crop Science Conference, Fukui, Japan, 21–23 August 1995, in press.

Ilag, L.L., and Juliano, B.O. 1982. Colonisation and aflatoxin formation by *Aspergillus* spp. on brown rice differing in endosperm properties. Journal of the Science of Food and Agriculture, 33, 97–102.

IRRI (International Rice Research Institute) 1980. Annual report for 1980. Manila, Philippines, IRRI, 25–38.

Itani, T., and Fushimi, T. 1996. Influence of pre- and post-harvest conditions on 2-acetyl-1-pyrroline concentration in aromatic rice. In: Proceedings of the 2nd Asian Crop Science Conference, Fukui, Japan, 21–23 August 1995, in press.

Juliano, B.O. 1964. Hygroscopic equilibria of rough rice. Cereal Chemistry, 41, 191–197.

— ed. 1985. Rice: chemistry and technology, 2nd ed. St. Paul, Minnesota, USA, American Association of Cereal Chemists, 774 p.

— 1993. Rice in human nutrition. Rome, Italy, Food and Agriculture Organization of the United Nations-Los Baños, Laguna, Philippines, International Rice Research Institute, 162p.

— 1994. Concerns for quality maintenance during storage of cereals and cereal products. In: Highley, E., Wright, E.J., Banks, H.J. and Champ, B.R., ed., Stored product protection: proceedings of the 6th International Conference on Stored-product Protection, Canberra, Australia, 17–23 April 1994. Wallingford, Oxon, U.K., CAB International, 2, 663–665.

— 1995. Identification of rice varieties. In: Wrigley, C.W., ed., Identification of food-grain varieties. St. Paul, Minnesota, USA, American Association of Cereal Chemists, 265–274.

— 1996. Research on rice grain quality evaluation at the Philippine Rice Research Institute. In: Proceedings of the 2nd Asian Crop Science Conference, Fukui, Japan, 21–23 August 1995, in press.

Juliano, B.O. and Chang, T.T. 1987. Pre-harvest sprouting in rice. In: Mares, D.J., ed., 4th International Symposium on Pre-Harvest Sprouting in Cereals, Port Macquarie, New South Wales, Australia, 10–14 February 1986. Boulder, Colorado, USA, Westview Press, 14–21.

Juliano, B.O. and Duff. B. 1991a. Setting priorities for rice grain quality research. In: Naewbanij, J.O., ed., Grain postharvest research and development: priorities for the nineties. Proceedings of the 12th ASEAN Seminar on Grain Postharvest Technology, Surabaya, Indonesia, 29–31 August 1989. Bangkok, Thailand, ASEAN Grain Postharvest Programme, 201–211.

— 1991b. Rice grain quality as an emerging priority in national rice breeding programs. In: Rice grain marketing and quality issues: selected papers from the International Rice Research Conference, Seoul, Korea, 27–30 August 1990. Manila, Philippines, International Rice Research Institute, 55–64.

Juliano, B.O., and Hicks, P.A. 1996. Rice functional properties and rice food products. Food Reviews International, in press.

Juliano, B.O. and Perez, C.M. 1993. Critical moisture content for fissures in rough rice. Cereal Chemistry, 70, 613–615.

Juliano, B.O., Perez, C.M. and Chang, T.T. 1990. Varietal differences in mean viability periods of rough rice stored under ambient conditions. Seed Science and Technology, 18, 361–369.

Juliano, B.O., Perez, C.M. and Cuevas-Perez, F. 1993. Screening for stable high head rice yields in rough rice. Cereal Chemistry, 70, 650–655.

Juliano, B.O., Perez, C.M., Maranan, C.L., Abansi, C.L. and Duff B. 1989. Grain quality characteristics of rice in Philippine retail markets. Philippine Agriculturist, 72, 113–121.

Juliano, B.O. and Villareal, C.P. 1993. Grain quality evaluation of world rices. Manila, Philippines, International Rice Research Institute, 205p.

Kongseree, N. and Juliano, B.O. 1972. Physiochemical properties of rice grain and starch from lines differing in amylose content and gelatinization temperature. Journal of Agricultural and Food Chemistry, 20, 714–718.

NRI (Natural Resources Institute) 1991. Postharvest discolouration of cereal grains. In: Report on operational programmes: 1989–91. Chatham Maritime, Chatham, Kent, U.K., NRI, 256–258.

Perez, C.M., Juliano, B.O., De Datta, S.K. and Amarante, S.T. 1990. Effects of nitrogen fertilizer treatment and source and season on grain quality of IR64 rice. Plant Foods for Human Nutrition, 40, 123–130.

Phillips, S., Widjaja, S., Wallbridge, A. and Cooke, A. 1988. Rice yellowing during post-harvest drying by aeration and during storage. Journal of Stored Products Research, 24, 173–181.

Phillips, S., Mitfa, R. and Wallbridge, A. 1989. Rice yellowing during drying delays. Journal of Stored Products Research, 25, 155–164.

Quitco, R.T. 1991. Aflatoxin studies in the Philippines. In: Champ, B.R., Highley, E., Hocking, A.D., and Pitt, J. I., ed., Fungi and mycotoxins in stored products: proceedings of an international conference, Bangkok, Thailand, 23–28 April 1991. Canberra, ACT, Australia, Australian Centre for International Agricultural Research, ACIAR Proceedings No. 36, 180–186.

Rockefeller Foundation 1993. Summary report: workshop on potential for carotenoid biosynthesis in rice endosperm, New York, New York, USA, 10–11 June 1993. New York, New York, USA, Rockefeller Foundation, 7 p + xii.

Roettger, U., ed. 1982. Paddy deterioration in the humid tropics: documentation of the GASGA-seminar, Baguio City, Philippines, 11–18 October 1981. Eschborn, Germany, German Agency for Technical Cooperation, 232 p.

Saito, S., Arisaka, M., Ishli, S. and Nakajima, K. 1974. Effects of rough rice drying on the rice cracker processing suitability of glutinous rice. Report of the Food Research Institute Niligata Prefecture, 13, 57–67. (in Japanese)

Satake, R.S. 1994. New methods and equipment for processing rice. In: Marshall, W. E. and Wadsworth, J. I., ed., Rice science and technology. New York, New York, USA, M. Dekker, Inc., 229–262.

Siriacha, P., Tanboon-Ek, P. and Buangsuwon, D. 1991. Aflatoxin in maize in Thailand. In: Champ, B.R., Highley, E., Hocking, A.D. and Pitt, J.I., ed., Fungi and mycotoxins in stored products: proceedings of an international conference, Bangkok, Thailand, 23–26 April 1991. Canberra, ACT, Australia, Australian Centre for International Agricultural Research, ACIAR Proceedings No. 36, 187–193.

Taira, H., Taira, H. and Fujui, K. 1980. Influence of cropping season on lipid content and fatty acid composition of rice bran and milled rice. Nippon Sakumotsu Gakkai Kjji, 49, 559–568.

Tulpule, P.G., Nagarajan, V. and Bhat, R.V. 1982. Environment causes of food contamination. New Delhi, Government of India, Department of Environment, Environment India Review - Series 1.

Tyler, P. 1992. Heat and discoloration of bagged maize. World Grain, 10(7), 14–16.

Umali, D.L. and Duff, B. 1990. The Philippine rice marketing system: implications for grain quality improvement. In: Naewbanij, J.O., ed., Advances in grain postharvest technology generation and utilization: proceedings of the 11th ASEAN Technical Seminar on Grain Postharvest Technology, Kuala Lumpur, Malaysia, 23–26 August 1988. Bangkok, Thailand, ASEAN Grain Postharvest Programme, 317–349.

Unnevehr, L.J., Duff, B. and Juliano, B.O. 1992. Consumer demand for rice grain quality: terminal report of IDRC projects. Manila, Philippines, International Rice Research Institute, Ottawa, Canada, International Development Research Centre, 248 p.

Vohra, P., Shariff, W. G. and Juliano, B. O. 1980. Relative nutritional value of some rices for growth of *Tribolium castaneum* larvae. Qualitas Plantarum Plant Foods for Human Nutrition, 30, 187–193.

Wicklow, D.T. 1994. Preharvest origins of toxigenic fungi in stored grain. In: Highley, E., Wright, E.J., Banks, H.J. and Champ, B.R., ed., Stored product protection: proceedings of the 6th International Working Conference on Stored-product Protection, Canberra, ACT, Australia, 17–23 April 1994. Wallingford, Oxon, U.K., CAB International, 2, 1075–1081.

WHO (World Health Organization) 1985. Energy and protein requirements: report of a Joint FAO/WHO/UNE Expert Consultation. Geneva, Switzerland, World Health Organization, WHO Technical Report Series 724, 206 p.

Wrigley, C.W., Gras, P.W., and Bason, M.L. 1994. Maintenance of grain quality during storage — prediction of the conditions and period of 'safe' storage. In: Highley, E., Wright, E.J., Banks, H.J. and Champ, B.R., ed., Stored product protection: proceedings of the 6th International Working Conference on Stored-product Protection, Canberra, ACT, Australia, 17–23 April 1994. Wallingford, Oxon, U.K., CAB International, 2, 666–670.

Yap, A.B., Ilag, L.L., Juliano, B.O. and Perez, C.M. 1987. Soaking in *Aspergillus parasiticus*-inoculated water and aflatoxin in parboiled rice. Human Nutrition: Food Sciences and Nutrition, 41F, 225–229.

Yap, A.B., Juliano, B.O. and Perez, C.M. 1990. Artificial yellowing of rice at 60°C. In: Naewbanij, J.O., ed., Advances in grain postharvest technology generation and utilization: proceedings of the 11th ASEAN Technical Seminar on Grain Postharvest Technology, Kuala Lumpur, Malaysia, 23–26 August 1988. Bangkok, Thailand, ASEAN Grain Postharvest Programme, 3–20.

Grain Drying in China: Problems and Priorities

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Abstract

China's annual grain harvest of 425–450 million tonnes (Mt) includes a large proportion (approx. 30 Mt) that is received at high moisture content. Grain drying is the most important factor in minimising postharvest losses, since it directly affects safe storage, transportation, distribution, and processing quality. Currently, considerable losses are incurred annually during storage and transportation of grain, as a result of inadequate drying. This paper outlines the current status of the problem.

THE People's Republic of China (China) is a vast country, with its main grain producing areas situated between latitude 20–50°N and longitude 95–120°E (Fig. 1). Within this area, geographic and climatic conditions vary greatly. This is reflected in the different grains, and varieties of grains, that are grown in China, and accounts directly for the wide range of moisture contents at which these grains are harvested. A diversity of postharvest technologies has been developed to handle and store the different grains produced in the different growing regions. Since 1984, the annual grain harvest has exceeded 400 million tonnes (Mt) and in 1994 it reached a record 450 Mt (Ren 1991). Of this, rice comprises 40–45% of China's total grain production, with wheat and maize each contributing 22% (Garnaut and Ma 1992).

Geographic Distribution of High Moisture Content Grain

Nationally, about 70% of all grain produced is kept by farmers for food, seed, and stock feed. Of the grain delivered by farmers to depots of the government Grain Handling Bureaux (GHB), approximately 30 Mt are received at high moisture content (Table 1) and must be dried. The grains involved are mainly maize and paddy, with small quantities of soybean and wheat. These grains are produced in three main growing regions (Fig. 1).

Northeast growing region

This region produces approximately 35% of the maize grown in China, which is 55–60% of the region's total agricultural production. Northeast China is characterised by its low ambient temperatures and a short growing season. These crops are harvested in autumn, a time when the weather is not always favourable for this activity. Days are short with reduced sunshine and there is usually only a short frost-free period before winter. Under such conditions it is very difficult for the crop to dry in the field. This results in a harvest of maize (and soybeans) that is taken in by the farmers at very high moisture content.

Consequently, every year GHB depots in the region receive very large quantities of high moisture content grain. When maize is received at GHB depots, its moisture content (m.c.) is normally between 22 and 30%. Thus, drying this grain to a level that permits safe storage is the principal activity of grain depots during winter and spring, an activity that must be completed before the ambient temperatures rise during summer.

Recently in this region, the area of land planted to paddy has been extended very rapidly. This is because premium rice produced in the region is better than that grown in southern China and has very good consumer acceptance. However, due to the prevailing low ambient temperature, the crop requires a considerably longer growing period than it does in southern China. Consequently, over 90% of the rice produced in the region is harvested at high moisture contents and must be dried before it can be safely stored until the following summer (Zhang 1995).

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Table 1. Geographical distribution of high moisture content grain (stored in grain depots).

Geographic location	Provinces, cities and regions	Varieties	Quantities (Mt)	Range of moisture content (%)
Northeast (maize belt)	Heilongjiang, Jilin, Liaoning and eastern Inner Mongolia	Maize	18–21	18–30
		Soybean	1–1.5	14–17
		Paddy	1–2	17–20
Centre (wheat belt)	Beijing, Hebei, Shanxi and Shandong	Wheat	0–2	14–18
		Maize	2.5–4	15–19
South (paddy belt)	Anhui, Jiangsu, Hubei, Jiangxi and Zhejing	Paddy	5–10	16–24

Central growing region

This region, which includes the city of Beijing, and Hebei, Shanxi, and Shandong, produces some 50–60% of the maize grown in China. Some 3–6 Mt of the high moisture content grain handled in China is grown in this region. The crop is normally harvested during October and November at an average moisture content of 16%, though it is not unusual for some of the crop to be harvested at up to 19% m.c. In addition, the GHB depots in this region can expect to receive some of the high moisture content grain grown in northeastern China.

Wheat is also grown in this region. The crop is harvested during May and June, a time when the weather is normally hot and dry. However, sometimes prolonged spells of rain may wet the grain before and during the harvest. This can cause the grain to sprout, and may even lead to moulding, which occurs rapidly because of the combination of increased moisture content and high ambient temperatures.

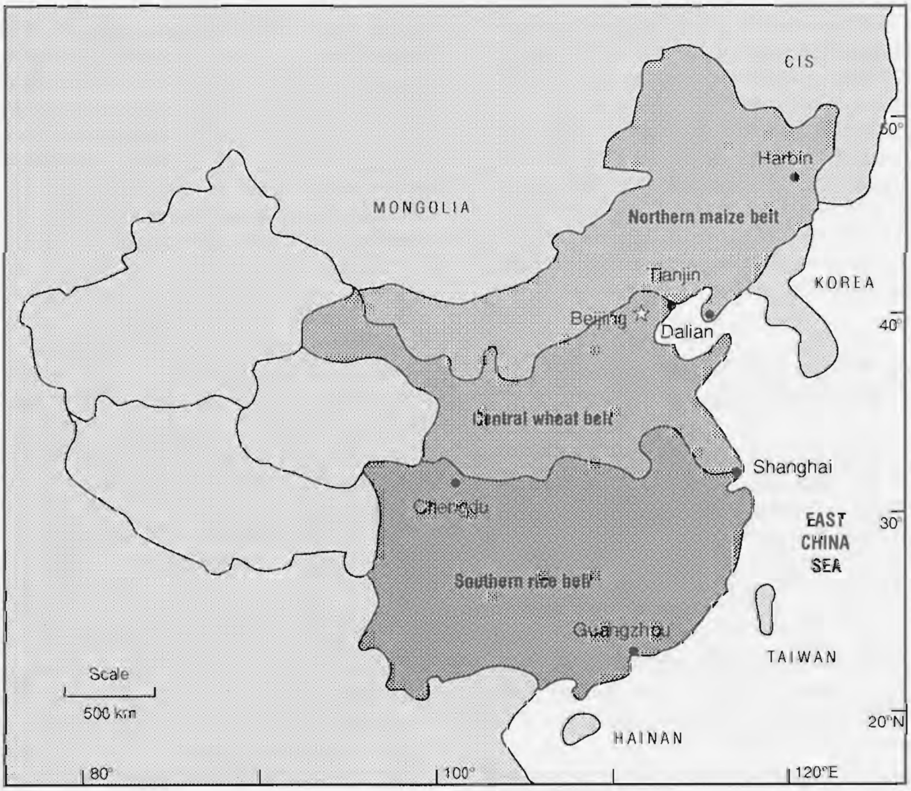

Figure 1. Map of China showing distribution of high moisture content grain.

Southern growing region

Paddy is the main crop produced in this region. Two crops are harvested annually (Wang 1986) in the provinces of Anhui, Jiangsu, Hubei, Jiangxi, and Zhejing. The second crop is harvested at a time when rain and high ambient relative humidities can be expected, which results in a harvest with moisture contents in the range 16–18%. These may rise to 20–24% in very wet years, causing losses due to moulding and sprouting (Zhuge et al. 1993). On average some 5–10 Mt of high moisture content grain are harvested annually in the region.

On-farm Grain Drying

Due to the small-scale of the farms, farm level mechanisation of postharvest handling of grain is seriously underdeveloped at present. There is a complete absence of mechanical or artificial grain drying methods at the farm level, so that sun drying and natural aeration are the only methods applied to remove moisture from 'wet' grain after the harvest. They are applied in the following ways.

In-field drying

In the northeastern and central growing regions, as the crop matures, the grain kernels cease growing and start to dry. At this stage the moisture content of the kernels is still high—around 30–40%. Nevertheless, the crop can be harvested provided proper drying facilities are available. However, traditional grain storage structures are unsuitable for preserving grain at this high moisture content. Thus, the standing crop is left in the field for about a month to dry. Normally, when it has dried to between 15–18% m.c. it is harvested. To hasten the drying process, farmers remove the husks from the cobs when the grain is in the waxy stage. This procedure not only removes moisture but also promotes maturation.

In-crib drying

Cribs built with slatted walls and floors using sorghum canes or reeds to allow easy ventilation are extensively used for drying maize on the cob. The open design allows a good flow of air through the grain, particularly when cribs are sited in the path of the prevailing wind. Such cribs are built with one or more sections, each with a capacity of approximately 6 m^3.

Seed drying

Maize on the cob, particularly for use as seed, may be dried in bundles, indoors suspended from rafters of a dwelling, or outdoors from the branches of a tree.

Sun drying

Sun drying is widely practiced and, at present, accounts for 98% of the grain dried by farmers. It is labour intensive, requiring the grain to be spread in a 2–3 cm layer and regularly turned until it has dried to approximately 12–13% m.c. In summer, with favourable weather, this usually takes two days for wheat and indica rice. However, in autumn when the maize and japonica rice are harvested, these grains can be dried to only 14–16% m.c. due to the overcast skies and weak solar radiation (Semple et al. 1992; Xu et al. 1989).

The roadside, concrete or earthen platforms, school sports fields, and even the roof tops of houses may be used for sun drying. Farmers frequently have their own drying yards in the front of their houses. Obviously, the efficiency of sun drying depends on the type and variety of grain being dried, and the locality where it is grown. However at farm level, where it is essential to prevent high moisture content grain from deteriorating, it is still the most rapid method of drying grain currently available. Losses incurred during sun drying amount to about 5% and are due to spillage, careless handling, and consumption by birds, rodents, and domestic poultry (Chi et al. 1992). Where roads are used to dry grain, considerable damage is caused to the highways so that they have to be re-paved prematurely. The costs involved in re-paving roads and highways are very high and thus the practice has been prohibited and other means for grain drying are being promoted.

Grain Drying at Government Grain Depots

Three main grain drying methods are used by the GHBs: sun drying, aeration drying, and mechanical drying. Currently, about 30% of high moisture content grain is mechanically dried, 10–25% of high moisture grain is dried by an aeration method, and the balance is sun dried.

Sun drying

This traditional method of grain drying is still widely used and is applied to 45–55% of the high moisture content grain received by the GHBs. Commonly, high moisture content grain is spread out in a 5–10 cm layer on a yard that may be paved. Most intermediate grain depots have their own drying yards, over which grain is spread and turned every 2–3 hours to ensure uniform drying (Zhang 1988). In the northeastern and central growing regions about 5 days are required to reduce the moisture content of maize by 3–5%.

In the northeastern growing region the ambient temperatures at the end of winter and the beginning of spring are very low and the relative humidity is comparatively high (Table 2).

Table 2. Ambient temperatures at the end of winter and beginning of spring in the northeastern growing region.

Month	Temperature (°C)	Relative humidity (%)
December	−12 to −16	70–75
January	−13 to −17	55–60
February	−7 to −12	40–50
March	−3 to −8	60–65

Under such conditions it is very difficult to sun dry grain to a moisture content that allows safe storage. Most grain dried in this manner is treated during a short period just before the end of spring. This is an immense task given the quantities of grain involved, particularly as the procedure is heavily dependent on good weather conditions. To complete the task in the short time available, the GHBs must seek assistance from local government agencies to provide sufficient space for the purpose. Roads, school sports fields, other paved public spaces, even airport landing strips have been used to dry high moisture content maize before the temperature rises in spring. Prolonged spells of bad weather increase the risk of losses occurring. Additionally, the handling losses incurred during sun drying can be quite substantial.

Sun drying is labour intensive and makes extensive demands on space, particularly in the case of existing large-scale operations of the centralised storage system in China, where more than 70% of the grain is handled and transported in bags. Although labour is cheap, the expense of sun drying nationwide is considerable, particularly when the costs of the losses incurred are taken into account.

This makes sun drying a very expensive operation. Some local governments have offered farmers incentives to encourage them to undertake sun drying at farm level in an effort to alleviate the problems incurred in the central storage system. However, this has not proven successful because in spring all available farm labour is required to prepare the fields for the next crop.

Mechanical drying

Design and manufacture of mechanical dryers in China commenced in the late 1950s utilising Russian design, theory, and engineering principles. The late 1970s and early 1980s were years of successive bumper crops, which created an immense grain drying problem. This situation produced the impetus to develop and extend the application of mechanical drying, which has since continued rapidly. Nowadays, most grain dryers are designed and manufactured by provincial engineering research and design institutes, or end users.

Three types of grain dryers are commonly used in China: tower dryers, rotary drum dryers, and fluidised-bed dryers (Wang 1988; Zhang 1995).

Tower dryers

Tower dryers are extremely effective where there is a need to dry very ‘wet’ grain. Thus, they are most common in the northeastern growing region, where they are used to dry maize. They are classified as direct or indirect dryers. In the former, the heated gas/air mixture makes direct contact with the grain and consequently has a higher drying and energy efficiency than the latter, where heat exchangers are used. There is, however, a risk of contamination in direct tower dryers and to minimise this risk they are usually fired with anthracite rather than lignite. Coal-fired tower dryers have a capacity in the range of 10–20 t/hour with the ability to remove 8–12% moisture per pass through the dryer. Since there is no risk of contaminating grain when indirect tower dryers are used, no special fuel arrangements are required. However, their energy consumption is greater. An example of this is the steam dryer, in which grain is dried as it falls into a drying chamber over a series of pipes heated by a water/steam mixture. This chamber is ventilated by fans that remove hot moist air resulting from the drying process.

Rotary drum dryers

Paddy is commonly dried in rotary drum dryers (Zhao 1996). These are fuelled mainly with paddy husks or coal and operate at high temperatures (grain drying temperatures of 60°C are attained). Their capacity ranges from 5–15 t/hour. Before the grain is fed into the dryer it is cleaned and preheated with hot air recycled from the dryer. Typically, such dryers can reduce grain moisture content by 3% per pass. However, they can increase the number of cracked kernels (Zhu 1988).

Fluidised-bed dryers

Fluidised-bed dryers are popular in the southern growing area for drying paddy (Zhao Simong 1996). These dryers also operate at high temperatures and are fuelled with rice husks or coal. However, grain residence time within fluidised-bed dryers is short—approximately 2 minutes. In addition, because the grain is well mixed with the drying air during the fluidising process, the capacity of such dryers is greater, ranging from 3–15 t/hour. They are capable of reducing grain moisture content by 3–5% per pass. Typically, a tempering and cooling tower is incorporated into these dryers.

Aeration drying

Use of aeration to dry grain commenced in the 1970s when engineering design for this purpose was introduced. Since then its use has spread rapidly. The form of construction required for aeration is simple. It is economic because grain is dried in-store with no extra handling costs. Aeration is used to dry maize in the central growing region and paddy in the southern growing region. Currently 70–80% of the high moisture content maize (approx. 18% m.c.) in the central growing region and 80–85% of the paddy in the southern growing region is dried by aeration. The capital investment in equipment is also lower than that required for mechanical dryers. In addition, aeration has an advantage because there is no appreciable reduction in grain quality. Aerated grain is kept fresh, retains a good colour and remains free from contaminants. Of particular importance with paddy is the increased head rice yield compared with that obtained after mechanical drying.

In the northeastern growing region, aeration is managed with reference to grain moisture content, and ambient temperature and relative humidity. After March aeration fans are operated intermittently, usually from 10:00 am to 3:00 pm when the relative humidity is low. It normally requires 35–80 days of fan operation to reduce maize moisture content from 24 to 14% without use of an additional heat source. This drying system is more economic and has added advantages of better grain quality in terms of reduced fissuring (stress cracks) and absence of mycotoxins.

Aeration is also used in the northeastern growing region as part of a two-stage drying strategy. The first stage involves use of a high temperature mechanical dryer to reduce maize moisture content to approximately 18% during winter. The second stage involves aeration, which commences around mid May.

Aeration is also extensively used in the northeastern and central growing regions to dry bulk maize and paddy stored outdoors. These grain bulks may be horizontally retained within walls of bagged grain or vertically stored in silos made of reed and/or bamboo matting. The horizontal bulks are normally 10 × 10 × 1 m (width × length × height) with a number of ducting systems to aerate the grain from the bottom of the bulk. Matting silos are generally 4–5 m high and 4–5 m in diameter, and have a capacity of 50–70 t. The grain is aerated through a duct 2–3 m long and 0.5–1.0 m in diameter that is positioned centrally at the bottom of the silo.

A number of permanent horizontal storages constructed with in-floor aeration ducts are in use in the southern growing region.

Grain Drying Problems

In China, minimisation of postharvest losses has always been a key issue in management of stored grain. This is particularly important in a situation where large quantities of high moisture content grain are involved. It is also a matter of concern when crops are wet by rain during the harvest, leading to the presence of mycotoxins (Semple et al. 1992). At present the major postharvest problem confronting the GHBs is a severe shortage of mechanical drying capacity to handle the large quantities of high moisture grain taken into storage. In the absence of mechanical drying, substantial inputs of labour, materials, and money are required to sun dry the crop (particularly maize in the northeastern growing region), and prevent moulding or other damage occurring during storage and distribution.

Before 1990, farmers were able to delay delivery of their grain to government grain depots until January of the year following the harvest and maximum receival moisture contents were set (maize at 16–20% and paddy at 16–18%). At that time approximately 20 Mt of high moisture content grain would be received into the government grain depots. Thus, on-farm storage of grain could extend for 1–2 months. However, since 1990 the amount of high moisture grain received at the government grain depots has increased rapidly. This can be attributed to:

- introduction of high yielding but late maturing maize varieties;
- successive bumper harvests; and
- a requirement for farmers to deliver grain to storage depots as soon as possible after the harvest.

A combination of these factors means that enormous quantities of very high moisture content grain have to be dried and delivered to the GHBs over a very short period, a task that is virtually impossible given China's lack of on-farm drying capacity. Thus, the total amount of high moisture grain delivered to the GHBs has risen by 10 Mt compared with the period before 1990. Another important administrative factor influencing delivery of high moisture grain is the policy of imposing only low penalty rates when high moisture grain is delivered to the GHBs.

In the case of maize, the maximum moisture content for grain received into GHBs was raised by 2–5% to facilitate the requirement for early delivery. In practice much of the maize harvest is frozen when it is taken into storage. This is because farmers must wait until the maize is frozen on the cob by low winter temperatures before it can be shelled. Otherwise the grain would be severely damaged by mechanical shelling due to its high moisture content.

Under the existing management system, GHBs now have to procure immense quantities of high moisture content maize within a short period after the harvest. Although ambient temperatures are low and such grain can be stored through winter until late February without drying, this strategy presents great risks (Wang 1988). In years when frosts are early, the problem is further exacerbated, and even greater amounts of high moisture content maize are delivered to the GHBs.

The high moisture content paddy harvests in the southern growing region present a second serious grain drying problem in China. Their average moisture content is lower than that of maize, but the higher ambient temperatures in southern China greatly increase the risk of deterioration. Thus, it is essential to dry the paddy harvest as rapidly as possible (Wang 1988). It has been shown (Zhuge et al. 1993) that a 3–5 day delay in drying paddy adversely affects germination rate, reduces head rice yield and, in indica varieties, produces a significant increase in the number of discoloured grains.

Grain Drying Priorities

It is estimated that, by the year 2000, grain production in China could reach an upper limit of 500 Mt (Garnaut and Ma 1992). Should this figure be achieved, the quantity of high moisture content grain produced, and the problems associated with it, would become very difficult to manage in the existing organisational structure. However, grain production has not kept pace with the demand of China's growing population. The gap between demand and supply has increased in recent years because grain consumption has increased more rapidly than production. To solve this food crisis, a need has been identified to tap new food resources and also to reduce postharvest losses

China in its ninth Five Year Plan has set national priorities for its grains postharvest industry which include the need to:

- establish effective management of its grain reserves;
- change from bag to bulk handling;
- reduce postharvest losses caused by insects and moulds;
- introduce new, non-polluting, processing methods for flour, oilseeds, rice and soybeans; and
- establish new national standards.

Steps have been taken to improve national grain storage, handling, and distribution ability through the China Grain Distribution and Marketing Project. This project will modernise the operations of the GHBs by providing a large number of bulk grain storage complexes incorporating mechanical grain drying facilities.

Specifications for these mechanical dryers will vary relative to the anticipated capacity of primary and intermediate storage depots at which they will be situated. Small-capacity dryers, to dry grain delivered by farmers, will be installed at primary depots. Large capacity dryers will be installed at intermediate depots where it is anticipated that greater quantities of maize from both farmers and some primary depots will have to be dried.

Investigations have been undertaken to study aspects of drying frozen grain (Liu et al. 1995). Other research that may be relevant was the demonstration that drying methods can affect storability. Maize dried at high temperatures has been shown to have reduced storability, while the effect of previous storage at high moisture contents can also decrease subsequent storability (Marks and Stroshine 1995). Whether this is applicable to high moisture content maize stored at freezing temperatures may have to be investigated further.

Design calculations have been carried out to minimise fissuring during mechanical drying of rice (Bakker-Arkema et al. 1994), and suggestions have been made that paddy losses in southeastern coastal areas of China may be minimised by developing husk fired mechanical dryers (Chi et al. 1992).

Priorities for drying high moisture content grain in China should be examined and established on a holistic systems basis commencing with grain production, harvesting, then proceeding through postharvest storage and handling, and distribution to end users. The major problem throughout the system is the lack of mechanical drying capacity. The requirements at each stage of the system may be broadly divided into hardware and policy (or management) requirements.

Hardware requirements include:

- design and development of mechanical drying systems, and regimes, specifically to accommodate the difficulties associated with drying frozen grain in the northeastern growing region (Dayanghirang et al. 1993; Liu et al. 1995; Ju 1996);
- development of drying regimes that minimise grain fissuring (Sutherland and Ghaly 1982; Kunze 1996);
- design and development of aeration-based drying strategies including computer simulations and control technology (Ghaly 1978; Wilson 1987, 1988, 1990a, 1990b; Wilson and Nguyen 1988; Abawi 1996; Cao and Ha 1996; Newman 1996; Zhao 1996);
- modelling drying regimes (Ghaly et al. 1974; Ghaly and van der Touw 1982; Sutherland and Ghaly 1982; Ghaly and Sutherland 1983, 1984; Driscoll et al. 1987);
- modelling moisture migration in stored grains (Thorpe 1996);
- application of computer based decision support systems for cost effective control of drying processes (Halid et al. 1995).

Policy requirements include:

- modernising farm-level postharvest technology as a means for improving the socioeconomic environment (Xu et al. 1989; Chi et al. 1988, 1992; Zhuge et al. 1993; Fegan 1996; Tumambing 1996);
- adjustment of prices paid for grain relative to production costs (Zhuge et al. 1993);
- introduction of price penalties for grain delivered at moisture contents exceeding the established limits;
- selection, breeding and introduction of *early maturing* high-yielding maize (and other grain) varieties that ripen early (prior to the onset of winter in the case of maize).

In the last 15 years China has moved away from a system of agricultural production and marketing based on communes, with rigid central planning and control, to a more decentralised and market-orientated system (Watson 1996). Previous policies emphasised self-sufficiency at all levels. Grain drying, and priorities for grain drying, are currently being addressed as China restructures its grain storage system through the China Grain Distribution and Marketing Project.

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References

Abawi, Y. 1996. Minimum daily temperatures as a predictor of dewpoint temperature. These proceedings.

Bakker-Arkema, F.W., Widayat, H., Hines, R.E., and Heng, C.H. 1994. A new rice drying system for China. Design calculations. Paper presented at the XII World Congress on Agricultural Engineering, Milan, Italy, 29 August–1 September 1994, 1569–1575.

Cao Guangzhi and Ha Zhenfang 1996. Grain condition detection, analysis, and control system. These proceedings.

Chi Ren-yong, Zhuge Gen-zhang, and Wan Shan-yang 1992. Loss assessments and factor finding analysis of grain post-production systems in China. In: Naewbanij, J.O., ed., Proceedings of the Thirteenth ASEAN Seminar on Grain Postharvest Technology, Bandar Seri Begawan, Brunei Darussalam, 4–7 September 1990, 370–392.

Chi Renyong, Zhuge Genzhang, and Zhang Boqi. 1988. Grain distribution and pricing system at farmer and state levels in the People's Republic of China. In: Naewbanij, J.O., ed., Advances in Grain Postharvest Technology Generation, Proceedings of the Eleventh ASEAN Seminar on Grain Postharvest Technology, 23–26 August 1988 Kuala Lumpur, Malaysia. ASEAN Grain Postharvest Programme, Bangkok, Thailand, 101–108.

Dayanghirang, D.D., Ghaly, T.F., Sutherland, J.W., and Patil, B.G. 1993. Heat induced damage in maize grains as a consequence of fluid bed drying. In: Naewbanij, J.O. and Manilay, A.A., ed., Proceedings of the Fourteenth ASEAN Seminar on Grain Postharvest Technology, Manila, Philippines, 5–8 November 1991, 267–273.

Driscoll, R.H, Adamczak, T., and Samsuddin, A. 1987. Control options for in-store drying. In: de Mesa, B.M., ed., Grain Postharvest Systems, Proceedings of the Tenth ASEAN Technical Seminar on Grain Postharvest Technology, Bangkok, Thailand, 19–21 August 1987, 44–51.

Fegan, B. 1996. Socioeconomic factors as determinants of technology requirements. These proceedings.

Garnaut, R. and Ma Guonan. 1992. Grain in China. East Asia Analytical Unit, Australian Department of Foreign Affairs and Trade, vii + 152.

Ghaly, T.F. 1978. An aeration trial of bulk stored peanuts for the control of insect infestation and quality loss. Journal of Stored Products Research, 14, 45–51.

Ghaly, T.F., Edwards, R.A., and Ratcliffe, J.S. 1974. Heat sensitivities of air drying wheat—a proposed technique to predict properties of exit product of a spouted bed drier. Journal of Agricultural Engineering Research, 19, 289–298.

Ghaly, T.F. and Sutherland, J.W. 1983. Quality aspects of heated-air drying of soybeans. Journal of Stored Products Research, 19, 31–41.

— 1984. Heat damage to grain and seeds. Journal of Agricultural Engineering Research, 30, 337–345.

Ghaly, T.F. and van der Touw, J.W. 1982. Heat damage studies in relation to high temperature disinfestation of wheat. Journal of Agricultural Engineering Research, 27, 329–336.

Halid, H., Longstaff, B.C., and Turner, J. 1995. Decision support tools for grain quality maintenance in the ASEAN Region. Paper presented at the 17th ASEAN Technical Seminar on Grain Postharvest Technology, Lumut, Perak, Malaysia, 25–27 July 1995, 12p.

Ju Jin Fang 1996. Current practices and future prospects of grain drying in Heilongjiang Province of China. These proceedings.

Kunze, O. 1996. Effect of drying on grain quality. These proceedings.

Liu Qiang, Cao Chong Wen, Montross, M.D., Bakker-Arkema, F.W., and Hines, R.E. 1995. Frozen water content in maize at low temperatures and its effect on dryer performance. Paper presented at the 1995 International summer Meeting of the American Society of Agricultural Engineers, Chicago, USA, 18–23 June 1995.

Marks, B.P. and Stroshine, R.L. 1995. Effect of previous storage history, hybrid, and drying on the storability of maize grain (corn). Journal of Stored Products Research, 31, 343–354.

Newman, C.J.E. 1996. Design parameters for aeration and drying systems. These proceedings.

Ren Yonglin 1991. Outdoor storage of grain in China. GASGA Newsletter, 15, 16–17.

Semple, R.L., Hicks, P.A., Lozare, J.V., and Castermans, A., ed. 1992. Grain storage systems in selected Asian countries. Proceedings of the Workshop/Study Tour of Grain Storage Systems, Zheijang Province, People's

Republic of China, May 1988. Regnet–UNDP/FAO Project RAS/86/189. Bangkok, Reapasia Publication, 111–159.

Sutherland, J.W. and Ghaly, T.F. 1982. Heated air drying of oilseeds. Journal of Stored Products Research, 18, 43–54.

— 1992. Rapid fluid bed drying of paddy rice in the humid tropics. In: Naewbanij, J.O., ed., Proceedings of the Thirteenth ASEAN Seminar on Grain Postharvest Technology, Bandar Seri Begawan, Brunei Darussalam, 4–7 September 1990, 168–180.

Thorpe, G.R. 1996. Modelling moisture migration in stored grains. These proceedings.

Tumambing, J. 1996. Small-scale grain dryers. These proceedings.

Wang Hanbin 1986. Low temperature and CA storage of rice in bag in China. Paper presented at the Regional Workshop on Warehouse Management of Bag Storage of Grains, New Delhi, India, 8–17 September 1986. FAO/UNDP/Indian Ministry of Food and Civil Supplies.

— 1988. Overview of grain drying in China. In: Research and Development Issues in Grain Postharvest Problems in Asia. GASGA Executive Seminar Series, 2, 28–30.

Watson, A.S. 1996. Principles of grain marketing: some lessons from Australian experience. Canberra, ACIAR Technical Reports, No. 38, 47p.

Wilson, S.G. 1987. A theoretical transient model for the study of thermal and moisture boundary layers during aeration of paddy in a cylindrical silo. Division of Entomology Report No 39, CSIRO Australia, 27p.

— 1988. Simulation of thermal and moisture boundary-layers during aeration of cereal grain. Mathematics and Computers in Simulation, 30, 181–188.

— 1990a. DUCT: a PC program for sizing and evaluating grain-store ducts. In: Fleurat-Lessard, F. and Ducom, P. ed., Proceedings of the 5th International Working Conference on Stored-Product Protection, Bordeaux, France 9–14 September 1990, 1833–1841.

— 1990b. AERATE: a PC program for predicting aeration performance. In: Fleurat-Lessard, F. and Ducom, P. ed., Proceedings of the 5th International Working Conference on Stored-Product Protection, Bordeaux, France 9–14 September 1990, 1843.

Wilson, S.G. and Nguyen, T.V. 1988. Wet problem regions remaining after in-bin drying: a two dimensional model showing the formation of cool wet wall-regions during in-bin drying of wheat. Paper presented at the Sixth International Drying Symposium, Versailles, France, September 1988.

Xu, J., Zhuge, G.Z., and He, Y. S. 1989. Factors limiting the development of grain post-harvest technology in the area around Tai-Hu Lake in South China. In: de Mesa, B.M. ed., Grain Postharvest Systems. Proceedings of the Tenth ASEAN Technical Seminar on Grain Postharvest Technology, Bangkok, Thailand, 19–21 August 1987, 271–278.

Zhang Menghao 1988. Corn Drying Methods. In: Foodgrain Storage Structures and Methods, Report on FAO/UNDP/AFMA/CHINA Training Workshop 24–29 August 1987, Wuxi City, The People's Republic of China, 34–37.

— 1995. Techniques and equipments for drying paddy rice. Paper presented at the 17th ASEAN Technical Seminar on Grain Postharvest Technology, Lumut, Perak, Malaysia, 25–27 July 1995.

Zhao Simong 1996. Rice drying technology in China. These proceedings.

Zhu Zhugang 1988. Drying of High Moisture Paddy Rice. In: Foodgrain Storage Structures and Methods, Report on FAO/UNDP/AFMA/CHINA Training Workshop 24–29 August 1987, Wuxi City, The People's Republic of China, 27–33.

Zhuge Genzhang, Chi Renyong, He Yangshen, Huang Zuhui, He Yung, and Son Dulin. 1993. The Grain Postproduction System in China. In: Naewbanij, J.O. and Manilay, A.A., ed., Proceedings of the Fourteenth ASEAN Technical Seminar on Grain Postharvest Technology, Manila, Philippines, 5–8 November 1991, 21–37.

Problems and Priorities of Grain Drying in Indonesia

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Abstract

The current status of grain drying in Indonesia is discussed at various levels: farmers, cooperatives, private millers, collecting traders, feed industries, and seed processors. The performance of various grain drying systems operating in the field is also discussed. In relation to grain processing, constraints to the adoption of mechanical dryers are analysed, and the opportunities for grain drying development in the near future are illustrated.

INDONESIA is a significant grain producer. Output of paddy in 1994 was 46.7 Mt (MOA 1995), and in 1993, 6.6 Mt of maize and 1.7 Mt of soybeans were grown (BPS 1994). All the grain enters a postharvest chain in which drying is one of the key operations.

There are three major groups in Indonesia handling primary grain processing, including drying: the first group is farmers, who dry grain at the first stage from the initial harvested moisture content to about 18–20%; the second is cooperatives, private millers, wholesalers, and feed industries who dry grain at the second stage, from 18–20% to the final moisture content appropriate for storage; and the third group is seed processors, who dry grain from the harvested moisture content (22–25%) to the storage moisture content (12–13%) in a single operation.

In general, the farmers apply sun drying regardless of weather conditions, leading to maximum quality losses of about 4.5% for paddy (IDRC 1989), 8.25% for maize (Purwadaria 1988), and 4.0% for soybean (Purwadaria 1988) because of delay in drying during the wet season. During the wet season, private millers use mechanical dryers, but only as needed to supplement their large (1–2 ha) sun-drying floors. The collecting traders at the provincial capitals, and the feed industries, make use of mechanical dryers for locally purchased grain when its moisture content is higher than their required standard, 12–14%. The seed processors use mechanical dryers both in dry and wet seasons, complemented by the drying floor.

Data on dryer development in Indonesia have been sparse and inaccurate. BPS (Central Bureau of Statistics 1994) reported that the number of dryers increased from 1975 units in 1990 to 7034 units in 1993, but gave no information on the type and the capacity of the dryers. The figures might include the sun-drying floors of private millers. In an effort to characterise dryer development in Indonesia, the author carried out a survey of drying equipment associated with BULOG (National Logistics Agency), the Ministry of Agriculture, Cooperatives and Small Enterprises Development, and the Ministry of Industry in Jakarta, made field observations in South Sumatra and East Java covering various dryer manufacturers and dealers, and reviewed the available literature. Though much time was spent and many worthwhile observations were made and are reviewed here, it should be noted that this paper contains case studies and subjective analyses based on limited interviews. It is the author's hopes that this short report will stimulate a more detailed study by all parties concerned with dryer development in Indonesia, to identify the steps needed to improve implementation of grain drying technology among the various target groups mentioned.

Current Status of Grain Drying in Indonesia

Grain drying at farm level

Farmers commonly sun dry their grain on whatever land they have available, either the field or the yard around their houses. On 60 m^2 of land, a farmer can sun dry 2.4 t of paddy, which is the average produc-

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tion per 0.5 ha in Indonesia. Some farmers who do not have sufficient land for sun drying will sell to collecting traders called 'penebas', their mature grain as it stands in the field. The yield will be estimated and agreed to by both parties and the cost of harvesting will be borne by the penebas.

Grain drying at cooperatives

The government has provided the KUD (village unit cooperatives) with milling machines, sun-drying floors, godowns, and mechanical dryers. The distribution of KUD sun-drying floors and mechanical dryers in various provinces in Indonesia is shown in Table 1. The estimate of the total drying capacity is 39 504 t/batch on the total sun drying floor and 10 575 t/batch for all types of mechanical dryers. However, the real numbers of mechanical dryers operating in the field might be less than 5%, leaving the sun-drying floor as by far the primary means of grain drying.

Grain drying and seed processors

The seed processors use mechanical dryers in conjunction with the sun-drying floor. The largest rice seed supplier—a public company—its main station in West Java, which produces 14 000 t rice seed/year has 14 units of flat bed dryers with a total capacity of 148 t paddy/batch and 6 units of circulating dryer with a total capacity of 60 t paddy/batch. In addition to the mechanical dryers, the seed processor uses sun-drying floor with an area of 2 ha. About 75% of the total seeds produced are processed through the mechanical dryers.

Grain drying at other commercial operations

Various mechanical dryers are used by the private millers and the collecting traders, but their function is to complement sun drying, especially in the wet season. Whilst the area of the sun-drying floor at the pri-

Table 1. Sun-drying floor and mechanical dryers owned by KUD (Village Unit Cooperatives) at various provinces in Indonesia*

No.	Province	Sun-drying floor		Total capacity (tonnes paddy/ batch)	Mechanical dryer, units				Total capacity (tonnes paddy/ batch)
		Units	Area, m^2		LISTER	Flat bed		Bin dryer	
						Paddy husk	Diesel oil		
1.	Aceh	26	31 200	1 248	12	22	55	–	320
2.	North Sumatra	179	116 400	4 656	22	30	18	–	412.8
3.	West Sumatra	12	14 400	576	22	20	23	–	380.8
4.	Riau	–	–	–	10	10	–	–	160
5.	Jambi	–	–	–	10	10	6	–	169.6
6.	South Sumatra	58	34 800	1 392	33	30	–	–	516
7.	Lampung	8	9 600	384	28	20	39	–	874.4
8.	West Java	285	189 000	7 560	69	78	180	3	1 710.8
9.	Central Java	120	84 000	3 360	42	50	21	2	917.6
10.	Yogyakarta	21	15 000	600	–	–	10	–	16
11.	East Java	354	234 000	9 360	40	50	91	3	1 095.6
12.	Bali	38	27 000	1 080	6	–	12	2	271.2
13.	West Nusa Tenggara	89	60 600	2 424	43	30	71	–	844.4
14.	East Nusa Tenggara	70	42 000	1 680	–	20	40	–	144
15.	West Kalimantan	3	3 600	144	59	30	29	–	874.4
16.	Central Kalimantan	–	–	–	2	–	–	–	24
17.	South Kalimantan	4	4 800	192	3	30	37	–	215.2
18.	North Kalimantan	8	9 600	384	25	20	21	–	413.6
19.	South Sulawesi	164	111 600	4 464	39	50	117	1	945.2
20.	South East Sulawesi	–	–	–	–	–	–	3	270
	TOTAL			39 504	465	500	889	14	10 575.6

Capacity of sun-drying floor 0.04 tonnes paddy/m^2, LISTER 12 tonnes paddy/batch, flat bed dryer 1.6 tonnes paddy/batch (diesel oil) and 4 tonnes/batch (paddy husk), bin dryer 90 tonnes paddy/batch.

*Ministry of Cooperatives and Small Enterprises Development (1995).

vate millers could be estimated (Table 2), data on the numbers of mechanical dryers are not available. A rough estimate is that less than 10% of the rice-milling capacity has passed through mechanical dryers. Most of the mechanical dryers are purchased by the large-scale rice millers with a capacity of 1200 t/year or higher. This figure was obtained by taking the average capacity for the large-scale milling machines in Table 2. An IDRC-sponsored study by IPB (IDRC 1988) reported that an optimal scale for KUD rice milling was 2600 t of paddy plus 1000 t of maize per year when it had a mechanical dryer with 10 t grain/batch capacity, a sun-drying floor with an area of 1000 m^2, and a milling machine with a capacity of 5 t/hour.

Some feed industries receive locally produced maize and use large-capacity mechanical dryers such as 70 t/hour continuous dryers of U.S. origin (Table 3). Others purchase most of their supply from imported maize already at 12% moisture content (m.c.), and thus do not dry. Imported maize in 1993 reached about 1.1 Mt compared to 6.6 Mt of locally produced maize. The feed industries, in general, are making concentrate while the poultry shops or the poultry farmers add more ground maize to produce the final formulation for feeding chickens. The poultry shops and farmers obtain their maize from the collecting traders, or directly from the farmers who sun dry it. A major feed company has five branches in the big cities in Indonesia—Medan, North Sumatra; Bandar Lampung, Lampung; Jakarta; Semarang, Central Java; and Surabaya, East Java—and operates five units of continuous dryer, each of 70 t/hour capacity, and drying maize at up to 100–200 000 t/year/unit.

Types of mechanical dryers

Commercial mechanical dryers in operation, and their performance, are listed in Table 3, and compared with the pit dryer adopted by maize farmers (ACPHP 1988) and sun drying. The rate of sun drying (0.3–0.5% m.c. dry basis/hour) is lower than all mechanical drying (1.1–1.9% m.c. dry basis/hour) but, except for the 70 t/hour continuous dryer (Rp 4.0/kg), the cost of sun drying (Rp 7.5–9.0/kg) remains competitive with that of mechanical drying (Rp 6.4–13.4/kg). The imported Japanese-made dryers were obtained through a Japanese grant, while Taiwan and U.S.-made dryers were purchased commercially. One dealer confided that he had sold 25 units of a Taiwanese circulating dryer with a 6 t/batch capacity at East Java and West Nusa Tenggara in 1994–1995. More recently, a 5 t/hour fluidised-bed dryer was imported from Thailand and set up at one of the DOLOG technical units in Aceh. Its performance has yet to be documented.

The locally manufactured mechanical dryers commonly come as flat bed (Fig. 1), circulating (Fig. 2), and continuous-flow (Fig. 3) types. In general, the manufacturers produce mechanical dryers only to order while primarily engaged in the manufacture of other agricultural machinery such as hand tractors, threshers, rice milling units, and food and wood processing equipment. One manufacturer of a 15t batch circulating type dryer in East Java claimed that it sold only 9 units in 1988–1989. Another, in South Sumatra, reported of selling 11 units of a 5 t/hour continuous dryer for agricultural products in 1993–1995. Two of the units were used for paddy and maize drying, while the others were for coffee beans and black pepper. At least five manufacturers and three workshops are capable of manufacturing dryers: PT Agrindo, PT Meco Inoxprima, CV Alpha Omega, and PT Adhi Setia Utama Jaya at Surabaya, East Java; CV Gunung Indah at Lumajang, East Java; PT Maju Bersama and PT New Ruhaak at Jakarta; and Lukman at Palembang, South Sumatra.

Some other types of mechanical dryer are being introduced (Table 4) such as the solar collector (Trim and Gordon 1991; Damardjati et al. 1991), and the low temperature in bin drying system (CDAE 1995). Two mechanical dryers implemented at the KUD, the flat bed dryer using paddy husks as fuel and the Lister are no longer used, due to technical and cost disadvantages (IDRC 1988).

Table 2. Number of rice millers and their milling capacity in Indonesia, 1993

No.	Type of milling machine	Units	Milling capacity (tonnes/year)	Estimated area of sun-drying floor	
				Size (m^2)	Total area (ha)
1.	Large scale, > 0.5 tonnes/hr	1 618	2 047 335	1 200–20 000	955
2.	Small scale, < 0.5 tonnes/hr	40 663	21 005 622	200–1 200	1 220
3.	Compact rice milling unit < 0.5 tonnes/hr	26 035	12 903 324	200–400	781
4.	Polisher ~ 0.3 tonnes/hr	182	62 547	200–400	6
5.	Huller < 0.3 tonnes/hr	63	29 425	200–400	2
6.	Engelberg < 0.3 tonnes/hr	6 328	1 488 419	200–400	190
	Total		37 536 672		3 154

*Bulletin Info Agroekonomi, Ministry of Agriculture. 1994.

Table 3. Performances of sun-drying floor and various mechanical dryers in commercial operation in Indonesia.

Items	Sun-drying floor	Flat bed, diesel oil	Pit dryer	Circulating dryer					Continuous dryer, USA
				Indonesia		Taiwan	Japan 1	Japan 2	
Commodity	Paddy	Paddy	Cob Maize	Shelled Maize	Paddy	Paddy	Paddy	Paddy	Shelled Maize
Capacity, tonnes/batch	0.04 (t/m^2)	15	1	15	15	6	20	5	70 (t/hr)
Initial moisture content									
% w.b.	25	20	30	26	24	25	20	20	20
% d.b.	33	25	43	35	31	33	25	25	25
Final moisture content									
% w.b.	14	12	17.5	17	14	14	12	12	12
% d.b.	16	14	21	20	16	16	14	14	14
Drying temperature, °C	42	41	65	78	41	41	40	40	75
Drying time, hrs	16–24 (dry season) 24–32 (wet season)	15	13	8	11	11	7	10	–
Drying rate, % d.b./hr	0.3–0.5	0.7	1.7	1.9	1.4	1.5	1.7	1.1	–
Fuel consumption, L diesel oil/tonnes water removed	–	138	61 kg maize cob/t	110	110	110	110	106	26
Drying cost, Rp/kg*	7.5–9.0	13.4	12	7.0	8.0	6.4	9.0	7.0	4.0
Cent $US/kg	0.33–0.39	0.59	0.53	0.30	0.35	0.28	0.39	0.33	0.18

1 Cent $US = Rp 22.80
*not including the investment cost

Figure 1. Flat-bed batch dryer of 10 t capacity at a seed processor in West Java. (below)

Figure 2. Two units of a 15 t/batch circulating dryer in East Java. (right)

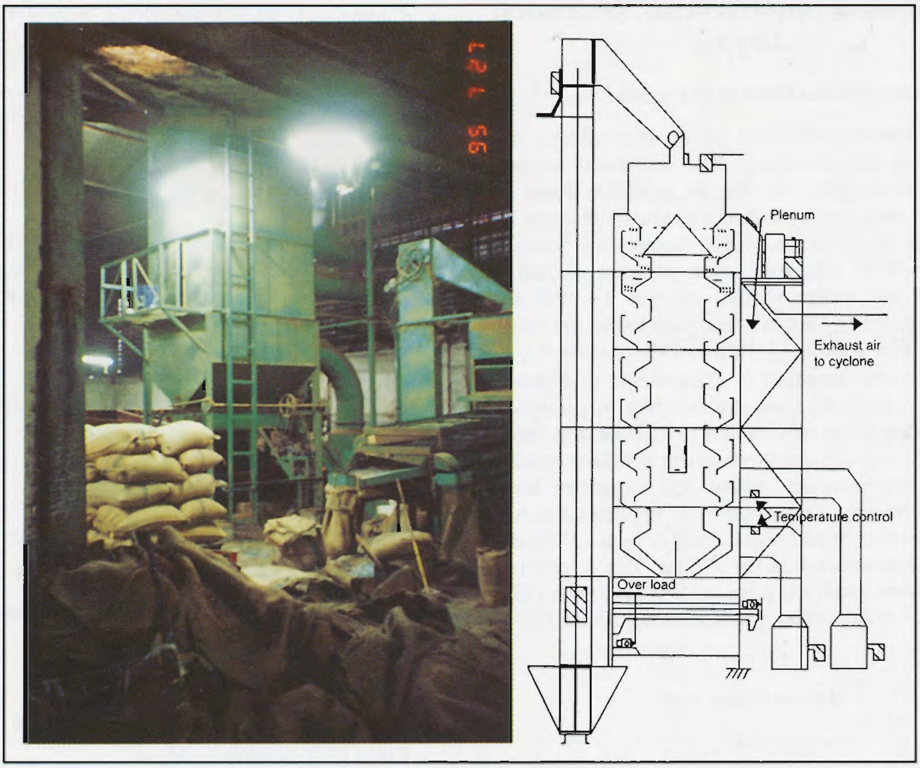

Figure 3. Cascading continuous-flow dryer of 5 t/hour throughput, used for drying rice and coffee beans in South Sumatra.

Table 4. Performances of various mechanical dryers from experimental results.

Items	LISTER[a]	Flat bed, paddy husk[a]	Solar collector[b]	LT-IBDS[c]
Commodity	Paddy	Paddy	Paddy	Paddy
Capacity, tonnes/batch	11	4	10	5
Initial moisture content				
% w.b.	24	24	25	22.5
% d.b.	31	31	33	29
Final moisture content				
% w.b.	14	14	14	12
% d.b.	16	16	16	14
Drying temperature, °C	38	38	45- day, 35 night	36
Drying time, hours	21	21	50	94
Drying rate, % d.b./hr	0.7	0.7	0.34	0.16
Fuel consumption, L diesel oil/ tonnes water removed	96	52 litres diesel oil 107 kg paddy husk	9	128
Drying cost, Rp/kg	9.0	9.4	16.4	18.7
Cent US$/kg[d]	0.39	0.41	0.72	0.82

1 Cent US$ = Rp 22.80
LT-IBDS= Low Temperature In-Bin Drying System
[a] IDRC, 1988; [b] Trim and Gordon, 1991 and Damardjati et al., 1991; [c] CDAE, 1995; and [d]not including the investment cost.

Problems in Implementing Mechanical Drying

No incentive for farmers to dry grain

Most farmers sell their paddy immediately after harvesting and threshing. The harvested moisture content of the paddy in the dry season is about 20–23% wet basis (w.b.) and in wet season is about 24–30% w.b. Soybean and maize farmers are forced to sun dry their produce, since soybean should be threshed and maize shelled only at 17–18% m.c. (w.b.). However, farmers rarely complete the second stage of drying from 17–18% to 14% m.c. (w.b.).

The present situation is exemplified in Figure 4. Currently, BULOG does not interfere in paddy purchasing and buys only milled rice. Thus, the market standard overrules the government standard referring only to the moisture content and impurities levels. During the wet season harvest in February–April 1995, the price of paddy at 27% m.c. (w.b.) (37% d.b.) and 6% impurities was Rp 410/kg (Fig. 4, point A). On the other hand, the price at 23% m.c. (w.b.) (30% d.b.) and 4% impurities was Rp 540/kg (point B).

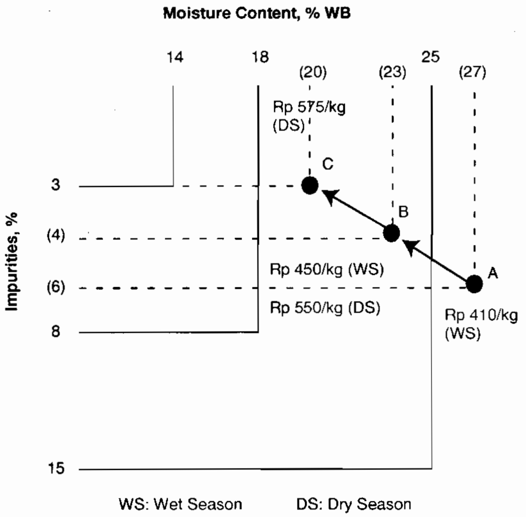

Figure 4. Diagram explaining market standards and price differentials for paddy in 1995.

Taking 1 tonne of paddy, the incentive calculation goes as follows

A: Value of 1 tonne paddy = Rp 410 000

B: Weight loss due to removal of moisture content
37% d.b. – 30% d.b./100% × (1 – 0.27) t = 0.05 t

Weight loss due to reduction of impurities =
6% – 4%/100% × 1 t = 0.02 t

Remaining weight of paddy =
1 – 0.05 – 0.02 = 0.93 t = 930 kg

Value of remaining paddy =
930 kg × Rp450/kg = Rp 418 500

Farmers will gain Rp 8500/t when they dry and clean paddy from A to B but taking into account the minimum cost of sun drying, which is Rp 7500/t (Table 3), the effort is hardly worthwhile.

In the dry season of July–September 1995, the price of paddy increased to Rp550/kg at 23% m.c. (w.b.) (30% d.b.) and 4% impurities (point B) and Rp575/kg at 20% m.c. (w.b.) (25% d.b.) and 3% impurities (point C).

B: Value of 1 t paddy = Rp 550 000

C: Weight loss due to removal of moisture content =
30% d.b. – 25% d.b./100% × (1 – 0.23) t = 0.038 t

Weight loss due to reduction of impurities =
4% – 3%/100% × 1 t = 0.01 t

Remaining weight of paddy =
1 – 0.038 – 0.01 = 0.952 tonnes = 952 kg

Value of remaining paddy =
952 kg × Rp575/kg = Rp547 400

In this case, even before counting the drying cost, the farmers will lose Rp2600/t rather than gain any added value.

More competitive investment for sun-drying floors

At the village level, where the cooperatives and the private millers are located, land remains relatively cheap. For example, in the Lumajang district, East Java, where a workshop manufactures 15 t/batch mechanical dryers at a selling price of Rp40 million and a dealer offers 6 t/batch imported dryers for Rp30 million, an entrepreneur can purchase 0.5 ha of land, meaning 150–200 t/batch, at Rp40 million. Land purchase is even more attractive, since land increases in value in the long term rather than depreciating. Furthermore, the entrepreneur can submit the land title as collateral to the bank to obtain credit. No bank will take a mechanical dryer as credit collateral.

Influence of weather on sun drying for some rice belt areas

Land prices are not so attractive in the urban areas such as Karawang district, the rice belt area of West Java—the largest rice-producing province in Indonesia—where the price of 0.5 ha block could be as high as Rp250–300 million.

Nevertheless, looking at the average rainfall distribution through the year (Fig. 5), one can understand the justification for wide use of sun drying, since the only months with average rainfall above 200 mm are January (330 mm) and February (240 mm). The peak harvest in the wet season comes in March–April, when average rainfall is below 200 mm/month.

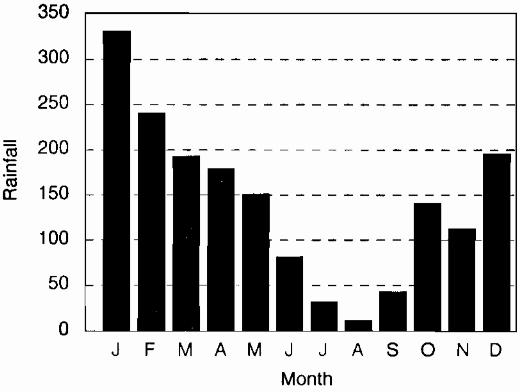

Figure 5. Annual distribution of average rainfall at Karawang, West Java.

Priorities for the Future

The following are recommendations for future development of grain drying systems in Indonesia.

1. A multipurpose mechanical dryer for grains and other estate crops such as black pepper, coffee, and cacao beans will likely capture more sales than a single purpose grain dryer.
2. Batch dryers with a capacity above 10 t/batch, or continuous dryers with a capacity of at least 5 t/hour, are recommended since the target groups are the seed processors, large-scale millers, and the wholesalers.
3. Urban areas should be the target for marketing dryers. Here land and/or labour are expensive.
4. The performance of the fluidised-bed dryer recently introduced should be assessed and compared with other mechanical dryers in use.

References

ACPHP (ASEAN Crops Post Harvest Programme) 1988. Analysis of the acceptability of the maize pit dryer at the village level in Yogyakarta, Indonesia. ACPHP–IPB–UGM–MOA–BULOG.

CDAE 1995. Development of LT–IBDS in Indonesia. Progress Report. GTZ–IRRI/Indonesia. BBP Alsintan, Serpong, Indonesia.

Damardjati, D.S., Haryono, Sutrisno and Trim, D.S. 1991. Sistem pengeringan di Indonesia dan pengembangan pengering surya model NRI–SURIF. (Drying system in Indonesia and development of solar dryer model NRI–SURIF). Proceedings of the Workshop on Grain Handling and Drying, Indonesia.

IDRC (International Development Research Centre) 1988. Studies on the improvement of postharvest system capabilities at village unit cooperatives (KUD) and private sector. Final report. IDRC–BULOG–IPB–UGM, Indonesia.

Trim, D.S. and Gordon, A.E. 1991. Technoeconomic assessment of the NRI/SURIF solar paddy dryer. Chatham, Kent, U.K., Natural Resources Institute.

The Rice Processing Industry in Malaysia: Problems and Priorities in Grain Drying

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Abstract

This paper discusses the evolution of paddy and rice policy in Malaysia since the 1960s and its impact on the drying sector. The major policies that have direct bearings on the drying sector are: minimum support price, LPN's (National Paddy and Rice Authority) involvement in marketing and milling of paddy and rice price control. The interventionist policy has resulted in the declining role of the private sector, direct transfer to farmers and millers, and overall milling inefficiency. A shift in policy in 1993 — to deregulate selected price of rice and corporatisation of LPN — is expected to improve the drying and milling sector in the future. Several priority areas for further development of the rice-processing industry are suggested.

A study made in 1988 by the World Bank concluded that Malaysia's rice was noncompetitive in price and quality. This conclusion reflected a multitude of structural problems underlying the industry. For more than two decades (until January 1993, when the price of super quality rice was floated) the paddy and rice sector was subject to price control, from farm through to retail levels. As shown by Fatimah (1995), the prices supported are much higher than the world prices making Malaysian rice noncompetitive with that of her neighbours. Quality defects in rice are a function of both technical and economic factors. Technically, poor quality of rice is attributable to improper drying and handling of paddy. This situation is aggravated by the paddy pricing system at the farm level which does not provide enough incentive for farmers to dry paddy (Chew and Fatimah 1987; Chew and Ghaffar 1985). In fact, it has been shown that it is more profitable for farmers to sell wet paddy to the rice millers, particularly to LPN (National Paddy and Rice Authority) complexes. As concluded by Fredericks and Mercader (1983), although postharvest losses for rice due to drying per se range from 1 to 5%, a significant portion of the losses incurred in storage and milling is related to drying. Improper drying, particularly during the wet season, contributes to losses due to rotting and downgrading of the quality of milled rice, as characterised by a high percentage of brokens, discolouration, and mould infestation. It is assessed that at the current estimate of 5% losses, MYR47 million worth of rice is wasted annually (during October 1995, ca 2.40 Malaysian Ringgit (MYR) = US$1). Clearly, drying is a significant function in determining the quality of rice and hence economic return and level of efficiency of the industry. This paper seeks to review the current status, problems, and priorities in paddy drying in Malaysia. The approach of the paper is as follows. The next section traces policy development in the paddy drying sector before January 1993 when the government decided to remove price control on super grade rice while maintaining control of the prices for premium and standard grades (LPN 1995). This is followed by a brief discussion on changes in paddy and rice policy particularly following deregulation of the prices of selected rice and the corporatisation of LPN on 7 July 1994. The last section discusses the implications of the new restructuring policy for the paddy drying sector.

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Paddy and Rice Policy in Malaysia

The development of the paddy drying and milling sectors is closely aligned with government policy. One of the earliest market interventions took the form of introduction of a guaranteed minimum price (GMP) for paddy of MYR15 per pikul (1 pikul = 60.5 kg) in 1949, to provide incentives to producers. The GMP has never been revised downwards, only upwards. In 1973, the name was changed to the minimum support price (MSP) and its objective has been expanded to include the need to provide producers with a high return and to protect consumers from the vagaries of the world rice market. As will be shown later, this pricing policy has contributed to the current structure of the processing sector.

In the 1950s, the processing sector was operating in an open economy, but in the early 1960s the government decided to intervene. The paddy processing sector was perceived as being monopolistic, and a cause of peasant indebtedness and poverty. Attempts to break the monopoly initially took the form of government owned mills and 'co-operativisation' of the mills (Tan Siew Huey 1987). Under this policy, the establishment of cooperative rice milling societies (CRMS) was encouraged, to provide small-scale milling services for milling paddy into rice to be consumed by the producers themselves, and to function as marketing agents for the members.

Between 1961 and 1963, the CRMS were given monopsony powers in some parts of the country. However, in the areas where the private market was well developed and there were close links between paddy dealers and private millers, there was considerable resistance to these moves. The policy was sharply criticised by the private sector and it was discontinued because it ran counter to the government's commitment to free enterprise (Fredericks and Wells 1983). At their peak, the CRMS took only about 4% of total paddy production (Vokes 1978).

By mid-1960s it was recognised that the cooperatives had failed to undermine the dominance of private traders in the paddy market. The private mills persevered in the market by offering better terms than the CRMS. The CRMS could not compete, as they were severely handicapped in their efforts by shortages of funds and expertise. The government attributed this failure to market imperfection and concluded that, rather than an increase in competition, greater regulation of the market was needed.

During the mid-1960s, the government embarked on the self-sufficiency in rice production program through increases in yields and an expansion of double-cropping. The failure of the cooperatives to provide a viable alternative to the private market and the need to ensure adequate processing capacity to cope with the expected increase in production led the government to introduce market regulations and invest in paddy and rice-processing plants.

A key step in the direction of greater market regulation was taken with the formation of the Paddy and Rice Marketing Board (PRMB) in 1966. The PRMB set up two types of schemes: regulatory and trading. The regulatory schemes involved the licensing of all paddy buyers and the enforcement of the conditions of the license. In its trading schemes, the PRMB undertook buying, selling, and milling of paddy. By 1972, PRMB schemes covered nearly 90% of the paddy land in West Malaysia (Selvadurai 1972). Despite this, PRMB could not change the fundamental structure of the paddy market. In 1978, the National Paddy and Rice Authority (LPN, Lembaga Padi dan Beras Negara) was established to provide a more coordinated and effective interventionist policy. LPN was charged with the responsibility of ensuring 'fair' prices for both farmers and consumers, and of achieving self-sufficiency in paddy production.

The formation of LPN marked an important turning point in the history of the paddy industry. Two major market interventions were made after it was set up. Firstly, rice price and import controls were introduced in May 1974 to protect consumers from sharp price increases in times of shortages. Secondly, the government, through LPN, entered the paddy processing sector, competing directly with the private mills.

The government's decision to play an active role in processing was based on the recommendation of a 1969 FAO study of the milling industry (U Thet Zin 1969). The study revealed the inability of existing mills to produce good quality rice and the serious milling losses to farmers and the economy. The study recommended that regulatory controls be imposed to improve the milling industry.

The government's involvement in paddy processing was also prompted by the need to ensure adequate drying facilities to handle the off-season crops, which were to expand rapidly, particularly in the Muda Agricultural Development Authority (MADA) and Kemubu Agricultural Development Authority (KADA) schemes. The expected increase in paddy output resulting from double cropping would require adequate support in the form of drying, milling, and storage facilities. Given the large capital outlay needed to purchase dryers, it was assumed few private millers would be able to take in the off-season crop. The government then decided to build drying and milling facilities in the major producing areas. By 1980, LPN had established 28 integrated milling complexes (Table 1). To ensure that its mills were being used to full capacity and to protect farmers' interest, LPN became a buyer of last resort.

Table 1. Number of LPN integrated complexes by date completed[a].

Year completed	Number	Cumulative total
Pre-1970	4	4
1970	2	6
1971	5[b]	11
1972	4[c]	15
1974	6	21
1975	4	25
1976	2	27
1981	3	30
1982	1	31
1995	–	31

[a] Refers to drying, milling, and storage installations with 10,000 t/season capacity.

[b] Originally all were drying complexes only, later upgraded to full integrated complexes.

[c] Originally three were drying complexes only, later upgraded to full integrated complexes.

Source: Lembaga Padi dan Beras Negara (LPN), Malaysia.

In the mid-1980s, the self-sufficiency target was reduced to 55–65% under the National Agricultural Policy (NAP) formulated in 1984 (MOA 1994). The same level was maintained in the 1993 NAP (MOA 1994). The reduction in the self-sufficiency target was in response to worldwide production and the increase in the country's purchasing power to import cheaper rice (Fatimah 1995). The continuous increase in fertilizer prices in the world market led the government to expand support to paddy producers' income through two major strategies: direct subsidies in the form of fertilizer and cash, and continued direct involvement in rice milling and marketing. Under the fertilizer subsidy scheme, farmers owning less than 2.4 ha of paddy land were given free fertilizers. The value of this subsidy amounted to about MYR231 per hectare, or about 33% of the cost of production per ha (Chamhuri 1985). The objective of the fertilizer subsidy scheme was to reduce the costs of production to farmers, increase farm incomes, improve and modernise paddy cultivation practices so as to boost paddy yields and total production to meet the self-sufficiency target.

The rationale for a direct cash subsidy was to increase the effective price of paddy to farmers, and hence their income and welfare, while providing them with the incentive to produce more paddy without jeopardising the current market channels and a stable rice price to consumers. With that premise, the government introduced a subsidy of MYR2 per pikul for every pikul of paddy sold to the authorised agent. This subsidy could be invested only in authorised banks. The farmers were in full support of the scheme but protested about the amount. In 1982 the subsidy was increased to MYR10 per pikul in the form of cash, and in 1990 to MYR15 per pikul. Thus, the effective price of paddy to farmers increased from MYR28 to MYR32 per pikul to a new range of MYR43 to MYR47 per pikul. The cash subsidy (which was given out in the form of coupons) is claimable from LPN or authorised banks, provided the farmers sell their paddy to authorised agents only. This arrangement has directed the flow of paddy from unlicensed traders (including millers) to authorised agents and LPN drying complexes. By 1985, the share of paddy handled by LPN had increased to 46% (compared with about 20% in the 1970s) (LPN 1991).

Combine harvesters were introduced in the 1970s, to cater for the increase in paddy production due to the rapid expansion of double-cropping areas in the mid-1960s. With harvesters, the harvesting time for paddy was reduced from 30 to about 15 days. The effects of the combine harvesters on the handling and drying of paddy were not anticipated. Until the late 1980s, paddy was handled manually, with the grain packed in gunny sacks and transported to the mills using lorries. Loading and unloading of paddy were done manually.

The introduction of the harvester affected the technical efficiency of the mills, particularly the LPN complexes. It was seen that the complexes were not able to cope with the intensive flow of paddy within a shorter time period (before combine harvesters were introduced the buying period stretched over about 30 days). The LPN complexes were designed to cope with a smaller intake of paddy spread over a longer period. This lag in handling technology explains the significant postharvest losses incurred by the LPN complexes in the mid-1980s. This problem was further aggravated by the policy stand of LPN as 'the buyer of last resort' which forced LPN to accept all deliveries regardless of its own drying or storing capacity and the quality of the paddy delivered by the farmers.

To rectify the problem and reduce the intake cost, LPN has invested in a bulk receival system, and grain coolers and dryers in some of its complexes (Table 2). According to LPN (1995) the system enhances the paddy intake operation and reduces the handling cost. The LSU drying and cooling system has proven to be able to increase drying capacity. DryerMaster, a computerised system designed to monitor the wet paddy content, has also proven effective. Overall, LPN found that the system brings positive results—it reduces operating costs (particularly electricity and petrol costs) and avoids overdrying of paddy (LPN 1995).

Table 2. Number and types of dryers and mills at LPN complexes, 1988–1994.

	Dryers (units)			Mill (units)
	LSU	FBD/IBD	Predryer	
1988	49	142	90	30
1989	49	142	90	30
1990	49	142	90	30
1991	49	142	90	30
1992	49	142	90	30
1993	49	142	90	30
1994	49	147	90	30

Note: Rated drying capacity of LPN complexes was 7861 t per day between 1988–91, increasing to 8567 t/day between 1992–94.

Source: Lembaga Padi dan Beras Negara (LPN), Malaysia.

Implications for the Drying Sector

The three major policy instruments that have direct implications for the paddy drying sector are: minimum support price (MSP), LPN direct involvement in paddy marketing and processing, and rice price control. A brief discussion follows, on the impact of these policies on the drying sector.

Declining role of private mills

As pointed out by Tan Siew Huey (1987), the involvement of LPN in the processing sector, especially when excess capacity already existed in the private mills, naturally crowded out these mills. In 1983, the private mills had a total capacity to mill 1,988,064 t of paddy while LPN's capacity amounted to 369,600 t. Before the formation of LPN in 1973, the private mills were purchasing almost 90% of the paddy sold by the farmers. By the mid-1980s, this proportion had dropped to half. The result was that the private processors were using about one-third of their capacity. Unfortunately, there are no data available on the number of private mills and their capacity in the late 1980s and early 1990s. However, a study made by LPN in 1986 on the private mills in Kedah/Perlis indicated that, in 1985, excess capacity was still a serious problem. During that year the annual rated drying capacity of the private mills was estimated at 952,187 t, but the amount of paddy purchased amounted to only 418,027 t, suggesting a utilisation rate of facilities of 43% (LPN 1986). In terms of milling capacity, their utilisation rate was about 51% (rated milling capacity was estimated at 812,135 t/year).

During the early part of 1985, LPN complexes were buying more paddy than they could mill. In order to cope with the heavy inflow of paddy to LPN complexes, the milling capacity was increased from 369,900 t/year in 1983 to 428,720 t/year in 1994. As shown in Table 3, the amount of paddy purchased by LPN is far in excess of its drying and milling capacities. Hence, LPN has to rely on the private sector to dry and mill its excess paddy. On average, LPN mills about 76% of the paddy purchased from farmers, while the rest is sent to the private millers under the grinding scheme either for further drying or milling. As will be shown later, this policy has resulted in unintended direct transfer to the miller.

In view of the unavailability of data concerning the current capacity of the private mills, it would be difficult to estimate the current extent of excess capacity. However, if one assumes that the capacity has not changed (an assumption which is supported by LPN), it would appear that the problem of underutilisation of the private mills has somewhat ameliorated. In 1994, the utilisation rate for private mills stood at 51%.

There is evidence that the private mill sector is static in numbers and growth (Tan Siew Huey 1987), a situation attributed to poor prospects of higher returns. Their margin has been fixed by LPN through the MSP of paddy and the rice ceiling price policy. In the last 20 years, the MSP has been revised upwards three times while processing cost has almost doubled. Hence, the margin of private miller has been squeezed so much so that it has been reported that some have to resort to rice adulteration and mixing to maintain an adequate return. As will be shown in the next section, the declining role of private mills led to a decline in milling efficiency.

Drying subsidy to growers and millers

LPN's paddy buying practices and pricing (and deduction system) subsidised farmers' and millers' incomes. As in other ASEAN countries, the paddy sold in Malaysia is subjected to penalties in the form of deductions from the price for wet and dirty paddy. This is to ensure that only high quality paddy enters the next stage of processing — milling. The deduction rates for Malaysia, however, were quite low by international standards (Chew and Fatimah 1987). The deduction rates were linear, whereas the drying cost per unit increases sharply at higher moisture contents. The private millers are generally stringent in the quality of paddy they accept for processing as this will impinge on their processing margin. LPN, due to its social obligation, could not adopt the same policy, instead it had to buy all paddy offered to it regardless of its capacity to handle it, or its quality. In short, LPN functioned as a buyer of last resort. It has been shown that LPN's deduction rates were so lenient as to encourage farmers to sell wet paddy. In effect, Chew and Fatimah (1987) showed that the farmers received a hidden subsidy for not drying their paddy grain. LPN was then stuck with a large influx of wet and poor quality paddy, particularly during harvest time. During harvest season, it is reported that delays at LPN complexes to sell paddy were up to 2–3 days, during which time exposed paddy might be soaked by rain, so that even paddy which was initially dry could suffer quality and value losses. This contributed to the physical loss of grain and to reduced rice quality due to spoilage.

Besides subsidising farmers' incomes, LPN also subsidises the millers. LPN was having difficulty in coping with the large influx of paddy to its complexes. By mid 1980s, LPN began to make efforts to support private milling through provision of subsidies. For instance, LPN helps upgrade private mills by securing bank loans on their behalf. In addition, LPN has a 'grinding scheme' in which paddy bought and dried by LPN is sent to private mills for processing on a commission basis. This move was an attempt also to foster the growth of Bumiputera-owned mills. This program spares these mills the costs of having to purchase paddy directly, and is thus a subsidy. It is estimated that the transfer from LPN to private millers of the drying cost amounted to MYR5 million in 1986 (plus the value of losses avoided through LPN's purchase of the poorer quality paddy). Some private mills had the luxury of choosing the paddy they were to mill.

As concluded by the World Bank, the drying subsidy (both to farmers and millers) adversely affected rice quality and processing costs and forced LPN to bear a disproportionate share of the losses. LPN's drying costs included not only the resource cost of drying, but also losses due to the deterioration of wet paddy waiting to be dried at overstrained facilities. The World Bank estimated that LPN's drying cost of about MYR30 per t is a direct subsidy to growers.

Table 3. Paddy purchases and drying by LPN complexes and private millers.

	Purchases				Drying			
	LPN		Private mills		LPN		Private mills	
Year	t	%	t	%	t	%	t	%
1971	111,067	11.0	895,933	88.9				
1972	127,238	12.4	890,762	87.6				
1973	88,305	7.8	1,034,695	92.2				
1974	55,960	4.7	1,126,040	95.3				
1975	144,076	12.9	971,924	87.1				
1976	134,230	11.8	1,001,770	88.2				
1977	134,375	12.6	925,625	87.4				
1978	127,410	15.9	671,590	84.1				
1979	219,215	35.4	400,785	64.6		- na -		
1980	317,033	35.8	568,967	64.2				
1981	338,205	31.8	726,883	68.2				
1982	332,394	30.6	753,884	69.4				
1983	325,066	31.2	717,227	68.8				
1984	286,354	27.1	702,616	72.9				
1985	560,157	46.1	654,680	53.9				
1986	630,877	48.8	661,162	51.2				
1987	703,137	52.2	643,300	47.8				
1988	604,224	44.9	740,886	55.1	478,973	35.6	866,137	64.4
1989	454,519	30.9	1,014,496	69.1	410,441	28.0	1,058,574	72.0
1990	693,561	44.5	865,152	55.5	514,058	32.9	1,044,655	67.1
1991	777,799	49.2	803,310	50.8	566,677	35.8	1,014,430	64.2
1992	769,982	51.8	714,248	48.2	567,242	38.2	916,988	61.8
1993	711,520	45.6	847,738	54.4	524,692	33.7	1,034,566	66.3
1994	789,258	53.9	673,896	46.1	551,845	37.7	911,309	62.3

Source: Lembaga Padi dan Beras Negara (LPN), Malaysia.

Milling inefficiency

The concentration of paddy to LPN complexes — in excess of their drying and milling capacities — resulted in the milling of poor quality rice. Due to its social obligation, LPN was unable to reject deliveries, and was more lenient on deductions. It is estimated that the recovery rate for rice at the LPN complexes was between 52 and 60%, despite the larger, newer, and better equipped mills as compared with the private sector. Private mills were able to achieve a 62–64% recovery rate. According to Tan Siew Huey (1987), LPN's processing cost was 42% higher than that of the private mills. As shown in Table 4, the processing cost increased from about MYR151 per t in 1985 to about MYR200 per t in the early 1990s.

Table 4. Drying and milling costs for LPN complexes (MYR per tonne of rice).

Item	1985[a]	1990	1991	1992	1993	1994
Buying cost						
(1) Variables cost						
Transport	7.14	–	–	–	–	–
Agent	2.82	7.64	7.98	6.41	2.65	2.50
Wages	0.87	5.10	5.50	4.86	4.37	4.01
(2) Fixed cost						
Emolument	3.06	6.25	6.05	7.15	6.69	5.79
Drying cost						
(1) Variables cost						
Unloading	4.85	8.97	9.16	7.76	5.60	5.23
Energy	13.74	19.42	21.30	21.94	21.76	20.31
Maintenance	3.13	8.14	10.28	8.93	7.08	6.61
Wages	3.29	5.00	5.31	4.75	4.78	4.46
(2) Fixed cost						
Emolument	2.43	10.27	9.77	11.89	10.68	10.50
Depreciation	19.13	16.49	12.41	15.37	13.18	11.63
Milling cost						
(1) Variables cost						
Unloading	2.31	2.70	3.49	2.50	1.81	1.76
Energy	8.01	9.96	8.49	10.99	12.01	11.65
Gunny sacks	7.41	13.54	13.81	13.91	14.31	13.88
Maintenance	3.38	5.79	7.36	6.46	6.52	6.32
Wages	4.32	2.87	3.12	2.92	3.12	3.27
(2) Fixed cost						
Emolument	6.36	11.98	8.37	10.22	9.29	9.13
Depreciation	10.51	8.96	6.96	7.04	8.06	7.75
Administrative cost						
Emolument	30.19	25.99	30.75	34.88	34.07	32.48
Transfer HQ cost	6.33	–	–	–	–	–
Other	12.82	33.95	39.75	37.29	43.09	27.32
Total fixed cost	41.49	89.15	95.80	91.43	84.01	80.00
Total variable cost	110.62	113.89	114.06	123.84	125.06	104.60
Total operating cost	152.11	203.04	209.86	215.27	209.07	184.60

[a] Based on the average of six LPN complexes studied by Roslan A. Ghaffar and Azman Hassan (1985).

New Shift in Policy

The new National Agricultural Policy announced in 1993 stipulates the need to create a more market-orientated agricultural sector and the need to reduce government expenditure on statutory bodies (MOA 1993). After a history of three decades of market intervention, the government came to realise that the paddy and rice sector policy needed to be revised to alleviate inefficiency and high cost to government. LPN also admitted that one of the constraining factors that resulted in inefficiency was the rigid rice pricing policy, maintained while costs for milling, marketing, and paddy have all increased (LPN 1995). Realising this, the government has taken two major steps that will change the structure of the paddy and rice industry. The first move was to revise the rice grading system and deregulate the price of selected rice in the market on 15 January 1993. Before the change, there were nine grades of rice ranging from A1 to A4, B1 to B4, and broken rice. Under the new system, there will be only three grades of rice: super rice, premium rice, and standard rice. There are different quality standards for each category. One of the major shifts in pricing policy is that the price of super rice will be allowed to float freely in the market, while the prices for premium and standard grades will be controlled. Also, there will be five price zones in Peninsular Malaysia. In each zone, the maximum price of each grade of controlled rice is fixed.

The second major policy decision was the corporatisation of the LPN, changing it from a government institution into a semigovernment entity known as BERNAS on 1 July 1994, this time operating under the Ministry of Finance. The functions of BERNAS are: buying and processing of paddy; sole importer of rice; marketing of rice; management and maintenance for the government of the rice stockpile; and management for the government of the price subsidy scheme for rice. There are three divisions in BERNAS: Production Division, Marketing Division and Finance/administration.

Implications of the New Policy

The bold moves outlined above will indeed bring about a change in the industry. Deregulating the price of high quality rice is expected to affect the various sectors in the paddy and rice industry in a positive way. For instance, consumers will now benefit in that they have access to high quality rice, if they are willing to pay for it. On the other hand, the price limitations on premium and standard rice will ensure that the rice consumption requirements of the lower income groups are protected.

Although the price deregulation policy is less than 3 years old, the market is responding fast. Discussions with BERNAS officers indicate that the lifting of price control has resulted in overall improvement in drying and milling efficiency. Before price deregulation, LPN produced a large proportion of a combination of A2 and B2 rice categories (equivalent to premium category under the new grading system). In 1994 (2 years after announcement), the composition of rice produced by LPN had already changed: 45% of the rice produced was super rice category (equivalent to A1 under the old grading scheme), 45% premium, and the remaining 10% of standard grade. According to BERNAS, the private mills are producing 100% super rice. The high percentage of high quality rice suggests that the mills (both LPN and private) have improved their drying and milling efficiencies to produce high quality rice. BERNAS has estimated that the average recovery rate will reach 65%. BERNAS also reported that the drying and milling cost of rice at LPN complexes fell in 1994 (Table 4) as a result of good quality paddy and better management practices.

From the fact that the mills are able to produce high quality rice, we can safely assume that the high price of super rice has been transmitted fully to the millers and farmers (super rice fetched MYR960/t ex mill in 1994). A high price for rice encourages millers to obtain good quality paddy and offer farmers higher prices for their paddy. If this trend continues, we would expect a revitalisation of the processing sector, as well as better return to, and prospects for the paddy production industry.

Another short-term effect of the lifting of rice price control is the closure of small and inefficient mills. In Kedah/Perlis it is reported that five mills increased their buying capacity from 2000 bags/day to 10,000–20,000 bags/day in 1994 to take advantage of the high demand for high quality rice (Kwang Meng Daily, 28 July 1995). It is further reported that these mills produced 150–200 bags of rice/hour or 2000 bags/day—a capacity which the small mills are unable to match. This phenomenon confirms the contention that the private mills were previously underutilised. Secondly, with an open-market system, we would expect that, in the long run, inefficient mills will be displaced by the efficient ones.

The corporatisation of LPN as BERNAS is expected to foster competition in the paddy and rice market. BERNAS is no longer a buyer of last resort: it is now driven by the profit motive. Its social obligations have been minimised to: monitoring the stockpile scheme and managing the price subsidy scheme for the government. With its new policy orientation, the former LPN complexes are expected to compete directly with the private traders — this time with minimal intervention from the government.

Conclusion

The paddy and rice policy in Malaysia evolved from a free market in the 1950s, to a highly regulated one — covering production, processing, marketing, importing, and pricing — in the 1980s. The interventionist policy came with a high price to the industry. LPN's direct involvement in procurement, processing, and rice price control undermined the role of the private sector.

The government policy also brought structural problems to the industry. The major consequences were the prevalence of excess capacity and of under-investment in drying facilities among private millers. Much of the investment in new capacity and machinery before 1993 was by LPN. The new investment in various instances has been shown to be ineffective in improving LPN's processing efficiency. LPN competed with the private millers in paddy purchases, not for economic reasons but governed by the social objective of protecting paddy farmers. By doing so, LPN complexes were overstrained with wet and poor quality paddy. The lenient paddy deduction system and the policy of commissioning paddy drying and milling to the private millers led to a direct income transfer from LPN, both to the producers and the millers. LPN, on the other hand, had to bear high losses due to deterioration of wet paddy at its overused facilities. The impact of the market intervention strategy on paddy drying was reflected in the low recovery rates for rice achieved by LPN complexes, i.e. between 55–60% compared with 60–65% by the private millers. Recognising these problems, the government decided to withdraw market intervention in stages, starting with the floating of selected rice prices in 1993 and corporatisation of LPN in 1994. Observation of the short-term effects of these two policies suggests that the market is responding well to the strategies. Although the new policy is aimed at liberalising the domestic paddy and rice market, the functions of the BERNAS do not imply so. This is because BERNAS is still a sole importer of rice—a strategic function which will have direct influence on the supply of rice in the country. Hence, the price of rice may not be freely determined by market forces as intended.

Despite the liberalisation, the government is currently inclined not to encourage new entry to the rice processing industry. A check with the Monitoring Division of the Ministry of Agriculture indicates that very few milling licenses have been issued recently. This appears consistent with the present situation in the industry, whereby excess capacity is quite severe. Among the private millers, many of those who were previously inactive are now back in business. This will also influence the down time of those who are already operating. Considering that the industry is responding well to market signals, there is a need to upgrade the technology of the industry, particularly in the private mills. As the industry is liberalised further, the market is expected to continue to demand better quality rice. Hence, investment in drying technology is clearly a direction that needs to be assessed. At the same time, the industry should be encouraged to converge toward a more competitive structure. Gradual liberalisation and reduction of BERNAS' dominance in the market would facilitate this.

References

Chamhuri Siwar 1985. Persistent poverty among paddy farmers: impact and implications of paddy subsidy scheme. Paper presented at the seminar on problems and prospect for rural Malaysia. Malaysian Agricultural Research and Development Institute, November 1985.

Chew, T.A. and Fatimah Mohd. Arshad 1987. Comparative paddy pricing systems in ASEAN. In: Grain protection in post-harvest systems: Proceedings of the 9th ASEAN Technical Seminar on Grain Post-Harvest Technology, Manila, 1987. Bangkok, ASEAN Crops Post-Harvest Programme, 303–315.

Chew, T.A. and Roslan Ghaffar 1985. Some economic aspects of drying of paddy by farmers in Selangor, Malaysia. In: Champ, B.R. and Highley, E., ed., Preserving grain quality by aeration and in-store drying. Proceedings of an international seminar held at Kuala Lumpur, Malaysia, 9–11 October 1985. ACIAR proceedings No. 15, 146–151.

Fatimah Mohd. Arshad 1995. Food security. In: Jomosundram, K.S., ed., 1995: Malaysia's economic development. Kuala Lumpur, Pelanduk Publications, in press.

Fredericks, L.J. and Mercader, J.P. 1986. Cost implications and implementing grain drying systems. In: Champ, B.R. and Highley, E., ed., Preserving grain quality by aeration and in-store drying. Proceedings of an international seminar held at Kuala Lumpur, Malaysia, 9–11 October 1985. ACIAR proceedings No. 15, 152–160.

Fredericks, L.J. and Wells, R.J.G. 1983. Rice processing in Peninsular Malaysia: an economic and technical analysis. Kuala Lumpur, Malaysia, Oxford University Press.

Ghaffar, R.A. and Azman, H. 1985. A preliminary investigation of the costs associated with rice drying and milling in Peninsular Malaysia. In: Semple, R.L. and Frio, A.S., ed., Research and development systems and linkages for a viable postharvest industry in the humid tropics. Proceedings of the 8th ASEAN Technical Seminar on Grain Post-Harvest Technology, Bangkok, ASEAN Crops Post-Harvest Programme, 391–398.

LPN (Lembaga Padi dan Beras Negara) 1986. Kajian Profail Kilang-kilang Swasta Negeri Kedah/Perlis. Kuala Lumpur, LPN.

— 1991. Annual report. Kuala Lumpur, LPN.

— 1995. Grade and price of rice adjustment. Kuala Lumpur, LPN.

MOA (Ministry of Agriculture) 1984. The National Agricultural Policy. Kuala Lumpur, MOA.

— 1993. The National Agricultural Policy (1992–2010). Kuala Lumpur, MOA.

Tan Siew Huey 1987. Malaysia's rice policy: a critical analysis. Kuala Lumpur, ISIS Issue Paper.

Selvadurai, S. 1972. Agriculture in Peninsular Malaysia. Kuala Lumpur, Ministry of Agriculture.

U Thet Zin 1969. Survey report of rice processing in West Malaysia, Parts I and II. Rome, FAO.

Vokes, R. 1978. State marketing in private enterprise economy: the paddy and rice market of West Malaysia, 1966–75. Unpublished PhD thesis, University of Hull, U.K.

Problems and Priorities of Grain Drying in the Philippines

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Abstract

Statistics on grain production in the Philippines are presented to indicate the extent of drying requirements. Rice, maize, and some legumes are covered.

The postproduction sector of the country is shared by government agencies, financial institutions, private traders/processors, farmers, and farmer organisations. The grains postharvest systems indicate where and who does the drying.

The status of grain drying in the Philippines is described in terms of the types of dryers, methods of drying, adopters of drying, and the suppliers/manufacturers of dryers.

The problems and constraints in the adoption of drying technologies include: inadequate pricing system; small volumes of produce; high cost of drying; inexperienced farmers organisations; lack of skilled dryer operators; lack of aggressive extension programs; and poor quality of, and lack of after-sales service on postharvest machinery.

Current priorities include: wet grain handling; banning of highway drying; cooperative development; provision of soft credit, technical assistance, and training of different postharvest sectors; increased R & D support; and direct government intervention through the Grain Production Enhancement Program (GPEP).

Short- and medium-term plans for postproduction R&D activities include a JICA–NAPHIRE program, project self-reliance, and implementation of a postproduction crisis act.

DURABLE crops such as grains and legumes normally need drying for preservation before storage or subsequent processing. Statistics on Philippines production of durable crops in 1993 are given in Table 1.

Because of the sizable volume of harvested rice and maize, the drying requirements of these two staple crops are more important than those of the other crops listed in Table 1. The problem lies in the fact that about half of the rice and maize is harvested during the rainy season (Sep.–Dec.). The rest of the harvest and harvesting of all the other crops normally coincides with the dry season of the locality or region. No problems ensue, because the normal way is sun drying on a concrete drying pavement. For the wet season paddy and maize harvest, on the other hand, about 7 Mt of grain need mechanical drying. Mechanical drying capacity in the country is estimated to be only 30% of the wet season requirement, leaving about 70% of the wet crop to be either sun dried with much delays (when sunshine is intermittent) or not dried at all. This results in much damage to the harvested grains and thus high postharvest losses are incurred.

Table 1. Areas and production of durable crops that need drying.

Crop	Area '000 ha	Quantity '000 t
Rice	3282.40	9434.30
Maize	3149.30	4798.00
Sorghum	0.52	1.36
Soybean	8.22	4.05
Mungbean	33.09	23.42
Peanut	44.91	34.03
Coffee	212.70	123.20
Cacao	16.80	7.70

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The postproduction sector

There are several players in the Philippine postharvest sector. The government is represented by agencies such as the Department of Agriculture (DOA), the National Food Authority (NFA), the Government financial institutions (Land Bank of the Philippines and the Development Bank of the Philippines), the Quedan Guarantee Corporation (QUEDANCOR), and the Agricultural Credit Policy Council (ACPC), and by R & D institutions such as the National Postharvest Institute for Research and Extension (NAPHIRE), the Philippine Rice Research Institute (PHILRICE), the State Colleges and Universities (SCUs), Bureau of Agricultural Research (BAR), the Philippine Council for Agriculture, Forestry & Natural Resources Research and Development (PCARRD).

Private sector players include farmers and farmer organisations, traders and processors, and wholesalers and retailers in the market.

Postharvest systems of durable crops

The postharvest systems for some of the durable crops are shown in Figures 1–5. It may be noted that drying takes place at different points in the various systems. Also, it should be observed that different subsectors assume responsibility for different postharvest operations. Drying is done both by farmers and by traders/processors, with the latter assuming the bulk of the responsibility for drying.

Status of Grain Drying in the Philippines

Drying remains the most neglected of postharvest operations. Farmers do not dry because they want to dispose of their produce immediately so as to get cash for their immediate needs. Besides, they cannot afford to buy mechanical dryers. The traders and processors can be selective in their procurement. They can simply stop buying from farmers if the grain is not dried or when their facilities are full. For farmers delivering grain to obtain the government floor price of PHP6.00/kg (during October 1995 ca 25 Philippine pesos (PHP) = $US1), the NFA normally encourages the delivery of grain that is clean and has been dried to 14% moisture content (m.c.), but it does not specify how the drying should be done.

The net result is thus generally poor quality of grains in the marketplace, due to delay in drying. In the case of rice, the subsequent milling process results in low milling recovery due to a high percentage of breakage in milling of inappropriately dried paddy.

The most prevalent drying practice up to the present is sun drying on concrete pavements, either on the highways or basketball courts. Before the advent of GPEP (Grains Production Enhancement Program) it is estimated that only about 12% of the grain harvest was dried using mechanical dryers. Of the total mechanical dryers then in the country, 90% are in the government sector (NFA, NAPHIRE, and SCUs).

Types of mechanical dryers

Different types of mechanical dryers, both locally manufactured and imported, are available in the market (Table 2). Most of the locally made dryers are of smaller capacity, while the large capacity installations are imported from the western countries, Japan, and China.

Government intervention: GPEP

Cognizant of the critical problem of drying, the government, through the Department of Agriculture, has embarked on a five-year (1993–1998) Grains Production Enhancement Program (GPEP) whose main components are irrigation, postharvest and farm-to-market road infrastructure. Other components of the program cover subsidies in production inputs, training, credit, and marketing.

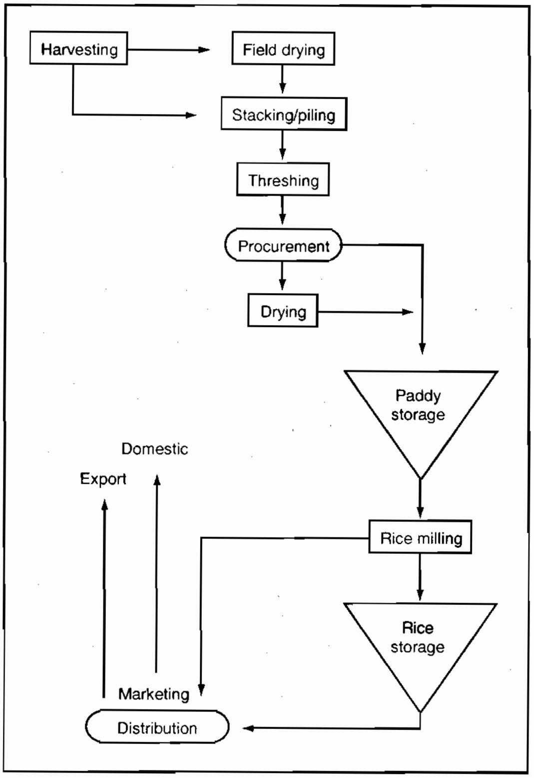


Figure 1. Flowchart of the commercial level rice postproduction system in the Philippines.

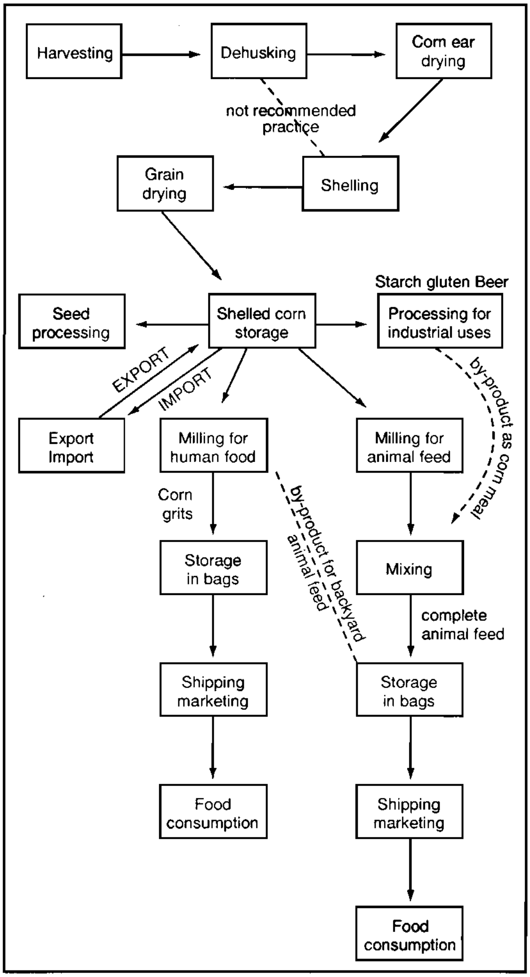


Figure 2. Flowchart of the maize postproduction system in the Philippines.

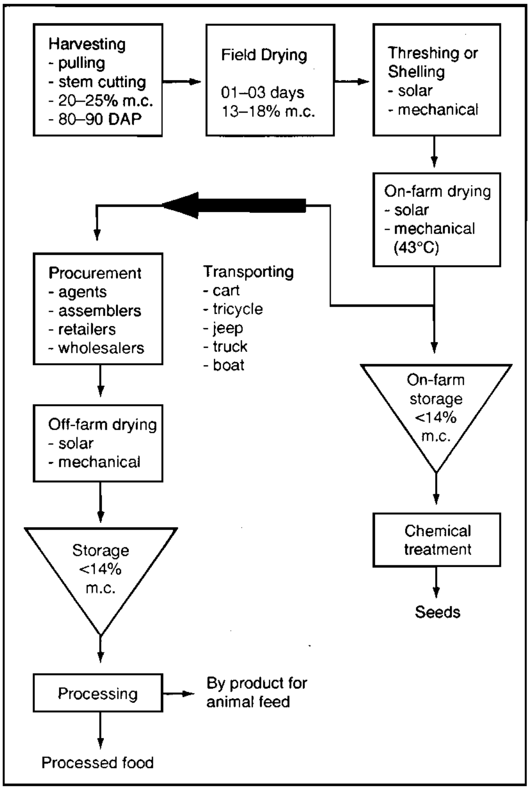
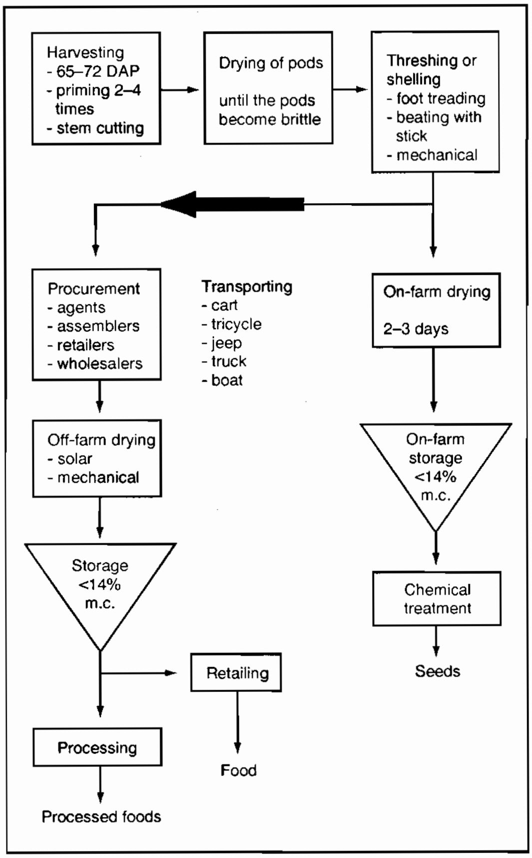


Figure 3. Flowchart of the soybean postproduction system in the Philippines.

The postharvest component of GPEP is a subprogram which aims to provide postharvest facilities to farmer organisations (cooperatives) through grants and/or soft credit for their purchase. A master plan for the postharvest component of GPEP was formulated, indicating the philosophy and vision of the subprogram and the yearly targets of different postharvest facilities to farmer organisations for each GPEP province and congressional district. The master plan has the aim of providing, as government intervention, 20% of the total postharvest facility requirements for each province and congressional district.

Assistance to a farmer cooperative is provided according to its level of development. For example, a newly organised and registered cooperative is given a multipurpose drying pavement (MPDP) for its drying needs close to the farms. On the other hand, a cooperative which is more developed, has a warehouse and has begun to engage in paddy trading, is given, as a grant, a small mechanical dryer to allow it to procure paddy even during the rainy season. Finally, those highly developed cooperatives that are already capable and experienced in business operations, will now graduate to a level where they can have rice mills and trucks to process and market their produce thus maximising their profits by adding value to their produce.

After two years of implementation, the postharvest subprogram of GPEP has distributed some 6000 MPDPs and about 3000 mechanical dryers, as grants, to farmer organisations and local government units. A budget of about PHP3 billion (US$120 million) had been spent or allocated by the government through GPEP up to 1996. This will be for both postharvest facilities (grants or loans) and operating capital for farmer cooperatives. The program implementation has been enhanced and well supported due to the recent rice crisis (shortage) and the advent of GATT- WTO participation. The yearly allocation of the different postharvest facilities is shown in Table 3.



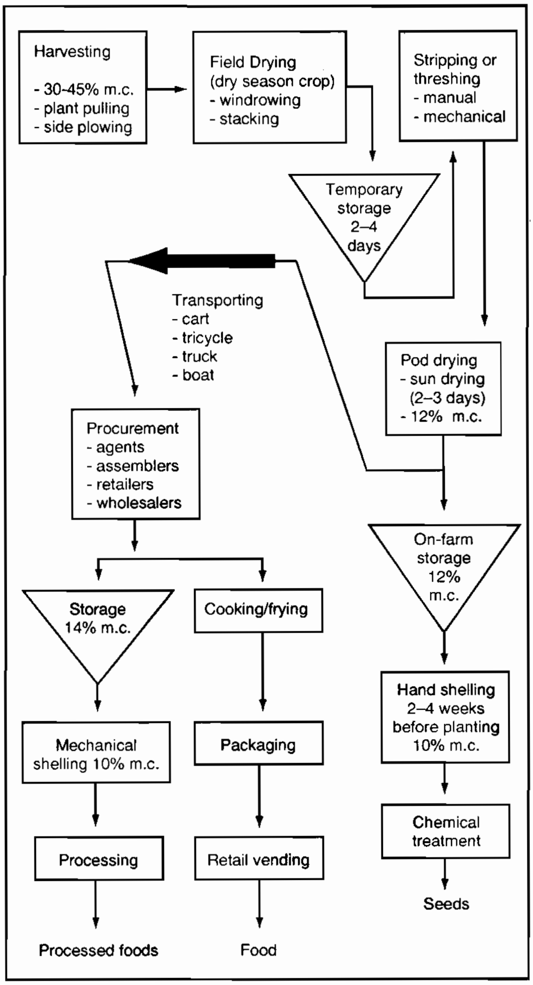


Figure 4. Flowchart of the mung bean postproduction in the Philippines. (above)

Figure 5. Flowchart of the peanut postproduction system in the Philippines. (right)

The postharvest component of GPEP is being implemented by various government agencies. NAPHIRE leads on the commercialisation of postharvest facilities. NFA and QUEDANCOR assist in the marketing aspect of farmers produce. ACPC and the Land Bank of the Philippines (LBP) provide soft credit. The National Agriculture and Food Council (NAFC) and the Agricultural Training Institute (ATI) provide training and information dissemination.

Problems and Constraints in Grain Drying

There are several constraints and problems that plague grain drying in the Philippines. Most of these are difficult to resolve because they are systemic to the Filipino culture and the poor state of the national economy, and would take much sociopolitical will to rectify. Described below are some of the constraints that are likely shared, at least in part, with other ASEAN countries.

Small volume of individual farmer's produce. The average land holding of the Filipino farmer is 1.5 ha for rice and 6.25 ha for corn. As such, the volume of produce harvested in one season does not warrant the acquisition of a mechanical dryer. The farmer thus tries to dispose of his product immediately, passing the responsibility for drying to the traders/processors. This results in delays in drying that lead to deterioration of grain quality.

No premium for good quality grain. There is insufficient incentive to farmers to dry their grain before selling to traders and processors. There is no difference in price between grain that has been promptly and well dried in a mechanical dryer and grain that has been dried after much delay or inappropriately. NFA simply requires clean, dry grain at 14% m.c.. It does not specify how or when the grain should be dried. In the case of rice, delays in drying or inappropriate drying result in breakage during the subsequent milling process. In the case of maize, delays in drying result in fungal infestation and aflatoxin contamination.

High cost of drying. There is a view that the cost of mechanical drying is too high compared with sun drying. Sun drying cost ranges from PHP3–5 per bag (50 kg) or 6–10 centavos per kg of grains while the cost of mechanical drying ranges from PHP6–12 per bag or 12–24 centavos per kg, depending on the fuel used for heating the drying air.

The comparison is not completely valid. During rainy days when sun drying is not feasible there is no alternative to mechanical drying. Most people in the postharvest chain take a risk and hope that the sun will shine tomorrow or later, and so they wait to sun-dry their grain. However, more often than not, the sun does not shine, or shines only briefly before a sudden shower rewets. The net result is delay in drying, and thermal and moisture stresses on the grain that result in breakage during rice milling and aflatoxin contamination of maize.

Table 2. Types, capacities, source of supply, and prices of grain dryers currently available in the Philippines.

Type of dryers	Capacity	Manufacturer supplier/dealer	Market price in Philippine pesos[a] as at August 1995
Batch Type			
Flat bed	2 t/6–8 hours	14 local accredited manufacturers	65,000
Twin bed	3 t/6–8 hours	Marinas Industries, Pila, Laguna	130,000
Reversible flat bed	2 t/4–6 hours	Kuizon, Tacloban Leyte	130,000
Columnar (Kongskilde)	10 t/8–12 hours	Scancon (imported), Manila	2.6 M
In-store	60 t/6 days	NAPHIRE	250,000
Continuous Recirculating type			
LSU	1–4 t/hour	Pasdiscor (local), Pasig Rizal	1–2 M
Cimbria	10–15 t/hour	Padiscor (imported, Denmark), Pasig, Rizal	~ 5–10 M
Shanzer	10–15 t/hour	Leverson (imported, USA), Pasig, Rizal	~ 10–15 M
Satake	5–10 t/hour	Mechaphil (imported, Japan), Pasig, M.M.	~ 3–5 M
Suncue	1.2–6 t/10–12 hours	H & E Enterprises Inc. (imported Taiwan), Tondo, Manila	400,000
Flash Dryers			
Columnar	500–600 kg/hour	14 local accredited manufacturers (all over the country)	100,000
Rotary	600–800 kg/hour	Jamandre, Iloilo City	100,000
Fluidised bed	500 kg/hour	ASIS, Cagayan de Oro City	85,000

[a] During October 1995, ca 25 Philippine pesos (PHP) = $US1.

Table 3. Number of units of different postharvest facilities as distributed and targeted in the GPEP Program.

Year	Multipurpose drying pavement	Mechanical dryer	Farm level grain centers, level 1	Farm level grain centers, level 2
1993–94	539	—	—	—
1994–95	4135	2553	221	15
1995–96	1733	505	150	30
1996–97	3723	5746	929	120
1997–98	1870	3196	2500	835
Total	12000	12000	3800	1000

The disparity in the cost of drying is acceptable when one considers that mechanical drying has advantages in terms of insuring the quality of the grain and reducing quantitative postharvest losses.

Some five years ago the feed industry was not willing to spend more than five centavos per kg for mechanical drying of maize. Lately, however, Purine, a U.S. based animal feed manufacturer, is paying 20 centavos/kg more for an aflatoxin-free maize for their feed product. Similarly, some enterprising rice millers invest in good mechanical dryers to produce milled rice with 95–100% whole grains for the high-end market in Metro Manila.

Cooperatives not ready to adopt modern postharvest technologies. The cooperative movement in the Philippines was initiated by government as early as the 1930s. At present, both government and non-government organisations (NGOs) support and encourage the formation of farmer cooperatives. The goal is to organise the Filipino farmers with small landholdings to combine their resources so as to have a collective undertaking that can afford to acquire costly but efficient machinery and facilities that are beyond the reach of individual farmers. Unfortunately, the development of cooperatives has been, in general, very slow. Successes have been few and more evident among groups led by religious organisations. Evidently the operating principle of cooperativism and the socioeconomic and moral values required of members are, for the most part, lacking. Thus, in spite of government and NGO assistance programs cooperatives remain at a primitive state of development. In general, the cooperatives are not able and willing to manage integrated postharvest facilities (specifically dryers and drying operations) for their entrepreneurial/business operation. More hands-on training and experience are needed for cooperatives to become entrepreneurs. The drying operation should be integrated into the whole business operation of procurement, processing, and marketing. At present most of the cooperatives would not satisfy bank requirements if they sought to borrow for postharvest facility acquisition.

Lack of skilled personnel for drying and other postharvest operations. In general, much more needs to be done to develop the technical personnel complement for the postharvest industry. While training courses have been conducted for technical people in the postharvest industry, most trainees subsequently took opportunities to get more challenging and better paid jobs, both at home and overseas. This resulted in a brain drain of technicians and operators from the postharvest industry to other sectors.

More technicians need to be recruited, and continuously trained, to fill the gap created by those who left for what they saw as greener pastures. Specifically, those who are to operate the dryers should be taught the basic principles of drying and its importance and implications for grain quality. Temperature control, fuel economy, and safety measures should also be on the curriculum.

The training programs needed have been initiated by government institutions such as Agricultural Training Institute, National Food Authority, and the National Postharvest Institute for Research and Extension. Also, the suppliers and manufacturers of dryers in government programs are required to conduct operator training as part of their after sales service to the end-users.

Lack of technology transfer and industrial promotion programs. Research and development in grain drying had been pursued by various institutions in the Philippines. As a consequence, many drying technologies have been generated during the last 30 years or so. In addition, other drying technologies were generated by overseas institutions. Unfortunately, few of these have been adopted commercially. Many of the technologies have remained in the display rooms and the bookshelves of R&D institutions. There is a need for more pilot testing, aggressive extension, and commercialisation of these technologies to the end users.

A stalemate usually occurs between the end users, the manufacturers, and the bankers. Normally, end users will not be interested and attracted to technologies that are not in commercial, ready-to-use units that have been tested and proven to work for their purpose. On the other hand, the manufacturers of these technologies are not willing to invest on jigs and fixture to mass produce units without a job order from end users. Likewise, the financial institutions (the banks) will not lend their money both to the end-users and manufacturers if their lending requirements are not met or complied with.

Our approach to this situation at NAPHIRE was to stimulate activity by creating a minimum inventory of postharvest machines (sheller, dryers, etc.) by placing an order of five units of each kind to accredited manufacturers, aggressively promoting the technologies to farmer cooperatives and local government units, and forging a tie-up with the Land Bank of the Philippines for soft credit.

Lack of capability to manufacture and to sustain an after-sales service to equipment end-users. One of the reasons why mechanical dryers are not popular in the Philippines is the fact that the end-users have had bad experiences with earlier units. Due to lack of manufacturing and business expertise, manufacturers/fabricators (specifically the small ones) did not strive to produce quality products. The workmanship was generally poor, and the units invariably broke down during critical operations when they were still relatively new. The end-users would then call up the supplier/manufacturer to repair or replace broken parts, only to be frustrated and disappointed because there was no immediate response. Meanwhile, the grain deteriorates and spoils because the dryers are not operational. Remedial measures are taken by the end-users, but with bad feelings towards the supplier/distributor of the product. After several incidents like this, other would-be adopters are discouraged and hesitant to risk having the same bad experience. Others who cannot dispense with drying resort to importation of branded products. Normally these are expensive and small-scale end-users cannot afford such equipment.

To maintain a healthy drying subsector in the postharvest industry (or any machine operation for that matter) the manufacturer should produce quality dryers so as to sustain the use of dryers by the farmers, cooperatives, private traders, and millers.

Current Priorities in Drying in the Philippines

It is a national goal to be self-sufficient in staple food and feedstuffs. It is everyone's desire to contribute to this noble goal. Farmers want to produce more and get the maximum return for their efforts. Consumers desire affordable and good quality food grains. In between the producers and consumers, it is also the desire of those in R&D, in policy advocacy, and in the business sector that food security, self sufficiency, and good food quality will be sustained. In this context, the following activities are considered high priorities in the Philippines.

Drying during the wet season and typhoons. Every year, everyone in the postharvest subsector recognises the need for mechanical dryers. This is very true during the rainy season in the major grain-producing areas such as the Cagayan Valley in the north, Region III in Central Luzon, Panay Island in Central Philippines, and practically the whole of Mindanao in the south. During this time all types of dryers are utilised. Every highway and paved road system is used when the sun shines between downpours of rain. NFA, NAPHIRE, and other government agencies allow their drying facilities to be used by farmers and cooperatives.

Banning highway drying. In 1992 a study was conducted to determine who was using the Maharlika highway, the main road that connects Metro Manila and Cagayan Valley in the north, for grain drying during harvest time. It was found that, on the 100 km from Plaridel, Bulacan to San José City in Nueva Ecija, 70% of the volume of the grains dried on long stretches of half of the road was owned by traders and millers. Only 30%, in short stretches, was owned by the farmers. The loss associated with highway drying was found to be about 3.0%.

In the province of Nueva Ecija, where NAPHIRE is located, a highway drying ban has been successfully implemented by NAPHIRE. Starting with the municipalities of Muñoz and Talavera, the project was launched in mid 1993. By the end of 1994 the whole province of Nueva Ecija was saturated with bill boards bearing messages of the disadvantages of highway drying, together with the municipal and provincial ordinances prohibiting the use of the highways for grain drying. Proven for both dry and wet seasons the ban was successfully implemented. Next in line was the province of Bulacan, towards Manila. Discussion with the Governor of Bulacan was initiated and, with his full support, the implementation was to be completed in the fourth quarter of 1995.

Farmer cooperative development through postharvest activities. As mentioned earlier in this paper, cooperative development in the Philippines has been very slow and less than succesful. One of the reasons for this is the fact that most of the existing farmer cooperatives are not equipped with integrated postharvest facilities, so much so that they sell their harvested grains in the raw unprocessed form to the traders/processors or to NFA. They add no value to their produce so that the returns on their farming efforts are not maximised. It is very strongly believed that the success of cooperatives will be enhanced if they are allowed to process their produce before selling it direct to the consumers. Instead of just selling paddy right after harvest, they could sell milled rice at the right time and the right price if they can acquire ricemills and warehouses. In the case of maize, the cooperatives could sell milled animal feed or corn grits for food if they are equipped with corn mills or feed mills instead of just selling the shelled maize or maize cobs.

Towards this goal of empowering the farmer cooperatives the government embarked on a program entitled the Grains Production Enhancement Program (GPEP), which provides both grants of small dryers and soft loans for the other postharvest facilities including operating capital to the cooperatives.

Assistance to postharvest facility manufacturers. To provide sustainability in the development of the postharvest sector in general and the drying subsector in particular, attention and assistance to the manufacturers should be given. Thus, with the initiation of NAPHIRE in collaboration with the National Agriculture and Food Council (NAFC), the Agricultural Machinery Testing and Evaluation Center (AMTEC), the Agricultural Machinery Manufacturer and Dealer Association (AMMDA), and the Committee on Agricultural Mechanisation (CAM), a program of accreditation among the manufacturers has been established. It is envisaged that the machinery and equipment produced by these accredited manufacturers will be of high quality thereby protecting the investment of end-users of such facilities. Plans for providing soft credit to manufacturers are being initiated to enhance the development of the dryer industry in particular, and the postharvest subsector in general.

Medium and Long-term Plans in Postharvest Subsector

As indicated above the GPEP is a five-year government intervention program that caters to about 20% of the total postharvest requirement of the country. To insure the sustainability of the GPEP postharvest component, medium and long-term plans are being initiated by the different units of the Department of Agriculture either for pilot testing, donor funding, or congressional legislation. The following three postharvest-related projects are being pursued.

A. Project Self Reliance (PSR). This scheme has been implemented as a pilot project in which two federations of primary cooperatives are allowed to take over the function of the National Food Authority (NFA). One federation (FEPACOM) is operating at a municipal level: some 30 primary cooperatives are federated to assume the function/activities of NFA in the procurement, handling, processing and marketing of rice in Muñoz, Nueva Ecija. The other federation (DAFEDACO) operates on a provincial level where some 50 big cooperatives are federated to take over the function/operation of NFA in the province of Davao Norte in Mindanao. Still plagued with operational problems, these secondary (Federated) cooperatives are determined to continue, since they see big potential for the empowerment of the farmers.

B. NAPHIRE — JICA Cooperative Development. This is a project that has been short listed by the National Economic Development Authority (NEDA) for submission to the Japanese International Cooperating Agency (JICA) which aims to enhance the participation and success of cooperatives through postharvest enterprise apprenticeship training. This project will provide the incubation period for a cooperative to practice, at a commercial-scale, the actual activities of a postharvest enterprise. Without investing in capital cost, the cooperative will run the postharvest business of procurement, handling, processing, and marketing of the farmers' produce. Upon gaining the experience and confidence in 1–2 years of actual business operation, the cooperatives will be ready to borrow money from the banks to put up their own processing plants. Costly failures are thus minimised to enhance its rapid development.

C. National Postproduction Crisis Act. The rice crisis that has plagued the country recently, where the price of the staple food (rice) had doubled due to shortage in production and the delay in rice importation, has prompted some legislators to initiate the *Postproduction Crisis Act.* The bill, presently being prepared by NAPHIRE, aims to avoid the recurrence of the crisis and to prevent the occurrence of shortages in other commodities such as maize, fruits, and vegetables. Among other provisions, the bill specifies that NFA should procure milled rice rather than paddy from the cooperatives. The bill also suggests that the private traders and millers should modify their business ownership from single proprietorship to corporations that include the farmers and cooperatives as stockholders of private millers. This would become the basis for a federation of primary cooperatives where the cooperatives now market milled rice to the millers, rather than paddy. The millers in turn would concentrate on marketing of the milled rice to the consumer markets. The cooperatives would thus retain the maximum profit of their farming operations by adding value to their produce before selling to traders, millers, or consumers.

Further Reading

Andales, S.C. et al. 1987. The Philippines recommends for rice postproduction operations. Los Baños, Laguna, PCARRD and NAPHIRE. PCARRD Technical Bulletin Series, No. 63, xviii + 130 p..

Andales, S.C. et al. 1990. The Philippines recommends for corn postproduction operations. Los Baños, Laguna, PCARRD, NAPHIRE, and IDRC. PCARRD Technical Bulletin Series, No. 71, xxi + 107 p.

Andales, S.C. et al. 1992. The Philippines recommends for legumes. Los Baños, Laguna, PCARRD and NAPHIRE. PCARRD Technical Bulletin Series, No. 73.

Quebral, F.C. et al. 1986. The Philippines recommends for soybean. Los Baños, Laguna, PCARRD. PCARRD Technical Bulletin Series, No. LXX, 6.

Recide, R.S. 1994. Selected statistics on agriculture. Manila, Philippines, Bureau of Agricultural Statistics/Philippine Statistical Association Inc., 7–10.

Tumambing, J.A. 1993. Status of grain drying in the Philippines. Proceedings of the workshop on standardization of grain dryers. CLSU, Nueva Ecija, NAPHIRE, 16 p.

Tumambing, J.A. et al. 1994. Commercial application of in-store drying in farmer cooperatives in the Philippines. Partial output of ACIAR Project 9008. CLSU, Nueva Ecija, NAPHIRE, 22 p.

Problems and Priorities of Grain Drying in Thailand

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Abstract

This paper describes changes that have occurred in the rice postharvest practices of Thai farmers. An abrupt development of the industrial sector caused a serious farm labour shortage which resulted in intensive use of farm machinery. Locally manufactured combine-harvesters have been widely used in the major rice-producing areas. A reduction in the times for harvesting and handling, together with high moisture content of the harvested product, caused a sharp drop in the price of rice to below its production cost. To solve the problem, the Thai Government remitted over 250 million baht in soft loans to millers and collectors to install dryers. It also provided subsidies of over 250 million baht to farmer institutions to secure appropriate dryers.

A follow-up survey of the method of drying and type of dryer installed showed that sun drying was still the major means of drying at mill and collector levels. Dryers in use were found to be mostly of the mixed-flow type, with holding capacities around 25 t. They were operating as grain recirculating batch dryers. Some of the dryers found were of the millers' or collectors' own designs. Fluidised-bed dryers were found to have some potential at the collector level. Twenty 6 t (holding capacity) dryers had been installed at 10 farmer groups. Only five of the groups were using them.

RICE is the major economic crop in Thailand. Rice occupies a planting area of about 9.6 million ha and involves more than 70% of the farmers in the country. The annual production of rice is around 20 Mt, of which 14 Mt is consumed locally (Pungbun Na Ayudhya 1994). Rice is planted in two crops per year. The main crop is planted in July and harvested in October–November and contributes about 89% of the total production. The second crop, planted in May and harvested in July–August, contributes the other 2.3 Mt.

Rice postharvest practices of Thai farmers have in the past been labour intensive. Harvesting was done manually, using a sickle to cut the stalks of rice, which were then bundled together and left in the field for 3–4 days for sun drying. The bundles were then collected together as a pile awaiting threshing. The pile of rice might remain in the field for over a week, until the farmer was able to hire a custom thresher. Those practices applied both to the main crop and the second crop. Quality deterioration due to insufficient drying was minimal.

The practices of farmers have now changed, however, due to the rapid development of the industrial sector. More and more labour has migrated to the industrial sector each year. Consequently, farmers have been forced to substitute machinery for manual labour. Harvesting, threshing, and cleaning, which were formerly labour intensive are now done by combine harvester. Yok-u-bol (pers. comm., 1995) estimates that there are about 1500 units of the locally manufactured combine-harvester being used in the central and upper central regions of Thailand. The average harvesting capacity of a combine-harvester would be about 20 t/day. They are operated on a custom hiring basis.

Problems and Priorities for Rice Drying

Due to the wide use of the combine-harvester in the major rice-production areas, the time needed for harvesting has been appreciably reduced. In addition, the

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harvested rice has a high moisture content (22–24%). This has created handling problems for the millers and local traders since farmers cannot dry their rice as previously.

The Department of Internal Trade of the Ministry of Commerce conducted a survey in 1992 on the number of mechanical rice dryers available in the major production areas. It found that there were only 117 dryers available in 17 provinces, having a total drying capacity of 7045 t/day or about 507240 t per harvesting season. Considering that 2.3 Mt of rice of the second crop are harvested in the rainy season, the capacity of those dryers could cover only 25% of this. Expansion of sun drying floor area is restricted due to the increasing price of land, and labour costs have risen. Sun drying has thus become an expensive operation.

The circumstances described above have caused serious problems to the farmers and millers. The price of rice dropped sharply to below production costs during 1992–1993. Millers and traders could not gamble on the rapid deterioration of high moisture rice.

Government Policy on Rice Drying

The government recognised the drying needs of the country, and implemented a four-year project in 1993 with a budget of over 500 million THB (during October 1995, ca 25 Thai baht (THB) = US$1.00) for millers, collectors, and farmer institutions to purchase mechanical rice dryers. The purpose was to distribute those dryers in the major rice production areas to help reduce the deterioration losses. The project has two strands: (1) providing soft loans for millers and collectors to install large dryers (120 t/day capacity); and (2) subsidising about 50 million THB per year for farmer institutions to purchase smaller drying units (30 t/day capacity). The former is undertaken by the Ministry of Commerce, and the latter by the Ministry of Agriculture and Cooperatives.

Technical and Operational Aspects of Dryers at Miller and Collector Level

Chern-ak-sorn (Unpublished data, 1995) conducted a survey on rice drying at miller and collector levels in the central region of the country and found that sun drying is still the major practice of millers and collectors. However, there is an increasing trend towards the use of mechanical dryers. The dryers found at rice mills and at collectors were imported, locally manufactured, or of the millers or collectors own design.

The imported dryers were mostly small dryers with a holding capacity of 6 t, or 10–18 t/day drying capacity. This type of dryer has been widely used in Japan and Taiwan, and is known as a finish dryer. It is a grain recirculating batch drying type equipped with automatic moisture control. Because of its small capacity per unit, millers or collectors have to purchase several units in order to satisfy their daily drying requirements.

At present there are about five dryer manufacturers in Thailand. Four of them make large dryers having drying capacities of over 120 t/day. Most of them are mixed-flow types using rice hulls or heavy oil as fuel for generating hot air for drying. The dryers operate as a grain recirculating batch dryers. A fluidised-bed dryer using 80% recycled hot air has recently being introduced by another manufacturer and is gaining acceptance by collectors due to its fast drying rate and low investment cost. Aside from the imported and the locally manufactured dryers, there were also quite a number designed and constructed by the owners of rice mills or by traders. Some of them had a poor drying performance.

Mechanical drying of rice is a rather new technology in Thailand. Many users and manufacturers are probably still struggling with the principles and practices of rice drying. Many of the large dryers having a holding capacity of over 25 t and operating as grain recirculating batch dryers can reduce moisture at only about 1–2% per hour, while the normal mixed-flow dryers used in the USA for multipass drying can reduce moisture by 3% per pass (Kunze and Calderwood 1980). Intensive training courses on the principles and operation of rice dryers should be provided for users and manufacturers. A National Standard and Test Code for the performance of rice dryers should also be established.

Technical and Operational Aspects of Dryers at Farmer Institutions

A dryer project for farmer institutions has recently been implemented. The project involves three government agencies. The Department of Agriculture, in cooperation with the Department of Agricultural Extension and the Cooperatives Promotion Department, sets out criteria for dryer selection. The Department of Agricultural Extension and the Cooperatives Promotion Department are responsible for selecting appropriate sites for dryer installation. During the 1994 fiscal year, five units of 120 t/day capacity were installed at the rice mills of cooperatives, and 20 units of 18 t/day (6 t holding capacity) were installed at 10 farmer groups. An intensive training course on dryer operation and management for dryer operators was conducted. A follow-up study on the utilisation of the dryer at farmer institutions was conducted in the following year. The results showed that the 120 t/day dryers installed at cooperatives' rice mills were intensively used. However, only 5 of the 10 farmer groups were using the 2 × 18 t/day dryers installed, and only two of those groups were using them intensively.

Drying Strategy

Rice drying in Thailand may be done in two ways depending on the prevailing prices. At collector or central market levels, the incoming wet rice may be partially dried to 18–20% moisture content, then sold to the millers within 2 days. The collector buys wet rice fresh from the field at about 20% below the official price. In addition, the collector deducts 12–15 kg per percentage point of excess moisture per tonne of wet rice. By so doing the collector has a margin of 20% to cover risk and transportation. The weight deduction per point of excess moisture is not by itself enough to cover the drying costs. However, the collectors might dry some amount of rice down to 15% if he feels that the future market price of rice will be higher. Rice millers, on the other hand, may not have sufficient drying facilities to cover mill requirements. They are forced to purchase the partially dried rice from the collector and further dry it to about 15% moisture content. The miller might also buy wet rice from the farmer, then custom hire drying facilities to dry his rice. The form of transaction for wet rice would be the same as that of the collector. However, if the miller brings partially dried rice from the collector, the price is set according to the official price, with 12–15 kg weight deduction per percentage point of excess moisture.

In the case of an individual member of a farmer group who owns about 12 t wet rice at an average 24% moisture content, if he uses the existing dryer at the farmer group he will pay for the drying service at THB20/t per percentage point of moisture reduced. In addition, he will pay another THB80 per batch for loading and unloading services. To dry the rice from 24 to 15% moisture content he will pay about THB2320 for drying services. Assuming the official price per tonne of rice at 15% moisture content is THB3500, then the net deduction including weight loss will be THB6768. However, if he sells his wet rice at the field the net deduction will be THB12,936. There will be a margin of THB6168 if he sells the dry rice to the miller.

References

Kunze, O.R. and Calderwood, D.L. 1980. Systems for drying rice. In: Hall, C.W., ed., Drying and storage of agricultural crops. AVI Publishing Company, Westport, Connecticut, USA, 381 p.

Pungbun Na Ayudhya, P. 1994. Agricultural statistics of Thailand: crop year 1993/94. Agricultural statistics No. 16/1994. Bangkok, Thailand, Centre for Agricultural Statistics, Office of Agricultural Economics, Ministry of Agriculture and Cooperatives.

Grain Drying in Vietnam: Problems and Priorities

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Abstract

Vietnam has become a major producer and exporter of rice in recent years. Drying of high-moisture paddy harvested in the rainy season is a major problem to be overcome to reduce postharvest losses and to increase rice quality in Vietnam. Issues in grain drying are discussed in the context of a short harvest time. Constraints are identified: lack of compatible technologies including hardware; lack of understanding of the mechanical drying process in both design and operation; and lack of extension activities.

Available solutions are discussed, a striking example being the current use of about 600 units of 4 t flatbed dryers in the Mekong Delta provinces of southern Vietnam. Other promising technologies under evaluation or pilot application are presented: two-stage in-store drying; one-stage low-temperature drying; rapid first-stage drying with the fluidised-bed dryer.

Proposed priorities in action include: a campaign to regenerate awareness that drying problems can be solved; an extensive technology transfer program to dryer users and builders; a banking credit scheme to speed up the dissemination of drying technology; and continued applied research in grain drying for the diverse conditions of Vietnamese rice production.

VIETNAM is an agricultural country with 70 million inhabitants in 1994, of whom 50 million are in agricultural households. Rice is the most important crop, cultivated on 82% of total farm area, and accounting for 85% of food grain output. In 1992, Vietnam produced 21.5 Mt of paddy on 4.2 million ha of rice land. This total production almost doubled that of 1980. From 1989 to 1994, the export of rice was 1.5–2.0 Mt/year. The second most important cereal grain is maize, with a total production of 0.9 Mt in 1994, which is far behind paddy output.

Vietnam stretches from 8°N to 23°N with 3200 km of coastline (Fig. 1a) and thus has several agroecological regions. However, from the paddy postharvest viewpoint, we can divide the country into two main zones.

The Mekong River Delta (MRD), with surplus rice. In 1992, with 2.7 million ha of rice land, MRD produced 10.9 Mt of paddy, which is about 50% of Vietnam's total rice output. With only 24% of the total population, MRD has accounted for more than 90% of Vietnam's rice exports in the past 6 years. The average farm size here is about 1 ha, although in some newly-reclaimed districts, 3–10 ha per household is not uncommon.

The weather in MRD is warm and humid all year round, and without typhoons (Fig. 1b). Rice is planted in two crops per year in most areas, 60% of which are rainfed lowland. The dry-season crop is harvested in January–February; and the wet-season crop during the rainy season from July to September, with maximum rainfall of 340 mm in September.

The rest of the country (Red River Delta, Central Coast, Central Highlands, Southern Eastern) *with self-sufficiency or deficiency in rice.* The average household farm size in these areas is 0.2 ha. The most important zone is the Red River Delta (RRD) with 800 000 ha of rice fields and 5.1 Mt total paddy production in 1992. The weather in RRD is tropical monsoon with a cold winter (Fig. 1c). The first rice crop is harvested in June–July, and the second in September, before the annual typhoons arrive.

In both MRD and RRD, one rice crop is harvested during the rainy season. In 1993, MRD harvested 3.9 Mt of paddy during the wet season, which is 35% of its annual production, and about the same as the RRD's output for a full year. This is a large increase over the 1.4 Mt of paddy harvested in the rainy season 10 years earlier in 1983.

Drying problems have thus become a major concern since the 1980s. Several surveys have estimated losses ranging from 10 to 25% due to non-existent, improper, or delayed drying. We need not concern

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ourselves with the exact figure, because they all translate to losses of hundreds of millions of dollars, and focus our concern on the need for solutions. Local figures of 40–80% crop losses for extreme cases were often heard in the early 1980s. Other causes of losses can be cited, such as traffic delays and danger due to sun drying on the highway.

With Vietnam exporting rice, improvement of rice quality for a competitive world market has become a concern for the rice-processing sector in Vietnam. One aspect of quality losses was recently stated by the Director of a Food Control agency as follows.

> The wet-season summer–autumn rice crop is exported at US$30/t lower than the dry-season winter–spring crop. With 400000 t of rice to be exported from this rainy-season harvest, the apparent annual loss thus is US$12 million.

In short, it has been generally agreed that drying paddy for the wet-season harvest is the number one priority to reduce losses and to increase export quality of Vietnamese rice.

This paper discusses different facets of the drying problems, the available solutions, and the priorities for action.

Problems in Drying

Peculiar features of drying season

Let us examine a typical farmer starting the wet-season crop. He/she just finished a good dry-season harvest in ample sunshine. His concern now is dozens of agronomic problems: tillage, seed, fertilizer, pests, and so on. Rain or shine, the weather is in some way beneficial to his growing rice plants. Then comes the harvest. Most probably, rainy days have occurred before his harvest. Only then does he think of some mechanical ways of drying, if he has heard about it. (In the early 1980s most farmers did not know what a mechanical dryer could do; even now, many of them remain sceptical about it because they have never seen a dryer in operation.) This view is established

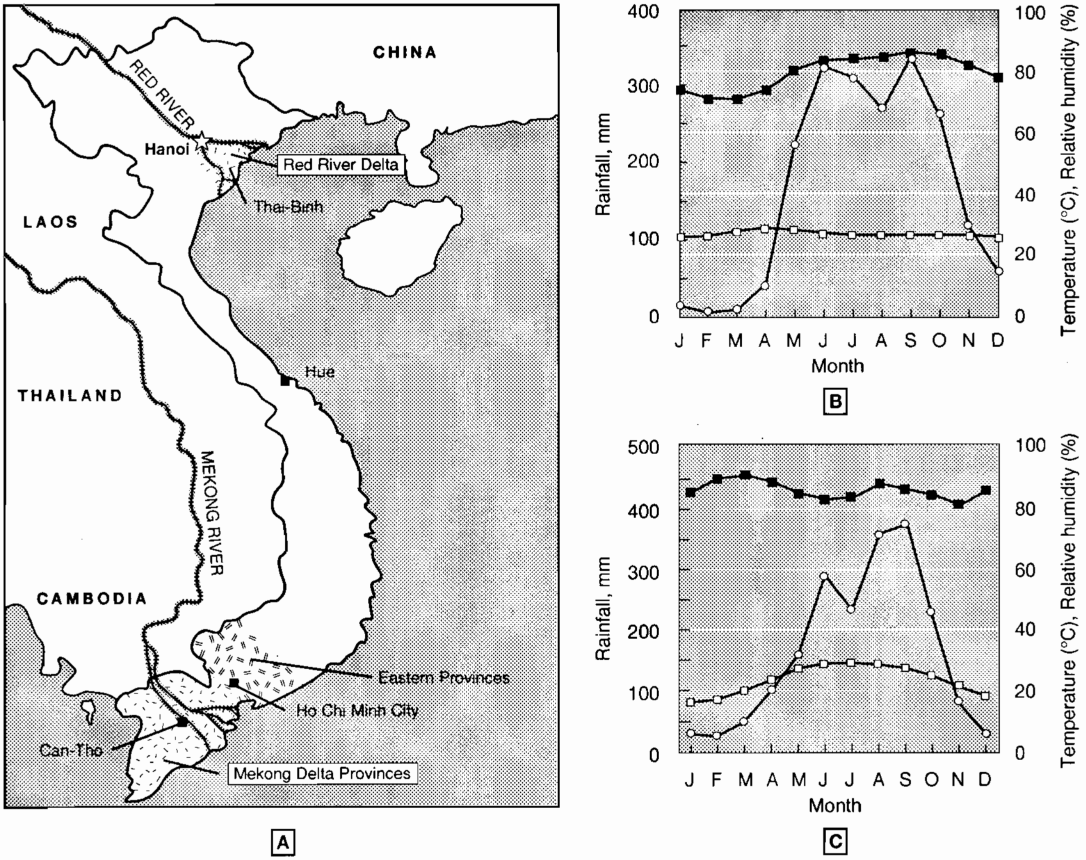

Figure 1. (a) Mekong Delta and Red River Delta of Vietnam; (b) chart of rainfall, temperature, and relative humidity for Ho-Chi-Minh City (representative of the Mekong River Delta); and (c) chart of rainfall, temperature, and relative humidity for Thai Binh Province in the Red River Delta.

through inquiries we received from farmers and users over many years. Most requests are like this: 'I badly need a dryer next week (or 10 days from now) because I will harvest at that time'. So, it is unlikely that he can get a dryer off-shelf for the urgent need. Meantime, he has to deal with the incoming harvest. This is the busiest time of the year. He has no time to go beyond the village to observe some dryer in operation. He still relies on sun drying. His harvest is quickly over, relieving him from that work burden. After some relaxed days, the farmer begins to plan for the next crop season, with again dozens of agronomic items. Good or bad, drying quickly becomes a memory of a recent past. A metaphor can be made between drying and toothache. Just before and just after the ache, one does not think of the dentist! The drying season is to the farmer relatively as short as the toothache period to the patient.

The above lengthy description serves as a context to discuss the following three constraints in drying: technology, know-how, and extension.

Lack of technologies compatible with local capabilities

Illustrations (Hien 1993) can be drawn from two categories of dryers, which have been either imported or locally developed by a dozen research institutions and factories.

High capacity dryer

These were complicated dryers of the recirculating or continuous-flow type. One example is the Russian-made ZSPJ-8 mobile dryer which weighs 12 000 kg. With its own generator and 11 electric motors, it cost four times the price of a 50-h.p. tractor in 1983. It can dry high-moisture maize to 14% at a rate of 2.0 t/hour, and consumes 26 L of diesel per tonne of maize dried. Another example is a locally designed 2.5 t/hour dryer, which has a drying chamber similar to that of the American Aeroglide dryer; its construction and installation consumes 30 t of steel. Further examples are dryers installed under FAO/UNDP sponsored projects. The only time most of the dryers in this category were used was during their days of commissioning. Reasons for this were many, but included lack of supply due to delayed transportation, drying interruptions when some components broke down and spare parts had to be imported, and high drying cost. The 'vicious circle of the drying cost' (Fig. 2) took effect and pushed the dryer into the storage shed or the junkyard.

Since 1990 at least eight manufacturers have fabricated recirculating dryers of their own design or patterned on/modified from imported models (Hien et al. 1995). Capacities of these dryers ranged from 0.3 to 2 t/hour (normalised to 10% moisture reduction, from 24–25% moisture content (m.c.) down to 14–15%). There are about 30 units installed in rice milling plants. The investment ranges from 25 to 600 million VND (during October 1995, 11 000 Vietnam dong (VND) = US$1), leading to a high drying cost of between 7 and 15% of paddy value. This explains why these dryers are hardly used except in adverse weather. Besides, the dried grain quality is not satisfactory, since most dryers, without the tempering bin, used the temperature range normally found in continuous-flow dryers (55–65°C). In most dryers, very moist paddy (30% m.c.) simply does not flow in the drying column.

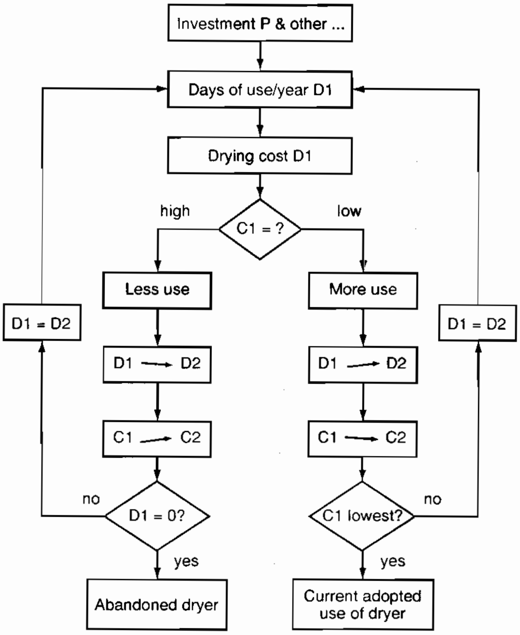

Figure 2. The vicious circle of the drying cost.

Natural draft, manually operated, and solar dryers

These were small dryers with capacities ranging from 100 to 500 kg/ batch. One example is the 400 kg batch dryer with a manually operated fan built at Minh Hai Province. Solar dryers were of Asian Institute of Technology (AIT)-type design, with two models: 100 kg (9 m^2 collector) and 500 kg (50 m^2 plastic collector) in 1983. Ten units were extended to various provinces. The drying time was usually more than one day. The dryers in this category were too small to meet the capacity demand; an average farmer household with 1 ha in the Mekong Delta might harvest 1–5 t/day. Although small, the dryer investment is relatively high for an individual farmer. Thus, after the prototype stage, these dryers did not spread further.

Lack of know-how

Lack of understanding of the drying process is reflected in both engineering design and operation. The above-mentioned recirculating dryers are examples of improper design. Another example is a flat-bed dryer designed to operate at 55°C, resulting in grain breakage. Even with flat-bed dryers correctly designed to operate at 43°C, many users modified the furnace to raise the temperature in order to reduce the drying time.

Lack of extension

Good news about dryers spreads slowly and with difficulty, while news of dryer faults is spread rapidly by word-of-mouth. This is our conclusion after years of installing dryers for different users. Questions repeatedly raised by farmers were: 'Does drying not roast the grain?', ' Is mechanical drying better than sun drying?', 'Does drying kill the germination?'. They could only be persuaded by observing the results themselves.

Even with a good dryer design and construction, correct and reliable operation by the users is particularly important. When wet paddy is in the drying chamber, no problems can be brooked. Otherwise, the drying cost will rise from, say, US$0.004/kg to about US$0.14/kg, which is the very price of this kg of paddy. This is different from the case of a tractor, plough, or a feed grinder, where a breakdown can be repaired within 2–3 days without affecting product quality.

Good performance of a newly installed dryer usually does not spread beyond the village boundary. Distant farmers are too absorbed by their own work to arrange for a visit to a good dryer during the 3-week drying season. Indeed, some dryer owners do not want to spread the good news; they wish to continue enjoying a monopoly on good drying in their localities.

On the other hand, improper drying and unsuccessful application of dryers in several localities leads to negative attitudes among farmers and even some agricultural officers. Small traders who buy any bad machine-dried paddy (high breakage, deteriorated grain, etc.) are rapid disseminators of bad news on dryers in general. The long-term result is prejudice against mechanical drying among farmers in these localities. In short, for farmers, mechanical drying amounts to no more than the specific model of dryer they happened to see at their village.

Available Solutions

Flat-bed dryers

With the above constraints, adoption of mechanical dryers has been very slow. It is estimated that by 1995, mechanical drying in the Mekong Delta accounted for less than 5% of its paddy output, while in the rest of the country, practically all paddy is sun dried. Yet, that 5% represents a good increase from almost 0% in 1980. It is the flat-bed dryer which dries a significant quantity of wet-season paddy harvested in the Mekong Delta.

The flat-bed dryer for grain is an old technology which existed probably since the 1950s in the United States and Japan. Since the 1970s, two designs have been released by the University of the Philippines at Los Baños (1.8 t/batch) and the International Rice Research Institute (IRRI) (1 and 2 t/batch), also in the Philippines. Since the 1980s these designs have been scaled up by the University of Agriculture and Forestry (UAF), Ho-Chi-Minh City and adapted for use in southern Vietnam (Hien 1993). The first 8 t/batch flat-bed dryer was installed in Ke-Sach District, Soc Trang Province in 1983. By the end of 1989, a total of 60 flat-bed dryers (with 2, 3, 4, 6, and 8 t capacities) were installed by UAF and cooperating manufacturers. Farmers–mechanics in Soc-Trang also adapted/modified the UAF design and installed about 100 units in their villages. From then on, flat-bed dryers have expanded rapidly to about 300 units in this province (out of an estimated total of 600 units for the entire country).

In terms of rice production and mechanisation level, Soc Trang ranks far below other provinces. Yet, in terms of mechanical drying, this province is a 'developed' province where flat-bed dryers are used for more than one-third of paddy harvested in the rainy season. Rice area sown for the wet-season crop in this province increased drastically from 60 000 ha in 1992 to 110 000 ha in 1995 (Tran-Van-Hao, pers. comm., 1995). The main factors contributing to this increase were: better irrigation, more suitable varieties, and mechanical drying. The Phu-Tam Village (with 2400 ha of rice), a cradle of farmer-built flat-bed dryers, had 47 dryers in 1993, and completely solved its problem of wet-season drying. There and in nearby villages, farmers have acquired the habit of bringing wet paddy to either the dryer-contractors, or to the rice mill, and taking home cash, after a deduction of 5% of paddy value for drying fees.

A typical 4 t/batch dryer (reducing moisture content from 24–27% to 15% in 6–8 hours) requires an investment of VND16–18 million (US$1500–1700). This does not include the 12 h.p. diesel engine (costing US$400), which is usually 'borrowed' from other equipment (thresher, pump, hand tractor) for use over the month long drying period. The drying cost is about 3% of paddy value. Thus, with 24-hour operation over 40 days, it is estimated (and confirmed by our preliminary surveys) that the pay-back period for the investment is one year.

Not all 'Phu-Tam dryers' are the same. There are 'good' dryers which give sufficient airflow, maintain drying temperature between 40–45°C all over the drying period, and yield high head rice recovery. There are 'bad' dryers with weak airflow, and drying temperatures of 50–58°C, resulting in high grain breakage. 'Good' and 'bad' are differentiated by the prices set by rice millers. This difference was VND50 /kg in September 1993 at Phu-Tam, which was equivalent to 5.4% of paddy value at that time. Luckily, there are more good dryers than bad, due to keen competition between dryer builders in the area.

Research on the flat-bed dryer at UAF resumed in 1993 with partial funding from a project sponsored by the Canadian International Development Research Centre (IDRC), and aimed at improving components of the popular dryer. The result is a 'standardised' flat-bed dryer (named SHG-4) with the following good features (Fig. 3):

- An axial-flow fan with adequate airflow (4 m^3/s @ 300 Pa). The fan (named SHT6 fan, and released by UAF in 1986) was selected from testing and observation of dozens of fans built by local industry or farmer–mechanics.
- A novel rice-husk furnace with a cylindrical combustion chamber (Fig. 4). The primary advantage of this rice-husk furnace as compared with the box-type furnace is its ability to extinguish sparks more thoroughly.
- A new 'side-duct' drying bin (Fig. 5) holding 4 t of paddy. Drying air enters a side duct, and turns left into side openings to the plenum. Tests with this new arrangement in 1994 showed that exit air velocity on the grain surface was acceptably uniform, resulting in the grain final moisture differential of less than 1.8% between any two points on the 4 × 8 m bin. This differential is between 2.5 to 5% in the conventional bin where air enters at one end of the plenum chamber. Details of construction and testing are given by Hien et al. (1995).

Besides the above technical advantage, the side-duct drying bin uses less materials in its construction than do existing bins. For the same holding capacity, the wall surfaces of the new bin are only 70–80% of those of existing models. Thus, the cost of the 4 t bin could be reduced by ca US$200 from the existing cost of US$900.

Figure 3. The new SHG-4 flat-bed dryer.

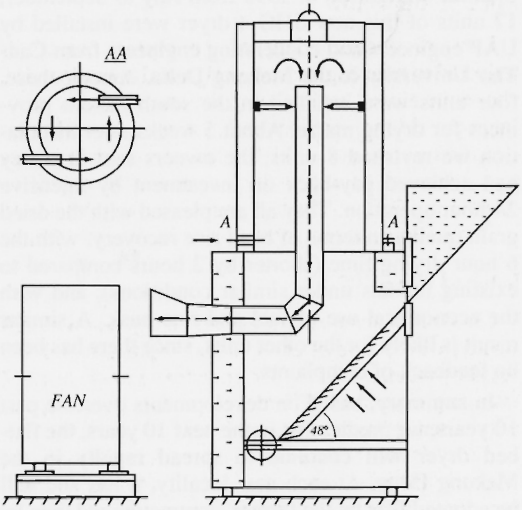

Figure 4. Rice husk furnace, with inclined-grate, and cylindrical combustion chamber.

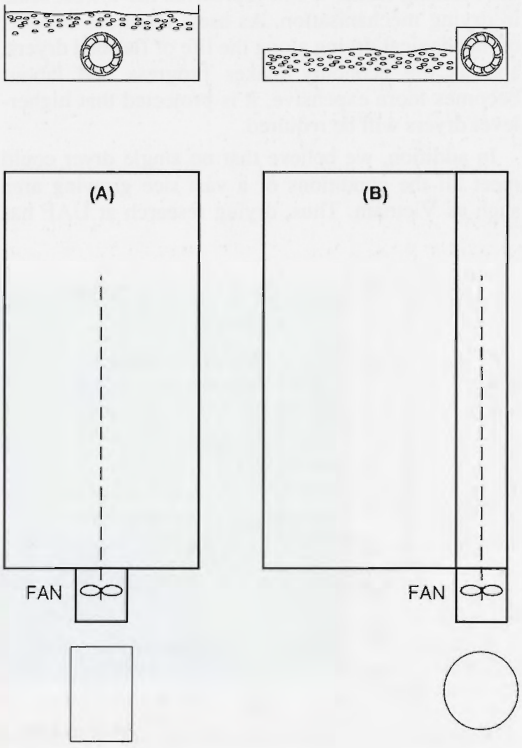

Figure 5. Two drying bin configurations: (a) with centre-line air inlet; (b) with side duct.

In the wet season of 1995 from July to September, 17 units of this new SHG-4 dryer were installed by UAF engineers and cooperating engineers from Can-Tho University in the Mekong Delta. Among these, four units were installed in the south-eastern provinces for drying maize. About 5 weeks after installation we revisited 8 units; the owners said that they had achieved pay-back on investment by intensive 24-hour operation. They all are pleased with the dried grain quality in terms of head rice recovery; with the 6 hour drying time (shorter by 2 hours compared to existing models under similar conditions); and with the economical use of fuel and rice husk. A similar result is likely for the other units, since there has been no feedback of complaints.

In summary, based on developments over the past 10 years, we predict that in the next 10 years, the flat-bed dryer will continue to spread rapidly in the Mekong Delta. At each new locality, it has and will be adopted first by the farmer–contractor, and then by the rice miller.

Other dryers

While the flat-bed dryer is increasingly adopted in the Mekong Delta, it still represents the lowest scale in drying mechanisation. As users learn the benefits of mechanical drying along the life of flat-bed dryers, and as the economy makes progress and labour becomes more expensive, it is projected that higher-level dryers will be required.

In addition, we believe that no single dryer could meet all the conditions of a vast rice growing area such as Vietnam. Thus, drying research at UAF has been diversified to seek appropriate solutions for different specific local conditions. The most promising results among these research are briefly described here [see Hien and Hung (1995) for more detail].

'Very low cost' in-bin dryer

In-bin drying technology has long been applied in temperate climate countries, and introduced to Asian countries some years ago (Kim et al. 1989). Nevertheless, the humid climate of the region requires careful consideration on ambient air temperature and relative humidity. Figure 6 presents average variation of a typical day in August 1994 at Can-Tho, which is very similar to that of other places in the Mekong Delta.

This technology was investigated in a German Agency for Technical Cooperation (GTZ)/IRRI–UAF Project. The target was to finish drying in one stage. This is convenient, since grain handling is reduced to a minimum. Various sizes of dryers are under evaluation. One has reached the extension level (Le Van Ban et al., these proceedings), as follows.

A 'very low-cost' dryer (named SSR-1) was designed for a specific class of target-users: poor, small farmer households with less than 0.5 ha of land, but which are in areas where electricity is available. In recent years, rural electrification in Vietnam has been accelerated. Major new hydropower plants with ample water supply in the rainy season would provide more energy to the agricultural sector. For example, in Thai Binh, a major rice-producing province in the Red River Delta, the power lines have reached all villages.

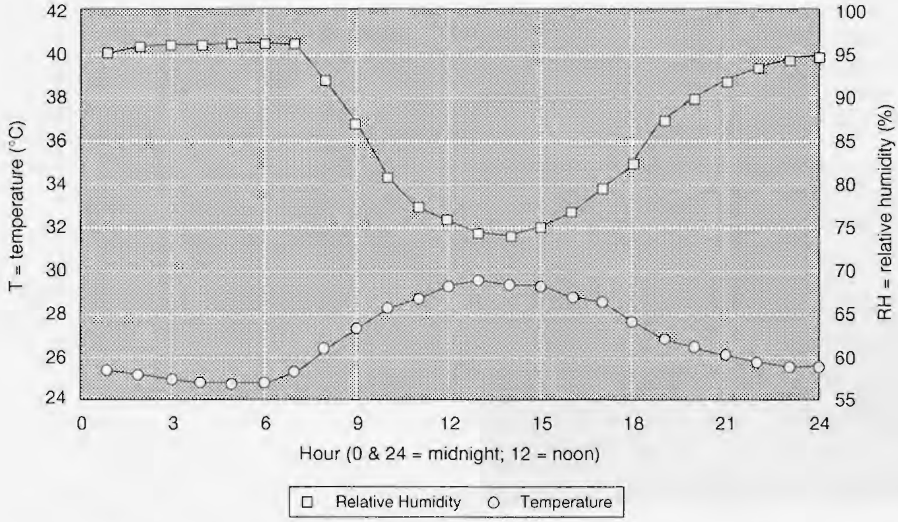

Figure 6. Average daily variation in temperature and relative humidity at Can-Tho in August 1994.

The SRR-1 dryer consists of 3 parts (Fig. 7): (1) a 1 t circular bin made from bamboo mats; (2) a 0.5 h.p. axial-flow fan; and (3) a supplemental 1000W resistor. In operation, the fan is turned ON during the day and usually OFF at night. The resistor is used only on the second night (with fan ON).

Tests at Long-An Province in the 1994 wet-season showed that 1 t of paddy at a high moisture of 26% can be dried to 14.5% in 4 days. The total fan-on time was 84 hours, and the total electric consumption was 70 kWh. The final moisture content was uniform within 1.5%, resulting in high head rice recovery. The drying cost was $4.5/ t, of which $3.2 was for electricity. With an investment of only US$55, this holds the record as the lowest cost mechanical dryer in Vietnam.

The response from small farmers has been enthusiastic: 12 units have been sold to farmers in Ho-Chi-Minh City and surrounding provinces such as Long An and Dong Nai. We anticipate that thousands of these dryers can be propagated in coming years, but subject to the major boundary condition of electricity being available.

Two-stage drying system

This technology is addressing large rice processing or trading centres, and has been used successfully in Australia and Thailand (Srzednicki and Driscoll 1994). At these centres, wet paddy is quickly brought down to 17–21% m.c. by mechanical means such as continuous-flow dryer or fluidised-bed dryer; it is then dried gently by an in-store dryer to the final uniform moisture content. In some cases, first stage of drying is the current practice of sun drying by farmers, also down to 17–21% m.c.

A project was started in April 1994 and funded by ACIAR to apply in-store drying as the second stage at the industrial scale. After initial experiments with a 4 t pilot dryer, an 80 t in-store dryer was built with the investment of Song-Hau Farm of Can-Tho Province in the Mekong Delta. In 1994, it took 157 hours to dry a 1.8 m depth grain bed from 18.5 to 14.5% m.c. In the 1995 dry season, it needed about 100 hours to dry a 2 m grain bed from 18.5 to 15.5% m.c. The appearance of rice from the in-store drying method was quite acceptable to control officers of Song Hau Farm, and head rice recovery was comparable with that from the usual drying method at Song Hau.

The supplemental heat for this dryer, to increase the ambient temperature by 5°C, was from a pneumatic-fed rice-husk furnace (Fig. 8). With a simple temperature control mechanism, the drying temperature was stable (±1°C variation). The furnace cost was low (US$500, comparable with the cost of a diesel burner) and thus did not increase the depreciation component of the drying cost. With rice husks, the fuel cost for 1 kg of in-stored dried paddy (from 20 to 15% m.c.) was only VND1 (US$0.0001) compared with VND5 using diesel (Nguyen V. Xuan et al., these proceedings).

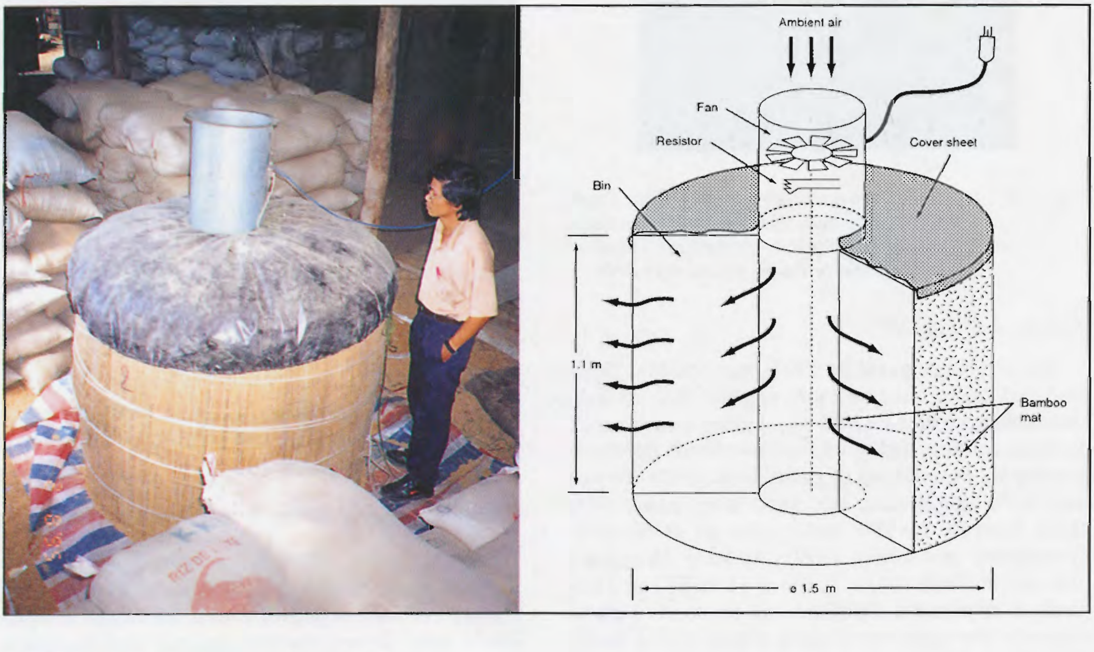

Figure 7. The 'very low-cost' dryer SRR-1.

Figure 8. (a) the 80 t in-store dryer at Song-Hau Farm, 1994; (b) rice-husk furnace with pneumatic feeder and cylindrical combustion chamber, used as heat source for the 80 t in-store dryer.

Fluidised-bed dryer

For very high moisture (30% m.c.) paddy, fluidised-bed drying may be more suitable than an ordinary columnar dryer where moist grain tends to stick to metal surfaces and block the flow. Batch fluidised-bed drying experiments of paddy in Australia showed negligible loss in head rice yield when paddy were dried from 26 to 18% m.c., using air at 60–90°C (Sutherland and Ghaly 1992). At King Mongkut's Institute of Technology Thonburi (KMITT) in Thailand, a continuous fluidised-bed dryer of 1 t/hour capacity also gave encouraging results drying paddy from 25 to 19% m.c. (Soponronnarit 1995).

This technique was evaluated by the UAF research team as a potential method for first-stage drying. Therefore, funded by ACIAR, a dryer similar to KMITT design was built at UAF and tested during the 1995 summer–autumn crop. Preliminary results showed that the dryer (Fig. 9) could reduce 31% m.c. (wet-basis) paddy down to 21% in 2 minutes, giving a drying capacity of 1 t/hour. This dryer also used a rice-husk furnace burning 40 kg rice husk per hour to maintain the drying temperature of 115°C within ±5°C (Truong Vinh et al., these proceedings). It is hoped that this technique, in combination with in-store drying, can contribute to solving the problem of paddy drying, taking into account quality improving aspects.

Figure 9. Fluidised-bed dryer at Song-Hau Farm, September 1995.

Priorities

Considering the present problems in drying and available solutions, the proposed priorities for action in Vietnam are as follows:

Campaign to regenerate awareness of grain drying

Since the early 1980s in Vietnam, drying of high-moisture grain has been raised as a major issue. Many conferences were organised both at the central and provincial level. Several research agencies were engaged in designing dryers. Aid projects worth millions of dollars were provided to reduce postharvest losses. Similar events occurred at the international level. More than twenty conferences and workshops were organised in Southeast Asia. Projects, also of million-dollar scale, were sponsored by international donors.

However, net results in 1990 were minimal: very few solutions have been widely adopted, farmers still rely on sun drying in their backyard or on the highway. This eroded the determination of the policy planners. Why repeatedly pose a problem when there is no solution?

This fact is reflected in the attitude of some Vietnamese agricultural officers, who still advocate the building of more sun drying yards as the main measure to cope with grain drying problems. UAF engineers made great efforts to persuade them that the problem is 'in the sky (where the rain comes from)' and not 'on earth (on the drying yard)'. Their reply was simply 'But we have not seen any profitable dryer'.

Abroad, IDRC seems to have withdrawn its support for postharvest research. At IRRI, postharvest seems to be not a major focus for the year 2000. A recent workshop on the IRRI–Vietnam collaboration in rice research was attended by top authorities and experts of both sides; in the subsequent 350-page proceedings (Denning and Vo Tong-Xuan 1994) there are just 4 lines mentioning postharvest losses!

What do all of these facts imply? Are there no more drying problems, or are the problems beyond solution?

Since the support of policymakers is all-important to speed up the change, the first task should be to re-ignite the awareness of these people that drying is still a severe problem and, more importantly, that the problem *can be solved.* One example has come from the flat-bed dryer of Soc-Trang Province. The development there has all come from farmers' investment. We presume that with active involvement of the government and the right support of international agencies, things could be accelerated.

Technology transfer

As analysed, extension is even more important than the design and fabrication of the dryer. A comprehensive (country-wide) extension program should be organised with the necessary budget. It can begin with the flat-bed dryer, and would consist of two main actions:

- Mass media communication (radio, TV broadcast, leaflet, publication) to create awareness among farmers and other potential users of drying technology
- Actual on-site demonstration. This requires careful scheduling from place to place to coincide with the short drying season.

Extension of dryers is in itself a big topic. We have discussed it only briefly here.

Credit scheme to speed up the dissemination

A 'sustainable' dryer should be one which is invested in by private farmers or rice millers, and is used through the years to yield profit to the users. However, a partial credit for the user to invest in the dryer at the earliest opportunity can be viewed as an aid to extension. The continued profitable operation of the dryer at the user's site is the most effective extension work; and since farmers still pay back the loan, it is also the cheapest form of extension.

Continued applied research

The above three points assume that some workable dryer is available: for example, the flat-bed dryer in the Mekong Delta. But in a dynamic economy starting from some low level, things will change rapidly. The role of research agencies is to provide designs of dryers that are compatible with the society's level of production. Too high or too low compared with that level means non-acceptance. A dryer worth US$1 million is unlikely to be accepted by a group of one thousand of farmers in the Mekong Delta who are earning a net profit of $100/each household for the entire wet-season crop. On the other hand, a $1500 flat-bed dryer might not be accepted in developed Malaysia. Neither will it be accepted in the year 2005 in Vietnam when it is expected that the economy will have evolved into a more prosperous state. The flat-bed dryer will by then have fulfilled its historical job, and maybe a $10 000 dryer will take its place.

Research agencies thus should be the 'watchdog' of this happy change, and be ready to supply the designs needed at each time. The task can be fulfilled with the necessary finance from the central government, and possibly with the additional support of international sponsors.

Manufacturers in developing countries like Vietnam have their own role. They are good and fast multipliers of proven designs. However, they usually are not strong enough in terms of engineering and financial capabilities to endure long-term research and testing.

A cautionary note on surveys

A word is in order on one non-priority item: the survey. Several partial surveys have been done in Vietnam, which indicated clearly enough the magnitude of the grain-drying problem, notwithstanding that these problems are not much different from those in other Southeast Asian countries. Another similar survey would be a waste of time and money unless it is expected that there will be follow-up actions with a hundred-fold budget compared with that spent on the survey. What has happened in the past has been the expenditure of some hundred thousand dollars for a survey, with the subsequent import of some million-dollar-ticket rice equipment, which later proved to be ineffective. Or a hundred-thousand-dollar survey for some recommendations which no agencies took up.

Conclusion

Drying of paddy to prevent grain deterioration and to enhance grain quality is still a major problem in Vietnam. Three constraints are identified in the context of a short harvest time: lack of compatible technologies, lack of know-how, and lack of extension. Nevertheless, solutions are available: one is the flat-bed dryer which has proven its effectiveness in Soc-Trang Province of the Mekong Delta. Other promising solutions have emerged to meet diverse demands of the rice sector.

The situation seems contradictory: all is lacking, but all is available. Therefore, priorities in action are needed, which include: a campaign to regenerate the awareness that there are practical solutions to drying problems; a comprehensive technology transfer program to dryer users and builders; a banking credit scheme to speed up the dissemination; and continued applied research in grain drying for diverse conditions of Vietnamese rice production.

References

Denning, G.L. and Vo Tong-Xuan, ed. 1995. Vietnam and IRRI. A partnership in rice research. Proceedings of the conference held in Hanoi, 4–7 May 1994. Los Baños, Laguna, Philippines, International Rice Research Institute.

Hien, P.H. 1993. Using batch grain dryers for summer–autumn crops in southern Vietnam. Proceedings of the 14th ASEAN Technical Seminar on Grain Postharvest Technology, Manila, Philippines, 5–8 November 1991.

Hien, P.H. and Hung, N.L. 1995. Drying research and application in the Mekong Delta of Vietnam. Paper presented at the 17th ASEAN Technical Seminar on Grain Postharvest Technology, 25–27 July 1995, Lumut, Malaysia.

Hien, P.H., Xuan, N.V., Tam, N.H. and Vinh, T. 1995. Paddy drying research and extension: activities and results, May 1993–May 1995. Final report to IDRC–UAF–PHI. Ho-Chi-Minh City, Vietnam, University of Agriculture and Forestry.

Kim, K.S., Slim, M.G., Kim, B.C., Rhim, J.H., Cheigh, H.S., Muhlbauer, W. and Kwon, T.W. 1989. An ambient-air in-storage paddy drying system for Korean farms. AMA Journal, 20(2), 23–29.

Le Van Ban, Bui Ngoc Hung and Phan Hieu Hien 1995. A low-cost in-store dryer for small farmers. These proceedings.

Nguyen Van Xuan, Troung Vinh, Pham Tuan-Anh and Phan Hieu Hien 1995. Development of rice husk furnaces for grain drying. These proceedings.

Soponronnarit, S. 1995. Drying of paddy and maize in Thailand. In: Champ, B.R. and Highley, E., ed., Postharvest technology for agricultural products in Vietnam. Proceedings of an international workshop held at Hanoi, Vietnam, December 1994. ACIAR Proceedings No. 60, 61–65.

Srzednicki, G.R. and Driscoll, R.H. 1994. Advances in research on in-store drying. In: Highley, E., Wright, E.J., Banks, H.J. and Champ, B.R., ed., Stored product protection. Proceedings of the 6th International Working Conference on Stored-product Protection, Canberra, Australia, 17–23 April 1994. Wallingford, U.K., CAB International, 351–358.

Sutherland, J.W. and T.F. Ghaly, T.F. 1992. Rapid fluid bed drying of paddy rice in the humid tropics. In: Proceedings of the 13th ASEAN Technical Seminar on Grain Postharvest Technology, Bandar Seri Begawan, Brunei Darusalam, 4–7 September 1990, 168–177.

Truong Vinh, Phan Hieu Hien, Nguyen Van Xuan, Nguyen Hung Tam and Vuong Thanh-Tien 1995. Development of a fluidised-bed dryer for paddy in Vietnam. These proceedings.

Perspectives on Drying Problems in the Southeast Asian Region and Results of R&D Projects to Solve Them

Dante de Padua*

Abstract

Ever since the green revolution of the early 1960s, and for the past four decades, research and development in the Southeast Asian region has grappled with grain drying problems. There was a recognised need for grain dryers mostly by academe and government, but the actual demand for grain dryers by industry was not there. The alternatives to sun drying were not competitive, or the incentive for investment was not there, or there was a failure in the market to recognise the advantages of investing in grain drying facilities. But mostly there has been some technological failure. The technologies developed in the engineering laboratories of the region did not address the unique requirements of the hot humid climates of the tropics, and of the production and marketing systems. Today, by all indications, triggered perhaps by farm labour shortage and increasing levels of mechanisation, and the premium prices for higher quality grains in the local and international markets, the grain industry is finally responding. There is now a demand for grain dryers, but local manufacturers still do not have what the industry needs. There is an urgency to review system requirements and to send the engineers back to the drawing board. There have been some recent breakthroughs in demonstrating what seems to be more cost-effective systems, if the industry can move from bag storage warehouses to bulk storage systems.

FOUR decades ago, we did not have a rice and maize drying problem in the region. We only had one crop a year that was harvested during the long summer months. The grain was reaped and left in windrows or field stacks to dry under the sun, after which it was gathered for storage. In Indonesia they used to harvest the panicles by hand in 'ani-ani' fashion, and stacked them in the yard. Here in beautiful Thailand I remember the farmers gathering the windrows of rice straw with the panicles and the farmers laying it on the ground for the bullock to thresh by trampling on it. In the Philippines, we also left the grain in windrows to dry and then made field stacks called the 'mandalas'. Those beautiful days of sun-drenched harvest scenes that painters love to romanticise on canvas are long gone, never to return.

The pressures for more grain to feed more people and livestock have changed farming practices. To start with, the rice and maize breeders have been so successful, and they should be after the millions of dollars they have spent, to produce non-photosensitive varieties that can be planted regardless of day-length, moon or tide, and with irrigation systems we can almost harvest all year round in the tropics. Increased yields and decreasing availability of farm labour have also conspired to increase levels of mechanisation of harvesting, particularly here in Thailand where the locally designed and manufactured rice combine is now in widespread use. What has not changed is the land tenure. Rice and maize farms in the Philippines and Indonesia range from fractions of a hectare to a high of seven hectares per farming household. This has important implications for the management of the harvested grain.

Grain drying has become a critical process for countries like Thailand and Vietnam that export premium grade rice. Mechanical dryers have also become a necessity where there is a shortage of farm labour. For several years researchers were up against a wall. Everyone recognised the importance of grain drying R&D, but processors were not investing in grain dryers. I distinctly recall an eminent agricultural economist during one of these conferences saying there was a market failure to recognise the value of

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investing in grain drying systems. Those were beautiful words that seem to describe the dilemma, but I didn't fully understand what it meant at the time. This brings to mind a question about how many economists it takes to change a blown light bulb. One economist said it depends on the wage rate. The second economist said two were needed, one to assume there is a ladder, and another to change the bulb. 'None', said the third economist : if it really needed changing, market forces would have caused it to happen. The fourth economist also said none–if the government would just leave it alone, it would screw itself in. The fifth economist said none–just wait for the unseen hand of the market to correct the lighting disequilibrium. Finally, an economics graduate student said, I am writing a dissertation on that topic, I should have an answer for you in five years. I do not know where all the engineers were during the survey.

Events have finally caught up with us. With the unforeseen hand of market forces, and I need an economist to explain this one, the problem now seems to be the lack of available dryers to meet the demand in the commercial rice and maize industry. We do not have the statistics, but the market for grain dryers is finally opening up in Thailand, the Philippines, Indonesia, and Vietnam. A couple of months ago, I visited a manufacturer here in Thailand to try to source a dryer for a project in the Philippines, and the manufacturer said he still had outstanding orders for 75 units of 30 and 100 t/hour dryers. We are now trying to source our dryer from Denmark or the USA. A local manufacturer in the Philippines cannot meet our requirements for a 20 t/hour unit, he has designs only for 1 and 2 t/hour LSU-type dryers. Some rice millers in the Philippines are putting up banks of 2 t/hour recirculating toys imported from Taiwan. In Vietnam, the demand for rice dryers is even more pressing. I've seen a miller with four units of 10 t flat-bed dryers taking up all the space in his mill. I was informed that Grain Systems International of the US has been contracted to supply drying and storage plants in Bugasari in Indonesia.

Some of the Basic Issues

Looking back, we were not exactly just waiting for market forces to change our light bulbs. We've had a very active research and development program. The questions is: have we failed to focus our research and development on what system is needed? Or perhaps we failed to correctly define the system we were designing for. Or have we identified the wrong target users of drying technology?

Grain drying and storage practices and requirements vs. available technologies have now reached centre court. Engineers are still very much concerned with the physics of drying and storage, and rightly so, but the problems in the application of grain drying and storage technologies require broader understanding of the marketing system. There are serious applied research concerns that merit multi- and interdisciplinary attention. In 1985 in one of our staff meetings in Canada, I was called into the inner sanctum of our division director. I was asked point blank why rice had to be dried. I must admit I was dumbfounded for a split second. At the time I thought it was a pretty stupid question. I would have dismissed the question as irrelevant if he had been an economist, but he was a plant breeder, with a biological science background. All I could say was, well you are a plant breeder and if you develop a cultivar that is harvested dry ready for storage then we do not have to dry the grain, or better still a cultivar that is already milled ready for the rice cooker, then we eliminate the need for drying and milling technologies. Much later, I found out that the question was asked of him by a member of our Board of Governors, apparently irritated by the continuing number of research proposals received on grain drying and storage technology development, *with very little success in their application by supposed end-users of the technologies*, and which was competing for funds with her favoured proposals on gender issues.

Grain Drying Technologies for the Three-hectare Farmers

For the farmers in the dell

There seems to be some confusion on the target beneficiaries of research and target users of technology developed by R&D in grain drying and storage. Many of our research benefactors' mandates are to help the small and poor farmers. That means if you want their money your research proposal must target the small and poor farmer as the beneficiary. This has literally been taken to heart by the engineers whose imagination is limited to tinkering with the nuts and bolts. This has led to the development, for example, of the flat-bed dryers, the micro-mills, and grain storage bamboo baskets. In Rome they call these appropriate technologies. The same romantic notions are carried on to the highest levels where research allocation decisions are made.

The millions of Filipino rice farmers tilling small patches of land retain some of their harvest for their own household requirements, and sell the rest. For the average 2 ha farm, yielding 4 t, or 10 t at the most, even if theycould afford it, it does not make economic sense for them to invest even in the simplest flat-bed, heated-air forced convection grain dryer that they will use only 5 days a season. With 10 t of grain harvested over several days, the farmer will wait for the sun to come out to dry his harvest. Where traders are active as in the Philippines, and they are all over the place trying to make a fast buck, the farmers are only too happy to unload their freshly harvested surpluses to the traders. The concept of providing the farmers the technology to dry their grain so they can hold-off for better prices, just doesn't make sense for 4 t of grain, even 10 t. The best postharvest service that can be done for these small farmers is to buy their marketable surpluses at fair prices.

The scenario is altogether different in Vietnam. There is so much grain at harvest time, the law of supply and demand requires that the farmer dries his harvest before he can sell it. The freshly harvested rice has to be dried before it can be brought to town to the trading centres. In the remote villages, sun drying is not an option. The farmers are not allowed to dry in the main roadways. There is a demand for farm dryers, and Dr Phan Hieu Hien's 6 t flat-bed dryers have taken root firmly. In one Putham village we visited, every other household had a dryer in his backyard. The dryers can be fabricated in the village, including the fans. Off season, the dryer is used as a pig pen. The trouble is, even the millers in town have adopted the flat bed dryer, and the flat bed dryer is not an industrial dryer.

IRRI has spent a lot of resources to study sun drying or design dryers collecting solar energy, and IDRC and USAID have supported some of these researches. As far as I know there have been no major breakthroughs, in the sense that these devices have been adopted.

The flat-bed dryer has been described as a high temperature, high airflow, low capacity drying technology, and indeed it is. I came across the first flat bed dryer design when I was reviewing the literature for my thesis dissertation at Louisiana State University in 1958. It was used in the US rice industry before the second world war. When the farmers had to go to war, because of the ensuing farm labour shortage, they had to mechanise the process. Thus was born the columnar designs. Much later I saw one huge flat bed dryer in a rice estate in Paramaribo, South America. When I got home, the Japanese were selling little one tonner baby cribs. Well we thought at UPLB that we should design one that could be put together from off-the-shelf materials. We even used a radiator fan of 6 × 6 trucks. Our target user was the farmer. We missed the target with the first round by a metre to the left, and the second time around by a metre to the right, and the third time we didn't even have to fire because the econometrician said we had it just right. The farmers didn't cotton to it, but it was popular with development workers. It was introduced in Indonesia, Malaysia, and even in Brazil. IRRI picked it up and came up with what they call an original IRRI design. Today, I still come across the UPLB flat-bed dryer complete to the last detail with maize seed growers in Mindanao, but now called the IRRI dryer.

Today, I think that the greatest use of the flat-bed dryer is as a laboratory pilot dryer. Students of drying theory have used it for relating airflow to static pressures and drying air temperature, to drying rates and grain quality; and for determining fuel utilisation efficiency. The entire drying process from the heating of the ambient air, to the adiabatic drying process could be traced by the student on a psychrometric chart, and actual performance data compared with theoretical values. As a teaching laboratory, the flat bed dryer can be configured as a deep bin or a shallow bed for the same volume of grain, and using the same fan to demonstrate how fan performance changes against the system curve.

Grain Drying Technologies for the Commercial Marketing System

The real arena for drying technology development is in the commercial marketing sector. To feed the increasing non-farming sector, or to supply the commercial livestock growers, drying, storage, and milling of grain has to meet the requirements of the marketing system. If you were asked to supply a drying plant, the system specifications would stipulate specific capacities to be met, the quality of the end product, the degree of sophistication of controls required, the boundaries for the cost of operation, and the integration of the drying plant with the other facilities. This is the playing field where research can have a pay-off.

Application of air psychrometrics and heat and mass transfer

In the late 1950s and into the early 1960s the prevailing thinking was that there was no need for more drying research. The grain drying and storage systems in the USA and Western Europe were highly developed, and all that was needed was to transfer these technologies. After several Shanzers, Bericos, Cimbrias, Butlers, etc., we now know better, although there are still a number of sales engineers who belong to the school of thought that we should be buying from them rather than manufacturing our own. There is nothing basically wrong, technologically, with these systems. Their operating modes could be altered to suit our hotter and more humid climates. This assumes an understanding of the psychrometrics, the heat and mass transfer involved in drying. This altering of operating conditions has been a problem for some. We need more local sales reps who can do this. For the past 2 weeks I have been in discussions with

American sales engineers. Their sales manuals stipulate capacities in bushels per hour, for a 10 point moisture reduction–from 25% down to 15% wet basis. I asked for capacities in tonnes per hour for a moisture reduction from 30 to 14%, and the fuel required in litres per hour. All of them had to refer the questions to the home office. A European sales rep pulled out his laptop and began punching in the data to come up with the dryer configuration and answers. Very impressive. His quotation too was quite impressive, four times the quote by the Americans. A local manufacturer underquoted everybody, except he could not guarantee performance.

Today, a cadre of highly trained engineers in crop drying science are available in all the universities offering the agricultural engineering curricula. Their impact in the local crop drying scene is now felt. I had several drying projects in my portfolio with IDRC. Some were successful, others just fizzled out. At Chiang Mai University, the crew of Dr Norkun Sittiphong developed a longan dryer that is now widely used. At the Institut Pertanian Bogor, Indonesia, Dr Hadi and his graduate students successfully designed and installed natural convection dryers for high value crops such as chilli. These engineers could be harnessed to address the local drying problem. There are now at least four big local Thai manufacturers of columnar continuous flow dryers of the LSU type or the cross-flow type, with capacities ranging from 10 to 100 t/hour.

Drying conditions and the biological properties of the grain

The conditions for drying rice and maize in the humid tropics are different from the temperate climates. Paddy and maize when harvested during the rainy months have moisture content levels of 26% for paddy and 30% for maize. After reaping the mature rice crop, the grain cannot be left in windrows or field stacks any more, it has to be threshed immediately. NAPHIRE research has shown that overnight, field stacked grain would suffer from heat damage. Heat damaged grain results in overall discoloration or loss of lustre, and the yellowing of some kernels. After threshing the 26% paddy, this has to be dried immediately. Again NAPHIRE research has shown that paddy can be dried down to 18%, and held at that moisture for 21 days without appreciable further damage. In other words, at the peak of the harvest season, to increase the volume of grain that can be dried by the drying plant, grain can be dried in two stages.

Maize on the other hand has to be dried immediately after picking and shelling to arrest mould infection and aflatoxin contamination. NAPHIRE research has also shown that freshly harvested maize would already have anything from 0 to 14 ppb of aflatoxin, depending on the harvesting conditions. This level of contamination was found to increase rapidly if there was any delay in drying. Within 12 days, the aflatoxin level was shown to have increased to about 126 ppb in one instance. They also observed that maize grains dried to levels between 14 and 18% were still susceptible to further aflatoxin build-up. In some experimental sites, maize that was dried down to 13.7% in 4 days had aflatoxin levels of only 3.38 ppb. NAPHIRE has firmly established that while there are many other factors affecting mould infection and aflatoxin contamination, immediate drying is the only cost effective way of controlling aflatoxin build-up in maize in the humid tropics (Paz et al. 1988). Parallel studies here in Thailand essentially came to the same conclusion. These studies have led to the investment in maize dryers by the feedmillers.

There is a difference in drying paddy and drying maize. With paddy, care has to be taken not to fissure the grain during the drying process so as not to affect head rice yields. We have long established that we can accelerate drying without affecting head rice yields, but that grain temperature has to be kept below 43°C to prevent formation of fissures. This is a time–temperature relationship. Continuous flow dryers that merely recirculate the grain have to keep the drying air temperature at no more than 43°C after the surface moisture has been removed and evaporative cooling has ceased. For multistage drying with tempering periods, higher temperatures can be used provided the grain temperature does not reach the critical fissuring temperature of 43°C. Very few systems, however, seem to be able to adapt to the multistage drying with tempering bins. The higher heat utilisation efficiencies of multistage drying are not appreciated or understood.

Requirements of the local marketing system

The more serious problem is the difficulty in designing drying systems to suit the local production and marketing systems. Why is this? For paddy there are too many varieties grown and entering the trade. Here in Thailand, a miller told me they have only four major commercial varieties. In the Philippines, during the last harvest season we had to contend in our Jalajala plant with 23 different varieties that we could not mix until we could establish in the laboratory their physical and biochemical properties. There is too much pilferage of uncertified seeds from IRRI that farmers are trying to gamble on. They think they may hit another C4, the ever popular UPLB variety. For both recirculating and CFD dryers, this situation is a drying plant operator's nightmare. We have tried getting several smaller dryers operating in parallel, but to be able to have the flexibility, they have to be completely independent of each other and not serviced by a common intake pit.

In a rice-processing plant, the rice mill is the heart of the system. The capacity of the rice mill dictates the minimum drying and storage capacity required. If there are two distinct harvest seasons, then paddy procurement must take care of the slack periods between harvest seasons to keep the mill in operation. In some cases, the drying storage capacity is influenced by rate of market sales, or the ability to turn over stocks with a harvest season. The point is that drying plant capacity must conscientiously be worked out. Where there is an undercapacity, the millers' business is restricted. An overcapacity is even worse as columnar dryers cannot be operated unless they have a full load.

NAPHIRE or extension agencies should develop monographs for the selection of dryer models that are designed as modules. For any given conditions, the proper selection of dryer models or capacities, and the corresponding auxiliary equipment such as elevators, precleaners, in line autoweighers, and empering bins could then be made. The margins or the value added and the cost of production of the final product should be imputed in the monographs. Unfortunately, many grain drying engineers do not care to understand the grain business to be able to advise clients properly.

Poor performance of some systems

Understandably, locally manufactured drying units are about half the cost of imported units, but are often not engineered properly. The result has been dissatisfaction with performance. Some of the complaints are:

(1) the unit does not have the promised capacity;
(2) the milled rice dried by the dryer does not have the lustre of sun dried grain;
(3) the cost of drying is too high compared with sun drying;
(4) parts in contact with the abrasive rice grain wear thin too quickly, adding to the cost of maintenance;
(5) high cost of system relative to added value;
(6) safety controls are not provided;
(7) parts are not standardised.

There is no question that dryer design engineers can tackle these problems but they have to work with the manufacturing industry.

Management of the grain processing system

The cooperatives are the most pampered group of rice processors in both the Philippines and Indonesia. The government showers them with all kinds of equipment, some of which they never asked for. I think the business is in the purchase of the equipment given to them, never mind if they are never used. Systems developed for cooperatives are not very good models for the industry to copy.

A cooperative engaged in the rice trade is a business enterprise which must make profits to be able to service its membership. It has been our experience that to be able to compete in the retail trade, despite the recent rice shortage in the Philippines, we have to be efficient and we have to consistently produce the grade of products that we promised to deliver. We therefore must have an efficient paddy grading system with conscientious grain classifiers. But an important operations policy is that we do not purchase paddy sun dried by the farmers. We only purchase freshly harvested paddy and handle the drying in our drying plant in order to maximise total and head rice recovery. The contributed direct cost for drying, which includes energy, causal labour, and plant operators, but excludes overhead costs, depreciation costs, and other business costs is P0.12 per kg of milled rice. That is lower than sun drying which is P0.13 per kg of milled rice. This is because with sun dried grain our total milling recovery is only 63%, and with grain dried in our dryers we recover as high as 67%. There is significantly less breakage in our dryers.

The private processors and traders operate a completely different system. In the Philippines and Thailand they have the filthiest plants, their plant layouts are the most disorganised, but they are the most profitable and have been able to sustain their business despite the lack of government support. In Vietnam, ever since the government adopted an open market policy, the private milling sector was reborn. There is keen interest in commercial drying technology that they can adopt. In a rice estate I've seen several dryer configurations being tried out. This only means that R&D, and E has to catch up with the situation.

Breakthrough in drying R&D

Not too long ago, we began hearing about two-stage drying strategies from the researches of Dr Robert Driscoll and Dr George Srzednicki (University of New South Wales, Australia) in ACIAR-supported projects in the region. The first stage required by the very wet harvest in the humid tropics should drop the initial moisture to 18%. The second stage down to 14%, in a take-your-time, bulk storage system blowing conditioned air through. At that time Dr Srzednicki was promoting in-store drying systems as a very cost-efficient technology compared with, say, the flat-bed or LSU systems, except that to be able to in-storage dry, the grain had to be predried in either the flat-bed or LSU dryers. For a long time I was confused with his logic, but last July I had the opportunity to review the ACIAR grain drying project (ACIAR PN9008) in the Philippines, Vietnam, and Thailand (Andrews and de Padua 1995).

The Dayap system. The Dayap Multipurpose Cooperative, a farmer-based cooperative, grants production loans to its members, and the members pay back their coop in paddy. The coop needed a dryer very badly. They bought a Japanese 1 t/hour recirculating dryer. This is another example of a dryer not meeting the drying load requirement to be effective. They were given by the government a multipurpose drying pavement, which made a good dance floor for the barrio, but was next to useless as a dryer during the rainy season. They were getting desperate for a dryer.

At this point Dr Srzednicki and Dr Justin Tumambing (NAPHIRE) were introduced to them. They promised to install in the cooperative a commercial-scale prototype in-store drying system. The project undertook detailed studies of the coop's operations to establish their drying requirements and the potential financial viability of investing in a dryer facility. The resulting system used a NAPHIRE 'flash' dryer for first-stage drying and a 66 t in-store dryer built onsite for the second stage. The in-store dryer consists of 6 bins with a total size of 3 × 22 × 3 m high, and is loaded by a mobile pneumatic pump conveyor. A central duct supplies drying air and serves as a manifold to plenum chambers beneath the perforated floor sheets of each bin. A backward curve centrifugal blower delivers the air at 500 Pa (2 inches) static pressure. A small kerosene pot burner is provided in case supplemental heat is needed. Their simulation studies indicated that for a 3 m depth and an apparent air velocity of 4 m/min, the estimated drying time to bring down the moisture from 18 to 14 % would take 12.5 days of continuous operation. The system is now in full operation, for the current wet-season harvest. I am now glad to report to Dr Srzednicki that what he was preaching as a practice is now working in principle. The coop has passed a resolution adopting the researchers as the patron saints of the cooperative. Dr Justin reports that the direct drying cost is P0.10/kg of paddy or P0.15/kg of milled rice.

The Song Hau system. As we all know, Vietnam has become a major exporter of milled rice to the international markets, albeit medium to low quality rice. The downgrading is due to the presence of yellow grain, an indication of delayed drying. The major rice production areas of Vietnam are in the Mekong delta in the south and the Red River delta in the north. The average land tenure of a farming household is about 1 ha. A few State farms have been allowed to continue operating. These are production estates where the management develops the land, the irrigation and drainage system, and provides all the production inputs and technology required. The farmers within the estate are obliged to sell their produce to the system. The State farms have provided the required economic scale for efficient integrated operations. These are similar to sugar estates or haciendas in the Philippines.

Dr Phan Hieu Hien came in late as a disciple of Dr Srzednicki. Low temperature, low airflow in-store drying technology was a new technology that had to be approached with caution. Dr Hien first tried a pilot 4 t dryer with a 2.5 m deep grain bed. Eight load tests were run successfully. This convinced the Song Hau State Board, which commissioned an 80 t capacity in-store dryer to further validate the results of the pilot dryer. With 2 m deep of grain, the grain was dried from 18 to 14% in 5 hours. In all tests, a rice-husk furnace provided supplemental heat. The direct drying cost was reported to be P0.09/kg of paddy, which is 0.01 centavo lower than in the Philippines.

With all these successful commercial trials in the Philippines and Vietnam, there still seems to be some confusion between the operational concept of a deep bin dryer and an in-bulk-storage dryer. In the design of a full scale in-store dryer, for example, in the conversion of a warehouse to suit a bulk storage in-store dryer, a detailed study of the handling and trading practices must be done. The study should establish categorically how long they can keep the grain in-store before it is sent to the mill. Short drying times will require large blowers and result in drying costs which may not be competitive.

The Wattana rice mill system. The Thai rice industry is well-placed to take advantage of in-store drying technology. Millers handle large volumes of grain in bulk in their warehouses and are very conscious of both quality and cost. As mentioned earlier, the changing patterns of harvesting have created a situation where there is now a demand for grain drying systems at the mill level. Dr Somchart Soponronnarit of King Mongkut Institute of Technology has spearheaded the studies and introduction of in-store drying technology in Thailand. As with their counterparts in the other countries, a lot of mathematical modelling, simulation, and validation studies have been undertaken to confirm that such a technology is feasible in the hot and humid tropical climates. The Kittisak Wattana rice mill complex owner has a son who studied at the Asian Institute of Technology, and was more open to experimenting with on-floor aeration systems. It was an easy step for them to adopt the technology when they built a new warehouse, with the help of Dr Somchart. A full scale 3000 t capacity warehouse was fitted with in-floor ducts spaced at 2.5 m, and centrifugal blowers delivering 0.5 cubic metres per minute of air per cubic metre of grain. This system configuration dried the paddy from an average of 19 down to 14% (wet basis) in 1.5 months, where operation is restricted to daylight hours with supplemental heat.

The Kittisak Wattana rice mill has successfully adopted the in-store drying technology, but Dr Somchart cautions that three other mills have experienced problems. This merely highlights the need to design the systems correctly and to provide the management with information on operating principles and procedures. This is what Dr Srzednicki calls the need for paring to optimal allocation of resources.

KMITT fluidised bed dryer. The most significant result of R&D activity by Dr Somchart's group at KMITT under an ACIAR project is the final development, after years of modelling, of a commercial model of a fluidised-bed dryer to handle the first stage of drying. A 5 t/hour fluidised-bed dryer is already being manufactured commercially by the Rice Engineering and Supply Co. and has several orders pending from millers. The system is compact and operates at temperatures of 100–120°C. The dryer removes the surface moisture down to 18% (wet basis) in 7 minutes. The project report indicates that from the results of extended tests, the users found it easy to operate, that the fast drying rates for high moisture grain affected head rice recovery only slightly and need fine tuning in this regard, that there was actually less energy consumption of both electricity and fuel oil, and that a more uniform productt resulted, compared with a columnar cross flow dryer.

The commercial unit in place was owned and operated by a paddy trader, and the fluidised bed was used in conjunction with an LSU dryer that did the final drying to 14%. There is great interest in Vietnam, Indonesia, and the Philippines in this fluidised-bed drying technology.

Research and Extension Service Areas

1. Very clearly, the adoption of R&D results, particularly drying technology, has to be accelerated to meet the demands of a market opening up. Assistance to the local manufacturing sector has to be provided, not only in providing technical drawings, but in understanding the principles behind the design. Grain dryers are unlike mechanical threshers, where the action of the machine is more evident. The more abstract concepts of fluid mechanics, air psychrometrics, and heat and mass transfer have to be explained. We must have some science in the designs, to guarantee performance.
2. The commercial in-store drying systems now in operation clearly demonstrate the technological possibilities. Bulk handling and storage is an established practice in industrialised economies but a new concept in the region. There is a psychological block that 18% moisture grain can be placed in-storage and dried slowly to 14%. The technology is still seen as a high-risk system with low quality assurance which is contrary to the objectives of commercial traders. But I am confident that commercial demonstrations such as established in Dayap, Song Hau, and Wattana will slowly dissolve any reservations.

References

Andrews, A. and de Padua, D.B. 1995. ACIAR Project 9008 review report. Canberra, ACIAR.

Paz, R. et al. 1988. Terminal report of IDRC supported project: Control of aflatoxin (Philippines). Muñoz, Nueva Ecija, National Post Harvest Institute for Research and Extension.

Lack of Incentives as Constraints to Introduction of Efficient Drying Systems

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Abstract

The basic equation governing paddy drying is reviewed. The conditions when this equation is not satisfied at the farm level, assembly points, and government drying complexes are discussed. Societies consume the type of rice that is commensurate with their economic status. If a particular society does not value high quality rice, then such rice will not be produced. There is then no premium attached to the dry paddy used to produce the high quality rice. As societies become affluent, a demand for good quality rice will emerge and paddy will be dried to produce a high quality product. There is therefore only so much a government can do to reduce the cost of drying. The more fundamental impetus to paddy drying comes from consumer taste, which is itself a function of the overall economic standard of a society.

THERE are many technical reasons for drying paddy. These include better recovery rate of rice from paddy in the milling process and reduction of losses, both qualitative and quantitative, during paddy storage. Dried paddy can be stored longer, hence enabling better utilisation of harvesting, storage and milling facilities. However, despite these reasons, drying of paddy will not take place anywhere along the postharvest chain, unless the *basic economic equation governing paddy drying is met.* In this paper, we discuss this equation, outlining the conditions when this equation is satisfied and those when this equation may not be satisfied. Some specific situations in selected ASEAN countries with regard to paddy drying are also discussed.

The Basic Paddy Drying Equation

The basic equation determining if paddy drying occurs or not somewhere along the postharvest chain is easily derived, as follows. With no drying, the value of rice recoverable from wet paddy is $Y_w r_w P_r$, where Y_w is weight of wet paddy, r_w is the recovery rate of rice from milling wet paddy and P_r is the price of rice. With drying, value of rice recoverable is $(Y_w - L)r_d P_r$, where Y_w is weight of wet paddy, L is loss in weight due to drying, r_d is the recovery rate of rice during the milling process from dry paddy (i.e. at 14% moisture content), and P_r is the price of rice as before. Drying of paddy will occur only if:

$$(Y_w - L)r_d P_r - Y_w r_w P_r > K \tag{1}$$

where K is the cost of drying, assuming that the cost of milling dry and wet paddy is the same[1]. This is the basic equation for drying.

One variation of this equation is given by:

$$(Y_w - L)P_{dp} - Y_w P_{wp} > K \tag{2}$$

where P_{dp} is the price of dry paddy and P_{wp} is the price of wet paddy. To get this equation, we are assuming that, under competitive market conditions, the price of dry paddy vis-à-vis wet paddy will reflect their different rice recovery rates from paddy.

Another variation of equation (1) is given by:

$$(Y_w - L)V_{dp} - Y_w V_{wp} > K \tag{3}$$

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[1] If the cost of milling for wet paddy is higher than the cost of milling for dry paddy, then the resulting K can be higher for the equations (1)–(3) to be still satisfied.

where V_{dp} is value of products obtainable from dry paddy while V_{wp} is the value of products derivable from wet paddy. Besides head rice, there are products of lesser value like broken rice and residual by-products resulting from the milling process. In a sense, therefore, equation (3) is more complete than equations (1) and (2), in that all products derivable from paddy milling are included in this equation. As in equation (1), we are assuming that the cost of milling is the same for both dry and wet paddy.

An added complication occurs when farmers sell paddy to paddy buyers—government agencies, private operators specialising in paddy drying, or millers. The standard price used in this transaction is the price of clean paddy at 14% moisture content (m.c.). Paddy buyers impose a penalty deduction on the weight of wet paddy, i.e. paddy with moisture content over 14%, to cover the cost of drying. The relationship between the penalty deduction, weight loss upon drying and the cost of drying can be derived as follows. The cost of purchase of paddy for the paddy buyers is:

$$(Y_w - D)P_{dp}$$

where D is the penalty deduction for wet paddy and P_{dp} is the price of dry paddy. The return from drying paddy is:

$$(Y_w - L)P_{dp} - K$$

where L is weight loss of paddy upon drying and K is the cost of drying. Paddy buyers will attempt to maximise their returns from drying by manipulating D such that:

$$(Y_w - D)P_{dp} < (Y_w - L)P_{dp} - K$$

which simplifies to:

$$D > L + (K/P_{dp}) \qquad (4)$$

Hence, the penalty deduction for moisture in wet paddy, D, must be at least equal to, or more than, the weight loss plus a factor for the cost of drying wet paddy. It is entirely possible that D is less than what is specified in equation (4), if millers can compensate for their cost of paddy drying with economic profits from elsewhere in the postharvest chain. Further, millers who can exploit economies of scale in the drying process may be able to offer more generous deductions to paddy farmers, compared to smaller millers who do not enjoy such economies of scale.

We will be using these four equations in our subsequent discussions on why the fundamental paddy-drying relationship may not be satisfied, why efficient drying systems of paddy may not be installed and, hence, why drying of paddy does not take place.

Who Will Dry the Paddy?

First, we examine here the question of who would be the most likely party to undertake the task of drying paddy in the postharvest chain. The party who benefits the most from drying paddy is the agent most likely to undertake this task. Who is likely to benefit the most or, to put it in the reverse manner, who is likely to suffer the most if the paddy is not dried?. This might be the paddy farmers themselves, independent drying agents such as cooperatives and private operators, or rice millers. The party that stores the paddy is the one likely to suffer the most from wet grain, because the loss resulting from storing wet paddy is the most severe of all the possible losses resulting from the presence of excessive moisture in paddy, due to grain rot, mould infestation, and grain discoloration upon milling. Depending on the situation, farmers may not store their paddy. For example, in Malaysia, it is cheaper for the paddy farmer to buy rice from the market than to consume his own rice, due to the intricate paddy subsidy and rice support system. Paddy farmers obtain a price of MYR711/t of paddy, made up of MYR463 as the guaranteed minimum price and MYR248 as the product subsidy (during October 1995, ca 2.40 Malaysian ringgit (MYR) = US$1). If the farmer were to mill the paddy himself, he would obtain about 610 kg rice valued at about MYR512, from which about MYR100 must be subtracted as paddy drying and milling costs. Therefore, paddy farmers in Malaysia do not store paddy on-farm. Hence, paddy farmers in Malaysia do not dry their product[2].

Compared with independent operators who undertake only paddy drying, rice millers have certain distinct advantages in terms of handling the paddy drying function. For example, millers have the option of blending wet grains with dry grains in the milling process, an option that may not be available to drying-only operators. Further, in terms of storage and marketing, rice millers can vary the proportion of rice stored as compared with paddy, so as to take advantage of price changes in rice, again an option not likely to be open to drying-only operators. Also, rice millers are likely to be more familiar than are drying operators with the retail rice market, and hence are likely to be able to take advantage of changes in prices in the retail market. An additional advantage open to rice millers would be for them to go a step further downstream and undertake processing of rice into rice flour, rice-based noodles (meehoon), and various rice-based confec-

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[2] This is only one of the reasons for not drying. The other reason why farmers in Malaysia do not dry their paddy is connected with the system of weight deduction for moisture in paddy used in government drying complexes.

tioneries, tapping synergistic benefits from closely allied activities. For these reasons, the existence of an independent paddy drying-only industry in ASEAN countries is rare and hard to justify.

Why Paddy Drying May not Occur

First, let us review the reasons as to why farmers do not dry their paddy at farm level. The reasons given (Fredericks and Mercader 1986) are:

(a) high acquisition cost of artificial dryers beyond the reach of small-scale farmers due to their low production volumes;

(b) unsatisfactory performance of some drying systems introduced;

(c) lack of technical know-how in dryer operations, resulting in inefficiency and poor milling results;

(d) capacity of dryers incompatible with farm production and other processing equipment; and

(e) the price structure of paddy, which does not seem to adequately reflect the cost of drying.

All the above reasons can be represented by equation (1). In other words, the benefit derivable from drying does not cover the cost of drying. The drying cost is high, either because of poor technical performance in operating the dryers or because of lack of economies of scale in the drying process as a result of the small volumes of paddy involved. We did some simulations of equation (1), using some typical Malaysian figures (Table 1a–c). In Table 1a, we assumed that the recovery rates of rice from paddy at 20% m.c. downwards are, respectively, 55, 56, 57%, and so on (the recoveries of rice from paddy at 14 and 19% m.c. are given as 61.67 and 56.62%, respectively, by Fredericks and Wells 1983).[3] In Table 1b, the rice recovery rates are lowered by 1 percentage point for every moisture level. In Table 1c, the recovery rates are put even lower, at probably unrealistic levels, for comparative purposes. The gains from paddy drying ranges from MYR19.96 to MYR8.03 in Table 1a and from MYR28.39 to MYR16.46 in Table 1b, on a per tonne wet paddy basis. We conclude that the gain from drying paddy is probably around MYR20/t, whereas the cost of drying paddy, as given in the literature, ranges from MYR30 to MYR69/t. Assuming that the rice derived from wet paddy is of a lower quality and hence fetches a lower price than rice obtained from dry paddy (this quality difference is not captured in our equations (1)–(3)), the gain from paddy drying is probably more than MYR20. Hence, we can infer that the benefit from drying paddy is quite small, at least in the Malaysian case.[4] Thus, we can conclude that farmers are behaving rationally when they do not dry their paddy. They will dry only if they are storing their paddy for future consumption. In that case, given the small volumes of grain involved, sun drying is probably economical.

At the assembly-point level where paddy drying is done by independent operators, it is reported also that artificial drying is not widely adopted. In West and Central Java, for example, it is reported that hundreds of KUDs (village unit cooperatives) had stopped using locally manufactured flat-bed dryers (Fredericks and Mercader 1986). The reason given is that the cost of drying paddy and its better quality are not reflected in a premium price for dry paddy.

The demand for dry paddy is a derived demand, derived from the value that customers placed on the better quality products obtained from dry paddy as compared with the discoloured, broken products obtained from wet paddy. If a particular society, such as a society with a low standard of living, does not differentiate a good product from an inferior product, then it does not pay to produce such a good product. A society consumes the type of rice commensurate with its economic status. If the standard of living in a particular country is low, such that good quality rice does not have a premium, then such rice will not be produced. Drying of paddy will not take place. This is the doctrine of consumer sovereignty, a fundamental principle in market economics.

Fredericks and Mercader (1986) seem to infer that K, the cost of drying paddy, is underestimated, with many implicit costs, such as the cost of the housing unit for the dryers, the costs of repairs and maintenance, and the opportunity cost of the farmers' time being not included in the estimation of K. Hence, given a larger actual K, equations (1)–(3) are not satisfied and drying of paddy therefore does not occur. Their explanation ended there. We take the argument a step further. We take the more fundamentalist view that if the value of products derivable from dry versus wet paddy is not so different (equation (3)), the result is a small K for equations (1)–(3) to be satisfied. In the existing literature, the emphasis is on K—how we can lower K through more technical competence and

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[3] It was pointed out to the author that no private miller would mill rice of over 16% m.c., because the milling machinery would clog. However, in the literature, we did find cases of rice recovery rate being cited for paddy at 19% m.c. This could be for small or experimental mills (Loo Kau Fa, personal communication).

[4] K is probably lower in other ASEAN countries than in Malaysia. However, there may be even less premium attached to good quality rice derived from dry paddy in these countries because of lower per capita incomes, again resulting in the basic drying equation not being satisfied.

improvements, lower fuel cost, less tax on imported components, and so on.[5] In this paper we are taking a more fundamental approach in the sense that, perhaps, the more important factor that determines if equations (1)–(3) are satisfied is not K, the cost of drying paddy itself, but rather the difference in society's valuation of the products derived from wet versus dry paddy. If society's valuation is sufficiently different,[6] K can be large and the equations (1)–(3) are still satisfied. Drying of paddy then occurs competitively, driven by free market forces.

If there is one group that tends to lose the most from moisture in paddy, it must be the private rice millers. They are the people who store the paddy for long periods and hence will suffer the most if the paddy is not dry. Generally, we do not hear of complaints that private millers do not dry their paddy, for market forces will drive them into bankruptcy if they do not adopt the best practice or technology prevalent in their given environment. In fact, to remain profitable, private millers generally search for the best technologies and practices available. For example, it is

Table 1. Gains from moisture reduction in paddy at various rice recovery rates.

(a) 55–60% recovery rate						
Initial moisture level	20%	19%	18%	17%	16%	15%
Value of extraction rate r_d		0.62	0.62	0.62	0.62	0.62
$(Y_w - L)r_dP_r$	483.1	489.65	495.70	501.74	507.79	513.83
Value of extraction rate r_w	0.55	0.56	0.57	0.58	0.59	0.60
$(Y_w r_w P_r)$	463.65	472.08	480.51	488.94	497.37	505.80
Gains from drying paddy from initial level down to 14%	19.96	17.57	15.19	12.80	10.42	8.03
Cost of drying from initial level down to 14%	From around MYR[a]30 to MYR70 /t					
(b) 54–59% recovery rate						
Initial moisture level	20%	19%	18%	17%	16%	15%
Value of extraction rate r_d	0.62	0.62	0.62	0.62	0.62	0.62
$(Y_w - L)r_dP_r$	483.61	489.65	495.70	501.74	507.79	513.83
Value of extraction rate r_w	0.54	0.55	0.56	0.57	0.58	0.59
$(Y_w r_w P_r)$	455.2200	463.65	472.08	480.51	488.94	497.37
Gains from drying paddy from initial level down to 14%	28.39	26.00	23.62	21.23	18.85	16.46
Cost of drying from initial level down to 14%	From around MYR30 to MYR70/t					
(c) 53 –58% recovery rate						
Initial moisture level	20%	19%	18%	17%	16%	15%
Value of extraction rate r_d	0.62	0.62	0.62	0.62	0.62	0.62
$(Y_w - L)r_dP_r$	483.61	489.65	495.70	501.74	507.79	513.83
Value of extraction rate r_w	0.53	0.54	0.55	0.56	0.57	0.58
$(Y_w r_w P_r)$	446.7900	455.22	463.65	472.08	480.51	488.94
Gains from drying paddy from initial level down to 14%	36.82	34.43	32.05	29.66	27.28	24.89
Cost of drying from initial level down to 14%	From around MYR30 to MYR70/t					

Notes:
Average drying cost in government complexes = MYR46.60, without administrative costs.
With administrative costs, drying cost per tonne of paddy goes up to MYR69.32 (Ghaffar and Azman 1985)
Average drying cost in private mills is around MYR30 to MYR40/t (Rice Millers Association 1984).
We are assuming that Y_w is 1000 kg, the price of rice is MYR0.84/kg. The cost of drying is for 1000 kg.
[a] During October 1995, ca 2.40 Malaysian ringgit (MYR) = US$1.

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[5] These factors are of course relevant and it is the government's duty to ensure that such impediments to paddy drying, in the form of onerous taxes, do not exist.

[6] Society will look for quality only if it is affluent enough. Quality is highly income elastic. One example is the case of Kobe beef.

inconceivable that private rice millers will not dry their paddy if the moisture level goes above 20%, for the loss of product would be massive at that level. It is possible that between 19 and 14% m.c., millers do not dry their paddy, if society does not attach a premium to products derived from paddy at 14% m.c. as against products above 14% up to 19%, assuming there is no long storage of such paddy. Further, broken rice has value in that it is used in the manufacture of rice noodles and rice-based confectioneries. Hence, the value of products derivable from paddy at between 19 and 14% m.c. may not be so great, again requiring a small K, such that equation (3) cannot be satisfied, for moisture levels from 14 to 19%.

The situation in government drying complexes in Malaysia is clear cut. Work done by Chew and Ghaffar (1986), showed that equation (4) is not satisfied. The penalty deduction for moisture at government drying complexes is not severe enough. Hence, farmers benefit from not drying the paddy they sell to government complexes. In seasons of bumper harvest, a disproportionately large amount of paddy is directed to government complexes, with the private millers taking the best quality grains because of the more stringent deduction for moisture in such complexes. Hence, the government drying facilities become overloaded and unable to handle the large throughput involved. The Malaysian case is truly unique and probably the only one of its kind in ASEAN, for efficiency, in this case, is made secondary to larger political, social, and equity goals.[7] However, changes are in the offing. As of 1 July 1994, the National Paddy and Rice Authority (LPN or Lembaga Padi dan Beras Negara), was reborn as BERNAS (Padi Beras Negara), a government owned corporatised body, that may eventually be privatised. It is said that BERNAS is now no longer the paddy buyer of last resort. BERNAS, as a corporatised body, will therefore have to minimise its losses at least, if not to maximise its profits.

Concluding Remarks

From the simulations of the basic equation (1), governing the drying of paddy, it is shown that K, the cost of drying must be small, around MYR20/t for the Malaysian case. If the actual cost of drying exceeds this figure, drying of paddy is not economically viable and will not take place. This seems true for paddy moisture regimes of around 19 to 14% m.c. Given this small K, farmers are behaving rationally when they do not dry their product unless they are storing it for future consumption. A major deterrent against farm-level drying is the small volume of paddy involved, making economies of scale in the drying process unreachable for small farmers using artificial dryers.

Private millers will dry the paddy if the price is right. However, judging from the literature, it would seem that for Indonesia and the Philippines at their current status of development, consumers do not differentiate much between rice products derived from paddy at moisture levels from 14 to 19%. The literature is replete with statements that there is not much premium attached to dry paddy (and maize). The result is again a small K in equations (1)–(3), making drying an unprofitable activity unless its cost can be kept low.

There is therefore only so much the government can do to minimise K, the cost of drying, through tax policies and the improvement of engineering skills in paddy drying. The more fundamental impetus to drying comes from changes in consumer taste. As societies become affluent, the demand for better quality rice (better quality in terms of lower percentage of brokens, no discoloration, right amount of stickiness and fragrance, and so on), is bound to increase. There will be a premium for such quality rice, with the premium being transmitted down to the paddy that is used to produce such rice. There will then be a sufficient gap between the price of dry paddy vis-à-vis wet paddy, even permitting a larger K, for the equations (1)–(3) to be satisfied. Drying will then occur as a matter of course. This is in fact occurring now in Malaysia, where the super grade of rice, whose price is now left free to find its own level in the market, can cost as much as MYR2.40/kg compared with MYR0.90 for the lower, standard grade.

In a previous study (Chew and Fatimah 1987), we had concluded that Thailand has the most competitive paddy/rice postharvest industry, followed by the Philippines, Indonesia and Malaysia. This can be seen from the fact that the percentage of paddy handled by government agencies is the highest in Malaysia (estimated to be 30–40%), followed by Indonesia (10%), Philippines (7–10%) and Thailand (less than 1%). It is therefore consistent that Thailand has the smallest problem with regard to paddy drying. Further, Thailand is the world's leading exporter of rice. It is therefore safe to assume that the difference in prices for different qualities of rice in the world market will have filtered down to manifest itself as difference in prices for different qualities of paddy. If Malaysia, through BERNAS, fully privatises its paddy/rice postharvest industry, it will have taken a giant step in solving the ailments afflicting the industry, including the problem of paddy drying. Such a step is long overdue.

If there is any lesson to be drawn from the collapse of the economies of the socialist and communist governments of the world over the past decade, it is that,

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[7] It is true that when an economy is strong it can afford to carry a lot of excess baggage.

in general, market economies bring a much better allocation of resources and a higher standard of living than command economies. On a micro level, the same goes for paddy drying. Given the free interplay of market forces, if society demands high quality rice, the right type of paddy will be dried to produce such a high quality product. In the final analysis, it is the economics that determines whether or not a paddy drying technical innovation is adopted.[8]

References

Chew, T.A. and Fatimah Arshad 1987. Comparative paddy pricing system in ASEAN. In: de Mesa, B.M., ed., Proceedings of the Ninth ASEAN Technical Seminar on Grain Postharvest Technology. Manila, Philippines, ASEAN Crops Postharvest Programme.

Chew, T.A. and Ghaffar, R.A. 1986. Some economic aspects of drying of paddy by farmers in Selangor, Malaysia. In: Champ, B.R. and Highley, E., ed., Preserving grain quality by aeration and in-store drying. ACIAR Proceedings No. 15, 146–151.

Fredericks, L.J. and Mercader, J.P. 1986. Cost implications of implementing grain drying systems. In: Champ, B.R., and Highley, E., ed., Preserving grain quality by aeration and in-store drying. ACIAR Proceedings No. 15, 152–160.

Fredericks, L.J., and Wells, R.J.G. 1983 Rice processing in Peninsular Malaysia. Kuala Lumpur, Oxford University Press, 200 p.

Ghaffar, R.A. and Azman, H. 1985. A preliminary investigation of the costs associated with rice drying and milling in Peninsular Malaysia. In: Semple, R.L. and Frio, A.S., ed., Research and development systems and linkages for a viable post-harvest industry in the humid tropics: proceedings of the 8th ASEAN Technical Seminar on Grain Postharvest Technology. Manila, ASEAN Crops Postharvest Programme, 391–398.

Kuhn, T.S. 1970. The structure of scientific revolutions, 2nd ed. University of Chicago Press, 210 p.

Rice Millers Association of Peninsular Malaysia/Lembaga Padi dan Beras Negara 1984. Status of paddy/rice processing industry—problems and proposals. Seminar document submitted to LPN, 63 p.

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[8] Unless that particular innovation is a Kuhn-type revolutionary paradigm shift and not just an incremental improvement (Kuhn 1970).

Principles of Grain Drying and Aeration

Grain Physical and Thermal Properties Related to Drying and Aeration

Chong-Ho Lee* and Do Sup Chung†

Abstract

Knowledge of grain physical and thermal properties is essential not only in analysis and simulation of the physical and thermal phenomena in individual grain kernels and grain mass, but also in designing drying and aeration systems.

A compilation of the existing data on grain physical and thermal properties, such as specific gravity, density, porosity, static pressure through grains, isotherms, specific heat, thermal conductivity and diffusivity, heat of vaporisation, and drying rate constant, is presented for selected economic grains, including rice and maize.

The applicability and/or limitations of the existing data for practical and theoretical uses are reviewed. Research areas to secure more information on grain physical and thermal properties are identified.

WE look first in this paper at grain physical properties related to drying and aeration, then at thermal properties. Among the many parameters related to physical properties of grain, several that are related closely to grain drying, such as physical dimensions, volume, true density and specific gravity, bulk density, and porosity, are examined. Also, the pressure drop of airflow through paddy (rough rice) and maize is reviewed.

Physical Property Parameters

Physical dimensions of rice and maize

Physical dimensions, such as length, width, thickness, and volume of grain, vary with variety, agronomic practice, environmental conditions, maturity, grain temperature, and especially moisture content.

Because the grain kernel is hygroscopic, moisture content is related closely to physical dimensions of the grain kernel. Some information related to physical dimensions of rice and maize is tabulated in Tables 1–3. Some investigators have expressed the physical dimensions of grain as functions of moisture content, as shown in Tables 2–3.

Wratten et al. (1969) reported a linear relationship between the volumes of medium- and long-grain paddy and moisture content, whereas Fortes and Okos (1980) expressed the volume of maize as a function of temperature and moisture content of the kernel. Few reports have been found relating to physical dimensions, especially the volume of rice and maize. More research is needed on the measurement of kernel volumes by means of computer image-processing techniques. Also, more information on physical dimensions such as sphericity, axial dimensions, surface area, roundness, and projected area is needed for simulation studies of grain drying and aeration systems.

True density and specific gravity

True density is defined as the mass of the kernel per unit volume. It is sometimes referred to as kernel density or unit density.

True density is useful information for analysis of heat and mass transfer through grains, as well as simulation works on grain drying and aeration systems. It can be determined either by direct measurement or indirect prediction from specific gravity data. True density measurements shown in Table 4 indicate the variation with respect to moisture content. Therefore, some investigators have devised linear models to predict true density within the specific range of moisture content in which the measurement was conducted.

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Table 1. Some information related to physical dimensions of paddy.

Grain	Variety	Moisture content (%, wet basis)	Length (10^{-3} m)	Width (10^{-3} m)	Thickness (10^{-3} m)
Paddy	Short grain Caloro	10.4–22.6	7.46–7.59	3.46–3.56	2.28–2.39
	Medium grain Saturn	12–18	7.89–7.98	3.12–3.18	1.96–2.01
	Long grain Bluebonnet	12–18	9.68–10.03	2.59–2.69	1.91–1.98
	–	12–15	5–10	1.5–5	
Maize	Pfister	6.7	16.26 (0.91)[a]	20.27 (1.07)	12.80 (0.71)
	Beck	13.96–21.26	13.30 (0.99)	8.7 (0.76)	4.7 (0.68)
	–	12–15	8–17	5–15	
	Shelled, Yellow Dent	10.3–42.6	11.60–13.62	6.93–8.92	3.61–4.58

[a] Number in parentheses indicates the standard deviation.
Sources: Goss (1965), Thompson and Isaacs (1967), Wratten et al. (1969), Morita and Singh (1979), Fortes and Okos (1980), Nelson (1980), Pomeranz (1981).

Table 2. Linear models for physical dimensions of paddy.

Variety	Moisture content (%, wet basis)	Length (10^{-3}m)	Width (10^{-3}m)	Thickness (10^{-3}m)
Model[a]		$L = a + b M$	$W = a + b M$	$T = a + b M$
Short grain Caloro	10.40–21.89	$a = 7.318$	$a = 3.358$	$a = 2.287$
		$b = 1.22 \times 10^{-2}$	$b = 8.90 \times 10^{-3}$	$b = 8.90 \times 10^{-3}$
Medium grain Saturn	12–18	$a = 7.747$	$a = 2.842$	$a = 1.842$
		$b = 1.27 \times 10^{-2}$	$b = 7.62 \times 10^{-3}$	$b = 8.9 \times 10^{-3}$
Long grain Bluebonnet	12–18	$a = 8.941$	$a = 2.388$	$a = 1.765$
		$b = 5.84 \times 10^{-2}$	$b = 1.65 \times 10^{-2}$	$b = 1.43 \times 10^{-3}$

[a] L = length, W = width, T = thickness; M = moisture content.
Sources: Wratten et al. (1969), Morita and Singh (1979).

Table 3. Measurements and models for kernel volumes of rice, paddy, and maize.

Grain	Variety	Moisture content (%, wet basis)	Kernel volume (10^{-5}m^3)	Models[a]
Paddy	Medium grain Saturn	12–18	16.06–19.17	$9.7339 + 0.5097 M$
	Long grain Bluebonnet	12–18	18.35–19.66	$15.4038 + 0.2994 M$
Rice	Caloro	8.6	21.35 (0.38)[b]	
	Calrose	9.2	19.71 (0.288)	
	Hy Mix Early	8.8	17.86 (0.24)	
Maize	Beck 65	0	25.0	
	Pfister	9.0–30.8	26.9–36.9	
	Pfister 347	6.7	26.8(0.752)	

[a] M = moisture content (%, wet basis).
[b] Numbers in parentheses indicate the standard deviations.
Sources: Goss (1965), Thompson and Isaacs (1967), Wratten et al. (1969), Mohsenin (1986), Fortes and Okos (1980).

Table 4. True density measurements for rice, paddy, and maize from various sources.

Grain	Variety	Moisture content (%, wet basis)	True density (kg/m^3)	Models[a]
Rice	Caloro	8.6	1358.4	
	Calrose	9.2	1364.8	
	Hy Mix Early	8.8	1387.2	
Paddy	Medium	12–18	1324.3–1371.8	
	Medium	16.5	1395.3	
	Medium	11.5	1404.9	
	Long	12–18	1362.9–1384.0	
	Long	14–22	1027.4–1054.7	$1046.1 - 1.01M$
	Long	15.2	1403.3	
	Long	11.5	1391.1	
Maize	Pfister 347	6.7	1292.7	
	Beck 65	21.7	1236_13	
	Seed	16–44	1190.5–1293.3	
	Shelled	24–26	1369.1	$1370.0 - 0.028[100M/(100 - M)]$
	Yellow	9–27	1284.5–1313.4	$1327.8 - 1.60M$
	Yellow Dent	10.3–42.6	1237.0–1274.0	$1251.9 + 7.14M - 0.597M^2 + 0.0019M^3$
	Yellow Dent	12–23	1208.1–1250.0	$1300.7 - 3.23\ M$
	Unknown	15–45	–	$1402 - 535\ M$
	Yellow Dent	10.3–42.6	1228.0–1334.0	
	Dekalb	24.2–37.8	–	$1370–2.8(100M/(100 - M))$
	Shelled Yellow Dent	16.3	1287.7	

[a] M = moisture content (%, wet basis).

Sources: Goss (1965), Wratten et al. (1969), Chung and Converse (1971), Gustafson and Hall (1974), Calderwood (1973), Brusewitz (1975), Fortes and Okos (1980), Kim (1980), Nelson (1980), Kay et al. (1989).

Some linear models show that true density decreases linearly with an increase in moisture content. Nelson (1980), on the other hand, devised a third-degree polynomial with respect to moisture content to predict the true density.

The true densities of rice and paddy range from 1358 to 1387 kg/m^3 and from 1027 to 1405 kg/m^3, respectively, depending on the variety and moisture content. The true density of maize falls in the range from 1190 to 1369 kg/m^3 depending on the variety and the moisture content.

Specific gravity data from various sources are tabulated in Table 5. Specific gravity values of rice and paddy fluctuate between 1.11 and about 1.39, depending on the variety and moisture content. Specific gravity values of maize vary from 1.19 to 1.30, according to the variety and the moisture range in which the measurement was conducted.

Wratten et al. (1969) and Morita and Singh (1979) devised models to predict specific gravity values of short-, medium-, and long-grain paddy as shown in Table 5.

Bulk density values of rice and maize

Bulk density is defined as the density of material when packed or stacked in bulk, and represented as the mass per total volume of solid and air void. Test weight, which is used as a bulk density in the United States, is defined as the weight of a dockage-free sample per Winchester bushel (0.03524 m^3). Bulk density is much more important than true density in drying and aeration practices. It is affected by moisture content, the amount of fines and foreign material, and the degree of filling. In general, the bulk densities of rice, paddy, and maize are measured under the loose-fill condition.

The bulk density values of rice range from 570 kg/m^3 to 591 kg/m^3 as shown in Table 6. On the other hand, those of paddy fluctuate around the value of 576 kg/m^3, depending on the variety and moisture content.

Wratten et al. (1969) and other investigators reported that bulk density has a linear relationship with the moisture content of paddy within the range of moisture content in which the measurement was conducted. Five linear models indicate that the bulk density of paddy increases with increasing moisture content, in contrast to the tendency of the true density values.

Table 5. Specific gravity values of rice, paddy, and maize.

Grain	Variety	Moisture content (%, wet basis)	Specific gravity	Model[a]
Rice	Caloro	8.6	1.36	
	Calrose	9.2	1.36	
	Hy Mix Early	8.0	1.39	
	Hondurus	11.9	1.11[b]	
	Wateribune	12.4	1.12[b]	
Paddy	Short, Caloro	10.8–21.5	1.299–1.359	1.424 – 0.00564 M
	Medium, Saturn	12–18	1.325–1.374	1.465 – 0.076 M
	Long, Bluebonnet	12–18	1.384–1.385	1.436 – 0.0042 M
Maize	Pfister 347	6.7	1.29	
	No.1	9.0	1.19	
	Shelled, Yellow Dent	25.0	1.27[b]	
	Shelled, Yellow Dent	15.0	1.30[b]	
	Shelled, Yellow Dent	10.3–42.6		$1.2519 + 0.00714M - 0.005971M^2 + 0.00001088M^3$

[a] M = moisture content (%, wet basis).

[b] Calculated from the values of porosity and loose-fill bulk density and approved by the ASAE.

Sources: Zink (1935), Goss (1965), Wratten et al. (1969), Morita and Singh (1979), Nelson (1980), ASAE (1995).

Table 6. Bulk density values of rice and paddy.

Grain	Variety	Moisture content (%, wet basis)	Bulk density (kg/m^3)	Model [a]
Rice	Caloro	8.6	571.1(1.7)[b]	
	Calrose	9.2	570.7(6.2)	
	Hy Mix Early	8.8	591.2(9.3)	
Paddy	Short, Caloro	11.24–20.95	632–664	583.6 + 4.27 M
	Short	14–22	–	537.6 + 1.22 M
	Medium, Saturn	12–18	598.3–648.3	499.7 +8.33 M
	Medium	6–28	–	567.2 + 4.13 M
	Medium	13.2	590.0	
	Long	12–18	585.6–615.1	519.4 +5.29 M
	Long	9–11	561.0–598.0	
	Long	13.5	710.0–780.0	
	Long	14–22	–	$529.2 - 1.105\ M + 0.00955\ M^2$
	Unspecified	12–16	590.0	
	Unspecified	9.6–25	656.8–752.9	
	Unspecified	–	579[b]	
	Long, Tobonnet	12–24	480–604	

[a] M = moisture content (%, wet basis).

[b] Data approved by the ASAE.

Numbers in parentheses indicate the standard deviations.

Sources: Lorenzen (1957), Goss (1965), Kazarian and Hall (1965), Wratten et al. (1969), Brooker et al. (1974), Morita and Singh (1979), Mohsenin (1986), Siebenmorgen and Jindal (1987), USDA (1990).

The bulk density values of various varieties or hybrids of maize from various sources are summarised in Table 7. Excluding the extreme data, the variation of the bulk density of maize remains within the range of about 10% of 721 kg/m^3.

The second- or third-degree polynomials with respect to moisture content to predict the bulk density of shelled maize, which were devised originally by Brusewitz (1975) and Nelson (1980), were approved by the American Society for Agricultural Engineers (ASAE). Brusewitz (1975) commented that bulk density of seed maize reaches a maximum value at around 30% moisture content.

On the other hand, Brooker et al. (1992) reported that the test weight of grain usually increases during the drying process until a maximum is reached at a moisture content of 14–16% (wet basis, w.b.). In contrast to the trend of the values of bulk density for paddy, the linear models for flint and dent maizes devised by Vermuganti and Pfost (1980) show that bulk density of maize decreases as the moisture content increases.

Porosity values

Porosity is defined as the volume fraction of air void space and is presented as the ratio of air or void volume to the total volume. Porosity is determined usually by means of either direct measurement of the volume fraction of air or indirect prediction using the relationship between porosity, true density, and bulk density.

Porosity values for rice and maize are compiled in Table 8, some porosity data shown are approved by the ASAE. Wratten et al. (1969) and other researchers reported that the porosity of rice and paddy ranges from 46 to 60% depending on the variety and the moisture content. Porosity values of maize fluctuate within the range from 37 to 47.6 %, depending on the variety and the moisture content. Porosity values of maize approved by the ASAE remain about at the centre of this range. Wratten et al. (1969) and other investigators reported a relationship between porosity and the moisture content for paddy. On the other hand, Gustafson and Hall (1972) and Chung and Converse (1971) expressed the porosity of maize in relation to test weight or bulk density.

Table 7. Bulk density of maize.

Variety	Moisture content (%, wet basis)	Bulk density (kg/m^3)	Models[a]
Pfister 347	6.7	744.5[b]	
Shelled	7.3–23.9	656.8–752.9	
Shelled	12	659.96	
	12–16	745	
Shelled	–	721[b]	
Shelled	–	717.6	
Flint	6–28	644.8–789.1	$828.5 - 6.56M$
Dent	6–28	636.5–779.0	$818.1 - 6.52M$
Yellow Dent	10–35	638.5–742.2	$682.9 + 14.22M - 0.9843M^2 + 0.01548M^3$
Yellow Dent	12–23	698.4–784.3	$1086.3 - 2971M + 4810M^2$[b]
Seed	16–44	710.3–734.1	
Ear Husked	–	448.5	
Green Sweet	–	448.5	
Yellow Dent Shelled	0–15	749.7	$701.9 + 1676M - 11598M^2 + 18240M^3$ [b]
Yellow Dent Shelled	10.3–42.6	708–775	$682.9 + 14.22M - 0.9843M^2 + 0.01548M^3$
Stauffer	12–18.2	731–826	
B. Jac	11.8–17.6	735–821	
Shelled, Yellow Dent	16.3	752.7	

[a] M = moisture content (%, wet basis).

[b] Data approved by the ASAE.

Sources: Zink (1935), Goss (1965), Bakker-Arkema et al. (1971), Gustafson and Hall (1974), Hall (1971), Hall and Hill (1974), Brusewitz (1975), Nelson (1980), Chang (1986), Mohsenin (1986), Kay et al. (1989), USDA (1990), ASAE (1995).

Table 8. Porosity values of rice, paddy, and maize.

Grain	Variety	Moisture content (%, wet basis)	Porosity (%)	Models[a]
Rice	Hondurus	11.9	50.4[b]	
	Wateribune	12.4	46.5	
Paddy	Durar	11.4	51.0	
	Taichung	9.3	52.0	
	Kalinpong	9.7	54.5	
	Short	14–22	46.4–47.6	49.7 – 0.227 M
	Medium	12–18	58.5–53.1	65.6 – 0.475 M
	Medium	13.2	52.5	
	Long	12–18	56.9–59.6	69.5 – 0.885 M
	Long	14–22	48.4–50.8	$49.4 + 0.064\ M - 0.0099\ M^2$
	Unspecified	12–16	48.0	
Maize	No. 1	9.0	40.0	
	Shelled, Yellow Dent	25.0	44.0	
	Shelled, Yellow Dent	15	40	
	Yellow	9–14	38.5–47.6	
	Yellow	9–27	–	101.0 – 0.078pb
	Shelled	9–31	38.5–47.6	
	Yellow, Shelled	9–27	–	81.4 – 0.056 Wt
	Yellow, Dent	12–23.4	37–42	
	Unspecified	12–16	40	

[a] M = moisture content (%, wet basis), pb = bulk density (kg/m^3), Wt = test weight (kg/m^3).
[b] Data approved by the ASAE.
Sources: Zink (1935), Thompson and Isaacs (1967), Wratten et al. (1969), Hosokawa and Matsumoto (1971), Chung and Converse (1971), Gustafson and Hall (1972), Agrawal and Chand (1974), Brooker et al. (1974), Kim (1980), Haque et al. (1982).

In general, the value of porosity varies with the degree of filling, the amount of fine materials, bulk density, and moisture content. However, it seems reasonable for porosity to be expressed as a function of bulk density, because the degree of filling and moisture content are already reflected in the bulk density value.

Static pressure drop

In order to design a grain dryer or aeration system and to choose the correct fan, accurate information about the pressure drop for airflow through the grain bed is very important. Many investigators have found that airflow rate, the surface and shape characteristics of grain, the size and configuration of the voids, moisture content, the variability of the particle size, the bed depth, the extent of packing, and the amount of foreign material affect the pressure drop of airflow through grains.

Brooker et al. (1974) reported that the resistance pressure increases with an increase in the percentage of fines in the grain mass. Haque et al. (1982) investigated the effect of the moisture content of grain on the resistance to airflow. They reported that the static pressure through grain is influenced significantly by airflow rate and the moisture content. Hukill and Shedd (1955) developed a model to predict the pressure drop over an airflow range 0.01–0.20 $m^3/s\ m^2$ and determined the constants involved in the equation for several grains.

Haque et al. (1978) and Chung et al. (1985) expressed the static pressure or pressure drop as a second-order polynomial of airflow rate, moisture content of grain, and the percentage of fines present. Also, Siebenmorgen and Jindal (1987) developed a model to predict the pressure drop of airflow through a bed of paddy and identified air velocity as the major factor.

Kay et al. (1989) reported that the horizontal airflow resistances through shelled maize were about 58 and 45% of the vertical airflow resistance when airflow rates were above and below 0.1m^3/s m^2, respectively. Li and Sokhansanj (1994) devised a generalised equation to estimate airflow resistance of bulk grain with variable density, moisture content, and fines when porosity, moisture content, and fines concentration were specified. Jayas and Mann (1994) developed a modified Shedd's equation to solve for airflow rate explicitly in the case when the pressure drop is known and airflow rate is required. After testing that equation, they concluded that airflow resistance data can be summarised using a single equation with a modifier for each seed type, Shedd's equation gave a reasonable approximation at high airflow rates over 0.04 m^3/s m^2, but the error increased at low airflow rates below 0.006 m^3/s m^2.

The ASAE revised Shedd's equation to the form shown in equation (1) and approved it for determining the static pressure drop of airflow through a grain bed. The values of constants involved in that revised model for paddy and maize are tabulated in Table 9.

$$\Delta P/L = aQ^2/\ln(1 + bQ) \qquad (1)$$

where, ΔP = static pressure (Pa), L = bed depth (m), Q = airflow rate (m^3/s m^2), and a and b are constants.

However, the ASAE advises using two other empirical equations for predicting pressure drop when fines concentration and bulk density affect pressure drop of airflow.

Some of the models devised to determine the static pressure drop for rice and maize are illustrated in Table 10. It can be seen that these models include only a limited number of parameters among several that may affect the static pressure drop, such as airflow rate, bed depth, density, moisture content, the amount of fine materials, the degree of filling, and particle size.

In order for these models to be used for simulation work on grain drying and aeration systems, further research is encouraged to develop models including as many parameters as possible and to determine accurate correlations among these parameters.

Thermal Property Parameters

A knowledge of the thermal properties of grain is essential when studying the problems encountered in drying and storage of grain in bulk. In this section, specific heat, thermal conductivity, thermal diffusivity, isotherms, and heat of vaporisation are reviewed.

Specific heat

Specific heat is defined as the amount of heat necessary to raise the temperature of a unit mass of the material by a unit degree. In drying practices, information on specific heat is very important in calculating the total amount of heat necessary to raise the temperature of grain to a certain level. Some investigators have measured the specific heat of rice and maize. However, their studies were focused mainly on determining the relationship between these values and moisture content of grain.

ASAE (1995) approved and reaffirmed six linear models for predicting the specific heat of rice, paddy, and maize within a specified moisture range. These specific heat values and models, which originated from research conducted by Haswell (1954), Kazarian and Hall (1965), Wratten et al. (1969), and Morita and Singh (1979), are summarised in Table 11.

Regardless of variety, the values of specific heat of rice and paddy falls within a range from 1.3 kJ/kg K to about 2.0 kJ/kg K within the moisture range 10–20% (w.b.). On the other hand, specific heat values of maize range from 1.5 to 2.5 kJ/kg K at approximately 294 K when the moisture content varies between 10 and 30% (w.b.).

Table 9. Values for constants in airflow resistance equation.

Grain	Variety	Value of a (Pa∑s^2/m^3)	Value of b (m^2∑s/ m^3)	Range of Q (m^3/ m^2∑s)
Rice	Long, Brown	2.05×10^4	7.74	0.0055–0.164
	Long, Milled	2.18×10^4	8.34	0.0055–0.164
	Medium, Brown	3.49×10^4	10.9	0.0055–0.164
	Medium, Milled	2.90×10^4	10.6	0.0055–0.164
Maize	Ear (Lot 4)	1.04×10^4	325	0.051–0.353
	Shelled	2.07×10^4	30.4	0.0056–0.304
	Shelled (Low Airflow)	9.77×10^4	8.55	0.00025–0.0203

Sources:Shedd (1953), Calderwood (1966), ASAE (1995).

Table 10. Some models for determining pressure drop or static pressure and airflow rate.

Model	Parameter	Value of constants	Source
$\ln(Q) = a(\ln \Delta P)^2$ $+ b\ln(\Delta P) + c$	Q = airflow rate ($m^3/s\ m^2$) P = pressure (Pa/m) moisture content (12.8%, wet basis) bed depth (5–30 cm)	Paddy (long grain) a = –0.031 b = 0.92 c = –3.024	(1)
$\Delta P = C_1 Qa +$ $C_2 Qa^2 +$ $C_3 Qa(FM)$	ΔP = pressure drop (Pa/m) Qa = airflow rate ($m^3/s\ m^2$) (0.076–0.381) FM = % foreign materials (0–20) bed depth (45.72 cm)	Yellow dent maize C_1 = 436.67 C_2 = 7363.04 C_3 = 22525.82	(2)
$\Delta P = AV + BV^2$ $- CMV$	ΔP = pressure drop (Pa/m) V = air velocity (m/s) M = moisture content (%, wet basis) (12.4–25.3)	Yellow dent maize (clean loose-fill) A = 1611.7 B = 4949.3 C = 55.1	(3)
$Ps = (mD +$ $c)A^{oD+c}$	Ps = static pressure (mmH_2O) D = bed depth (cm) Q = air flow rate ($m^3/min\ m^2$) (1–6) moisture content (13.5%, wet basis)	Paddy m = 0.322 c = –1.32 D = 2.14 e = –0.0089	(4)
$Q = a(P^b/D^c)$	Q = airflow rate (cfm/ft^2) (10–70) P = pressure drop (inch H_2O) D = bed depth (ft) (2–8)	Shelled maize with impurities (20% w.b.) a = 150, b = 0.564 c = 0.646 Cleaned shelled maize a = 303, b = 0.422, c = 0.542	(5)
SP = A(AF) + B(AF)2 – C(AF)(MC) – D(AF)(FM)	SP = static pressure (Pa/m) AF = airflow rate (m^3/s m2) (0.0508–0.381) MC = moisture content (%, wet basis) (11.8–19.5) FM = % fine material (0–8)	Paddy (long grain) A = 3749.15 B = 8289.97 C = 117.12 D = 164.23	(6)
$P = V(b_1 F + b_2 M$ $+ b_3 D + b_4 V)$	P = pressure drop (Pa/m) V = airvelocity (m/s) (0.013–0.387) F = fines percentage (%) (0–30) M = moisture content (%, wet basis) (12–24) D = bulk density (kg/m^3) (480–604)	Paddy (long grain) b_1 = 25.859 b_2 = –90.056 b_3 = 5.587 b_4 = 9133.696	(7)

Sources: 1. Gunasekaran et al. (1983), 2. Haque et al. (1978), 3. Haque et al. (1978), 4. Husain and Ojha (1969), 5. Shedd (1945, 1951), 6. Chung et al. (1985), 7. Siebenmorgen and Jindal (1987).

Six linear models in Table 11 indicate that specific heat of rice and maize increases with an increase in moisture content.

Thermal conductivity

Thermal conductivity is defined as the rate of heat flow through a material by conduction. Thermal conductivity values of rice and maize have been determined by a few investigators using various methods.

Thermal conductivity values of paddy fluctuate within the range 0.1021–0.1270 W/m K depending on the variety and moisture content. Thermal conductivity values of maize range from 0.1405 to 0.1724 w/m K with an increase in moisture content from about 1 to 30% (w.b.).

The ASAE approved two equations for predicting thermal conductivity values of paddy and eight numerical values for thermal conductivity of maize at specified moisture levels. These equations and numerical values are tabulated in Table 12. They originated from research conducted by Oxley (1944), Kazarian and Hall (1965), Wratten et al. (1969), and Morita and Singh (1979).

Kazarian and Hall (1965) expressed the relationship between thermal conductivity and moisture content as a linear function within the moisture range 5–30% (w.b.), whereas Fortes and Okos (1980) expressed it as a function of moisture content and temperature.

On the other hand, Chang (1986) described thermal conductivity for two varieties of maize as linear functions of bulk density within a moisture range from about 12 to 18% (w.b.), as well as within a bulk density range of 731 to 826 kg/m^3. He commented that bulk thermal conductivity of maize increases linearly with the bulk density at a constant moisture content.

Table 11. Specific heat values for rice, paddy, and maize approved by the ASAE.

Grain	Variety	Moisture content (%, wet basis)	Temperature range (°C)	Mean temperature (K)	Specific heat[a] (kJ/kg K)
Rice	Shelled	9.8–17.6			1.202 + 0.00381 M
	Milled	10.8–17.4			1.181 + 0.0377 M
Paddy	–	10.2–17.0			1.110 + 0.0448 M
	Short	11–24			1.269 + 0.03489 M
	Medium	10–20			0.9214 + 0.0545 M
Maize	Yellow Dent	0.9	12.2–28.8	293.65	1.532
		5.1	12.2–28.8	293.65	1.691
		9.8	12.2–28.8	293.65	1.834
		14.7	12.2–28.8	293.65	2.026
		20.1	12.2–28.8	293.65	2.223
		24.7	12.2–28.8	293.65	2.374
		30.2	12.2–28.8	293.65	2.462
				293.65	1.465 + 0.0356 M

[a] M = moisture content (%, wet basis).
Sources: Haswell (1954), Kazarian and Hall (1965), Morita and Singh (1979), Wratten et al. (1969).

Table 12. Thermal conductivity values of paddy and maize.

Grain	Variety	Moisture content (%, wet basis)	Conductivity (W/m°K)	Estimation model (W/m°K)
Paddy	Short	11–24	0.113 – 0.127	0.10000 + 0.00111 M
	Medium	10–20	0.1020 – 0.1124	0.0866 + 0.00133 M
Maize	Yellow Dent	0.9	0.1405	
	Yellow Dent	5.1	0.1466	
	Yellow Dent	9.8	0.1520	
	Yellow Dent	13.2	0.1765	0.1490 + 0.00112M
	Yellow Dent	14.7	0.1591	
	Yellow Dent	20.1	0.1636	
	Yellow Dent	24.7	0.1700	
	Yellow Dent	30.2	0.1724	

[a] M = moisture content (%, wet basis).
Sources: Kazarian and Hall (1965), Wratten et al. (1969), Morita and Singh (1979), ASAE (1995).

Brooker et al. (1974) reported that thermal conductivity values of paddy and maize are 0.106 and 0.159 W/m K, respectively. Kim (1980) reported that thermal conductivity of paddy is closely related to the porosity value of bulk samples.

Thermal diffusivity

Thermal diffusivity can be determined either by direct measurement or by indirect prediction from thermal conductivity, specific heat, and density data.

Kazarian and Hall (1965) measured thermal diffusivity of yellow dent maize experimentally within a moisture range from 0.9 to 30.2% (w.b.) at a mean temperature of 286.95 K. The values fall within the range 0.000312–0.000367 m^2/h depending on the moisture content. They reported that the maximum difference between the calculated and the measured thermal diffusivity values was 16%.

On the other hand, Wratten et al. (1969) and Morita and Singh (1979) calculated the thermal diffusivity values for three varieties of paddy using thermal conductivity, specific heat, and density data. Their thermal diffusivity values for paddy range from 0.0003084 to 0.000395 m^2/h depending on the variety and moisture content. Regardless of variety, the maximum difference among diffusivity values of paddy is about 22%. They found that the bulk diffusivity data appeared to be linearly dependent on moisture content of grain kernels. Thermal diffusivity values for rice and paddy determined by Jones et al. (1992) fall into the range =0.0003600 to 0.0003852 m^2 /h depending on moisture content and bulk density.

Thermal diffusivity values of paddy and maize are given in Table 13.

Adsorption and desorption isotherms

The equilibrium moisture content (e.m.c.) is important in grain drying practice because it determines the minimum moisture content to which grain can be dried under a given set of drying conditions. The e.m.c. depends on the humidity and temperature of the environment as well as the characteristics of grain. Accurate information on e.m.c. becomes the basis of successful simulation and optimisation of grain drying and aeration systems.

Various theoretical, semi-theoretical, and empirical models have been developed for predicting the moisture equilibria of cereal grains. Some of these models have been tested for their accuracy and applicability by other investigators. Some of them are applicable within limited ranges of relative humidity and either the adsorption or desorption phase. Also, the applicability of some theoretical models is limited because of the lack of information on the product constants.

Many research works have focused on the desorption phase rather than the adsorption phase. A few experimental e.m.c. tests have been conducted successfully at relative humidities above 90%, but the equations are suspect in that region because of condensation on the grain sample or mould development during the experimental process, especially when adopting the static method. Therefore, Zuritz et al. (1979) and Brooker et al. (1992) suggested a dynamic method for study of isotherms at higher levels of relative humidity.

Banaszeck and Siebenmorgen (1990) investigated the effects of temperature, relative humidity, and initial moisture content on equilibrium moisture content of long-grain paddy under adsorption conditions and modified again the modified Henderson and Chung-Pfost equations to include the contributions of initial moisture content in predicting equilibrium moisture content.

Among the several e.m.c. models, four well-known ones are the BET equation, the Smith equation, the modified Henderson equation, and the Chung–Pfost equation. The Chung–Pfost equation and the modified Henderson equation have been evaluated as being more accurate than other equations over a wider range of relative humidity and for various cereal grains.

The ASAE approved these two equations. Table 14 shows the two equations and their constants for paddy and maize.

Heat of vaporisation

The heat of vaporisation of water in grains is defined as the energy required to vaporise a unit amount of moisture from the grain at a certain moisture content and temperature. The heat of vaporisation has been determined by either direct measurement or indirect prediction using equilibrium moisture content data for the specific grain. Therefore, accurate calculation of the heat of vaporisation is based totally on the correct choice of equilibrium moisture content data for the specific situation.

Table 13. Bulk thermal diffusivity values of rice, paddy, and maize.

Grain	Variety	Moisture content (%, wet basis)	Temperature range (°C)	Mean temperature (K)	Diffusivity[a] (m^2/h)
Paddy	Short	10–20			0.000451 – 0.00000585M
	Medium	10–20			0.000468 + 0.00000897M
Maize	Yellow Dent	0.9	8.7–23.3	286.95	0.000367
	Yellow Dent	5.1	8.7–23.3	286.95	0.000354
	Yellow Dent	0.8	8.7–23.3	286.95	0.000353
	Yellow Dent	14.7	8.7–23.3	286.95	0.000326
	Yellow Dent	20.1	8.7–23.3	286.95	0.000312
	Yellow Dent	24.7	8.7–23.3	286.95	0.000320
	Yellow Dent	30.2	8.7–23.3	286.95	0.000333

[a] M = moisture content (%, wet basis).

Sources: Kazarian and Hall (1965), Wratten et al. (1969), Morita and Singh (1979), ASAE (1995).

Table 14. Equilibrium moisture content equations and constants approved by the ASAE.

Equation[a]	Constants	Grain	
		Paddy	Yellow dent maize
Modified Henderson equation			
$M = \frac{1}{100}\left[\frac{\text{in}(1-RH)}{-K(T+C)}\right]^{1/N}$	K	1.9187	8.6541
	N	2.4451	1.8634
$RH = 1 - \text{Exp}\left[-K(T+C)(100M)\right]^{N}$	C	51.161	49.810
	SEM[b]	0.0097	0.0127
Chung-Pfost equation			
$M = E - F\,\text{in}\left[-(T+C)\text{in}(RH)\right]$	A	594.61	312.40
	B	21.732	16.958
$RH = \text{Exp}\left[\frac{-A}{(T+C)}\text{Exp}(-BM)\right]$	C	35.703	30.205
	E	0.29394	0.33872
	F	0.0046015	0.058970
	SEM[b]	0.0096	0.0121

[a] M = grain moisture (decimal, dry basis), RH = relative humidity (decimal), T = temperature (°C).
[b] SEM = standard error moisture.

It is known that the heat of vaporisation of grains increases as moisture content and grain temperature decrease and is higher than that of free water below a certain moisture content.

Palani-Muthu and Chattopadhyay (1993) reported that the moisture inside brown, parboiled rice behaved almost like free water when the moisture content was above 12% (w.b.). They also observed a curvilinear relationship between the heat of vaporisation ratio and moisture content and drew an expression for heat of vaporisation of moisture in terms of moisture content and grain temperature in the moisture range between 5% and 27% (w.b.).

Rodriguez-Arias et al. (1963) reported that the heat of vaporisation of shelled maize decreases with an increase in moisture content and approaches that of free water at a high moisture content between 30 and 50°C. Johnson and Dale (1954) reported that the heat of vaporisation of water in wheat and maize is between 1.00 and 1.06 times that of free water when the moisture content is above 12.3% (w.b.), and the requirement for vaporisation increases further below 12.3% (w.b.) moisture content.

Chung and Pfost (1967) reported that the isosteric heat in the desorption and adsorption phases ranged from 3508 to 2484 kJ/kg and from 3070 to 2470 kJ/kg, respectively, and the net heat of vaporisation varied from 1098 to 74 kJ/kg in the desorption phase and from 658 to 60 kJ/kg in the adsorption phase, when moisture content ranged from 4 to 20% at 31°C. They drew the conclusion that the net heat of sorption approaches zero as the moisture content increases.

Their conclusion was similar to that of Johnson and Dale (1954). Thompson and Shedd (1954) investigated the heat of vaporisation of maize and wheat by using Othmer's method (Othmer 1940) at five levels of grain temperature and six levels of moisture content. They concluded that it decreases with increases in moisture content and grain temperature. Wang and Sigh (1978) also developed an empirical equation in terms of moisture content and temperature for calculating heat of vaporisation of paddy using the e.m.c. data prepared by Zuritz et al. (1979).

Brooker et al. (1992) calculated the heat of vaporisation for maize by using the Clapeyron equation and the modified Henderson equation for determining the heat of vaporisation ratio and relative humidity, respectively. The calculated values are shown in Table 15.

Drying and rewetting rates

Accurate prediction of the drying and rewetting behaviour of deep beds of grain depends directly on an accurate description of the thin-layer process, under the assumption that the deep bed is composed of a series of thin layers.

Therefore, a number of investigators have tried to develop successful thin-layer drying and rewetting models for grain, especially for shelled maize. Each has developed an equation from their own data obtained under conditions of interest to them.

Thompson et al. (1968) developed a mathematical drying model to predict the performance of various types of grain dryers. Sharaf-Eldeen et al. (1980) developed a model for drying of fully exposed ear maize by using the general form of the solution to the diffusion equation and determined drying parameters. They commented that their model should be beneficial in describing bulk drying of ear maize.

Table 15. Heat of vaporisation of maize at different grain temperatures and moisture contents.[a]

Moisture content (%, wet basis)	Grain temperature (°C)				
	0	10	21.1	37.8	65.6
5	3035 (1.2140)	3007 (1.2139)	2979 (1.2144)	2928 (1.2144)	2846 (1.2147)
10	2949 (1.1796)	2921 (1.1832)	2893 (1.1794)	2844 (1.1796)	2765 (1.1801)
15	2837 (1.1348)	2809 (1.1340)	2783 (1.1345)	2735 (1.1344)	2660 (1.1353)
20	2721 (1.0884)	2695 (1.0880)	2670 (1.0885)	2625 (1.0888)	2551 (1.0888)
Pure water	2500	2477	2453	2411	2343

Model: $L = (2502.2 - 2.39T)\,[1 + \mathrm{Exp}(-BM)]$
where L = latent heat of vaporisation, kJ/kg
T = grain temperature, °C
M = moisture content, dry basis, decimal
Yellow maize : (A = 1.2925, B = 16.961)
Paddy: (A = 2.0692, B = 21.739)

[a] Numbers in parentheses indicate the ratios of latent heat of maize to latent heat of free water.
Source: Brooker et al. (1992).

Misra and Brooker (1980), Li and Morey (1984), and other investigators used equilibrium moisture content (M_e) when defining the moisture content ratio (MR). However, Hustrulid and Flikke (1959) and some other investigators introduced the dynamic equilibrium moisture content (M_s), instead of M_e, into models for determining the rate of thin-layer drying.

Misra and Brooker (1980) conducted their own experimental work for shelled yellow dent maize and compiled from other sources all useful data on thin-layer drying and rewetting in the temperature range of 2.2 to 71.1°C. They identified the model described in equation (2) as the most promising one through the preliminary analysis, then expressed the drying constants K and N as a function of air temperature (T), air humidity (H), air velocity (V), and the initial moisture content (M_0).

$$MR = (M - M_e)/(M_0 - M_e) = \exp[-Kt^N] \qquad (2)$$

where MR = moisture content ratio, M = moisture content (%, dry basis), Me = equilibrium moisture content (%, dry basis), and t = time.

Through statistical analysis of the combined data obtained from their own and other investigators' experimental work, they determined the values for the drying constants K and N shown in Table 16. They concluded that drying air temperature and the air velocity significantly affect the parameter K in the drying phase equation, and the air temperature and the initial moisture content significantly affect the parameter K in the thin-layer rewetting equation.

Li and Morey (1984) determined the drying constants K and N for yellow dent maize harvested in two consecutive years, by an approach similar to that used by Misra and Brooker (1980). After testing the effect of drying air temperature, airflow rate, initial moisture content, and relative humidity on thin-layer drying rate, they concluded that drying air temperature had the greatest effect on drying rates, and airflow rate and relative humidity had smaller effects. In addition, they suggested that relative humidity can probably be neglected when developing thin-layer models for use in a deep-bed drying simulation.

On the other hand, Bakker-Arkema (1984) and Bruse (1985) suggested use of diffusion-type drying equations for most grains, instead of the existing empirical drying-rate equations. Jayas et al. (1991) reviewed 40 thin-layer drying and wetting equations for their applicability, and commented that the theoretical equations describe the thin-layer drying as broadly as the empirical one.

Wongwises and Thongprasert (1990) determined the drying rate of long-grain paddy under tropical conditions and devised an exponential model with the exponent as a function of drying air, relative humidity, and initial moisture content, and the coefficient expressed as a function of drying air temperature and initial moisture content of paddy.

Parti (1990) reviewed the existing thin-layer drying equations for grains and reported that the exponential law generally overestimates the drying rate in the first period of the drying and underestimates it in the last period. They also investigated the applicability of both temperature equilibrium and moisture equilibrium in grain drying.

Table 16. Drying constants for yellow dent maize.

Drying constants	K^a	N^a	R^2
Model	$K = \text{Exp}\,[-a + b \ln(1.8T + 32) + CV]$	$N = d \ln(H) + eMo$	
Drying	$a = 7.1735$ $b = 1.2793$ $c = 0.1378$	$d = 0.0811$ $e = 0.0078$	0.967
Rewetting	$a = 8.5122$ $b = 1.2178$ $c = 0.0864$	$d = 2.1876$ $e = -0.0167$	0.991
Model	$K = a + bT^2 + cTMo$	$N = d + eMo^2 + fT^2$	
Drying	$a = 1.091 \times 10^{-2}$ $b = 2.267 \times 10^{-6}$ $c = 7.286 \times 10^{-6}$	$d = 0.5375$ $e = 1.141 \times 10^{-5}$ $f = 5.183 \times 10^{-5}$	0.975

T = air temperature (°K), V = air velocity (m/s), H = air humidity (%), Mo= initial moisture content (%, dry basis).
Sources: Misra and Brooker (1980), Li and Morey (1984).

Banaszek and Siebenmorgen (1993) determined the asymptotic equilibrium moisture content and drying constant K for individual kernels of long-grain paddy and bulk samples by using the Newton drying equation. They found equilibrium moisture content to be a function of kernel width, and the drying constant to be a function of initial moisture content and the ratio of kernel width to thickness.

References

Agrawal, K.K. and Chand, P. 1974. Pressure drop across fixed beds of rough rice. Transactions of the American Society of Agricultural Engineers, 17(3), 560–563.

ASAE (American Society of Agricultural Engineers) 1995. ASAE Standards. ASAE, 2950 Niles Road, St. Joseph, Michigan 49085-9659, USA.

Bakker-Arkema, F.W. 1984. Selected aspects of crop processing and storage: a review. Journal of Agricultural Engineering Research, 30, 1–22.

Bakker-Arkema, F.W., Rosenau, J.R., and Clifford, W. H. 1971. Measurement of grain surface area and its effects on the heat and mass transfer rates in fixed and moving beds of biological products. Transactions of the American Society of Agricultural Engineers, 14, 864.

Banaszek, M.M. and Siebenmorgen, T.J. 1990. Adsorption equilibrium moisture contents of long-grain rough rice. Transactions of the American Society of Agricultural Engineers, 33(1), 247–252.

Banaszek, M.M. and Siebenmorgen, T.J. 1993. Individual rice kernel drying curves. Transactions of the American Society of Agricultural Engineers, 36(2), 521–528.

Brooker, D.B., Bakker-Arkema, F.W., and Hall, C.W. 1974. Drying cereal grains. AVI Publishing Company, Inc.

Brooker, D.B., Bakker-Arkema, F.W., and Hall, C.W. 1992. Drying and storage of grains and oilseeds. AVI Publishing Company, Inc.

Bruse, D.M. 1985. Exposed-layer barley drying: three models fitting to new data up to 150°C. Journal of Agricultural Engineering Research, 32, 337–347.

Brusewitz, G.H. 1975. Density of rewetted high moisture grains. Transactions of the American Society of Agricultural Engineers, 18(5), 935–938.

Calderwood, D.L. 1966. Use of aeration to aid rice drying. Transactions of the American Society of Agricultural Engineers, 16(3), 525–527, 532.

Calderwood, D.L. 1973. Resistance to airflow to rough, brown, and milled rice. Transactions of the American Society of Agricultural Engineers, 16, 525–527.

Chang, C.S. 1986. Thermal conductivity of wheat, corn, and grain sorghum as affected by bulk density and moisture content. Transactions of the American Society of Agricultural Engineers, 29(5), 1447–1450.

Chung, D.S. and Converse, H.H. 1971. Effect of moisture on some physical properties of grains. Transactions of the American Society of Agricultural Engineers, 14(4), 612–614, 620.

Chung, D.S., Gonzaga, L., Kim, M.S., and Haque, E. 1985. Resistance to airflow through rough rice mixed with foreign material. Unpublished Research Report, Kansas State University, Manhattan, Kansas.

Chung, D.S. and Pfost, H.B. 1967. Adsorption and desorption of water vapor by cereal grains and their products, Part I—III. Transactions of the American Society of Agricultural Engineers, 10(4), 549–557.

Fortes, M. and Okos, M.R. 1980. Changes in physical properties of corn during drying. Transactions of the American Society of Agricultural Engineers, 23(4), 1004–1008.

Goss, J.R. 1965. Some physical properties of forage and cereal crop seeds. American Society of Agricultural Engineers, Paper No. 65-813.

Gustafson, R.J. and Hall, G.E. 1972. Density and porosity of shelled corn during dying. Transactions of the American Society of Agricultural Engineers, 15(3), 523–525

Gustafson, R.J. and Hall, G.E. 1974. Equilibrium moisture content of shelled corn from 50°C to 155°C. Transactions of the American Society of Agricultural Engineers, 17(1), 120–124.

Gunasekaran, S., Jindal, V.K., and Shove, G.C. 1983. Resistance to airflow of paddy (rough rice) in shallow depth. Transactions of the American Society of Agricultural Engineers, 26(2), 601–605

Hall, C.W. 1971. Drying farm crops. Westport, Connecticut, AVI Publishing Company, Inc.

Hall, G.E. and Hill, L.D. 1974. Test weight adjustment based on moisture content and mechanical damage of corn kernels. Transactions of the American Society of Agricultural Engineers, 17(3), 578–579.

Haque, E., Ahmed, Y.N., and Deyoe, C.W. 1982. Static pressure drop in a fixed bed of grain as affected by grain moisture content. Transactions of the American Society of Agricultural Engineers, 25(4), 1095–1098.

Haque, E., Foster, G.H., Chung, D.S., and Lai, F.S. 1978. Static pressure drop across a bed of corn mixed with fines. Transactions of the American Society of Agricultural Engineers, 21(5), 997–1000.

Haswell, G.A. 1954. A note of the specific heat of rice, oats, and their products. Cereal Chemistry, 3(4), 341–343.

Hosokawa, A. and Matsumoto, H. 1971. Bulk thermal conductivity of grains. The Journal of the Society of Agricultural Machinery, Japan, 32(4), 302–305.

Hukill, W.V. and Shedd, C.K. 1955. Nonlinear airflow in grain drying. Agricultural Engineering, 36, 462–466.

Husain, A. and Ojha, T.P. 1969. Resistance to the passage of air through rough rice. Journal of Agricultural Engineering Research, 14(1), 47–53.

Hustrulid, A. and Flikke, A.M. 1959. Theoretical drying curve for shelled corn. Transactions of the American Society of Agricultural Engineers, 2(1), 112–114.

Jayas, D.S., Cenkowski, S, Pabis, S., and Muir, W.E. 1991. Review of thin-layer drying and wetting equations. Drying Technology, 9(3), 551–588.

Jayas, D.S. and Mann, D.D. 1994. Presentation of airflow resistance data of seed bulks. Applied Engineering in Agriculture, 10(1), 79–83.

Johnson, H.K. and Dale, A.C. 1954. Heat required to vaporize moisture in wheat and shelled corn during the process of artificial drying. Agricultural Engineering, 35(10), 705–709, 714.

Jones, J.C., Wooton, M., and Green, S. 1992. Measured thermal diffusivities of cereal products. Food Australia, 44(11), 501.

Kay, R.L., Bern, C.J., and Hurburgh, C.R. Jr. 1989. Horizontal and vertical airflow resistance of shelled corn at various bulk densities. Transactions of the American Society of Agricultural Engineers, 32(2), 733–736.

Kazarian, E.A. and Hall, C.H. 1965. Thermal properties of grain. Transactions of the American Society of Agricultural Engineers, 8(1), 33–37, 48.

Kim, M.S. 1980. Physical and thermal properties of grain. Ph.D. Dissertation, Department of Agricultural Engineering, Seoul National University, Suwoen, Korea.

Li, H. and Morey, R.V. 1984. Thin-layer drying rate of yellow dent corn (as affected by drying air temperature, airflow rate, initial moisture content, and relative humidity). Transactions of the American Society of Agricultural Engineers, 27(2), 581–585.

Li, W. and Sokhansanj, S. 1994. Generalized equation for airflow resistance of bulk grains with variable density, moisture content, and fines. Drying Technology, 12(3), 649–667.

Lorenzen, R.T. 1957. Effects of moisture content of mechanical properties of small grains. M.S. Thesis, University of California, Davis.

Misra, M.K. and Brooker, D.B. 1980. Thin layer drying and rewetting equations for shelled yellow corn. Transactions of the American Society of Agricultural Engineers, 23(5), 1254–1260.

Mohsnin, N.N. 1986. Physical properties of plant and animal materials. Volume I: Structure, physical characteristics and mechanical properties. Gordon and Breach Science Publishers.

Morita, T., and Singh, R. P. 1979. Physical and thermal properties of short-grain rough rice. Transactions of the American Society of Agricultural Engineers, 22(3), 630–636.

Nelson, S.O. 1980. Moisture dependent kernel and bulk density relationship for wheat and corn. Transactions of the American Society of Agricultural Engineers, 23(1), 139–143.

Othmer, D.F. 1940. Correlating vapor pressure and latent heat data. Journal of Industrial and Engineering Chemistry, 32, 841–856.

Oxley, T.A. 1944. The properties of grain in bulk. Society of Chemistry and Industry Transactions, 63, 53–57.

Palani-Muthu, V. and Chattopadhyay, P.K. 1993. Prediction of heat vaporization of moisture from cereal grains—a modelling approach. Drying Technology, 11(7), 1855–1862.

Parti, M. 1990. A theoretical model for thin-layer grain drying. Drying Technology, 8(1), 101–122.

Pomeranz, Y. 1981. Composition of cereal grains. CRC Handbook of Transportation and Marketing in Agriculture, Volume 2. CRC Press, Inc.

Rodriguez-Arias, J.H., Hall, C.H., and Bakker-Arkema, F.W. 1963. Heat of vaporization for shelled corn. Cereal Chemistry, 40, 676–683.

Sharaf-Eldeen, Y.I., Braisdell, J.L., and Hamdy, M.Y. 1980. A model for ear corn drying. Transactions of the American Society of Agricultural Engineers, 23(5), 1261–1265, 1271.

Shedd, C.K. 1945. Resistance of ear corn to air flow. Agricultural Engineering, 26(1), 19–20, 23.

Shedd, C.K. 1951. Some new data on resistance of grains to airflow. Agricultural Engineering, 32(9), 493–495, 520.

Shedd, C.K. 1953. Resistance of seeds and grains to airflow. Agricultural Engineering, 34(9), 616–619.

Siebenmorgen, T.J. and Jindal, V.K. 1987. Airflow resistance of rough rice as affected by moisture content, fines concentration and bulk density. Transactions of the American Society of Agricultural Engineers, 30(4), 1138–1143.

Thompson, H.J. and Shedd, C.K. 1954. Equilibrium moisture and heat of vaporization of shelled corn and wheat. Agricultural Engineering, 35, 786–788.

Thompson, R.A. and Isaacs, G.A. 1967. Porosity determination of grains and seeds with an air-comparison pycnometer. Transactions of the American Society of Agricultural Engineers, 10(5), 693–696.

Thompson, T.L., Peart, R.M., and Foster, G.H. 1968. Mathematical simulation of corn drying. Transactions of the American Society of Agricultural Engineers, 11(4), 582–586.

USDA (United States Department of Agriculture) 1990. Tables of weights and measures in agricultural statistics. Washington, D.C., U.S. Government Printing Office.

Vemuganti, G.R. and Pfost, H.B. 1980. Physical properties related to drying 20 food grains. American Society of Agricultural Engineers, Paper No. 80-3539.

Wang, C.Y. and Sigh, R.P. 1978. A single layer drying equation for rough rice. American Society of Agricultural Engineers, Paper No. 78-3001.

Wongwises, S. and Thongprasert, M. 1990. Thin-layer drying characteristics of Thai rough rice. ASEAN Food Journal, 5(3), 91–95.

Wratten, F.D., Poole, W.D., Chesness, J.L., Bal, S., and Ramarao, V. 1969. Physical and thermal properties of rough rice. Transactions of the American Society of Agricultural Engineers, 12(6), 801–803.

Zink, F.J. 1935. Specific gravity and air space of grains and seed. Agricultural Engineering, 16(11), 439–440.

Zuritz, C., Sigh, R.P., Moini, S.M., and Henderson, S. M. 1979. Desorption isotherms of rough rice from 10°C to 40°C. Transactions of the American Society of Agricultural Engineers, 22(2), 433–436, 440.

Further Reading

Agrawal, K.K., Nelson, G.L., and Clay, B.L. 1969. An investigation into the theories of desorption isotherms for rough rice and peanuts. American Society of Agricultural Engineers Paper No. 69-890.

Agrawal, Y.C. and Singh, R.P. 1977. Thin-layer drying studies on short grain rough rice. American Society of Agricultural Engineers Paper No. 77-3531.

Bakker-Arkema, F.W. and Patterson, R.J. 1967. Pressure drop-airflow relationship in granular materials such as grain. American Society of Agricultural Engineers Paper No.67-840.

Berker, H.A. and Sallans, H.R. 1956. A study of the desorption isotherms of wheat at 25 and 50. Cereal Chemistry, 33(2), 79–90.

Chen., C.C. and Morey, R.V. 1988. Comparison of four EMC/ERH equations. American Society of Agricultural Engineers, Paper No. 88-6068

Chen, C.S. and Clayton, J.T. 1971. The effect of temperature on sorption isotherms of biological materials. Transactions of the American Society of Agricultural Engineers, 14(5), 927–929.

Chittenden, D.H. and Hustrulid, A. 1966. Determining drying constants for shelled corn. Transactions of the American Society of Agricultural Engineers, 9(1), 52–55.

Chung, D.S. and Lee, Chong-Ho. 1986. Physical and thermal properties of grains. In: Champ, B.R. and Highley, E., ed., Preserving grain quality by aeration and in-store drying. ACIAR Proceedings No. 15, 53–66.

Gallaher, G.L. 1951. A method of determining the latent heat of agricultural crops. Agricultural Engineering, 32, 34–38.

Grama, S.N., Bern, C.J., and Hurburg, C.R. 1984. Airflow resistance of mixture of shelled corn and fines. Transactions of the American Society of Agricultural Engineers, 27(1), 268–272.

Hall, C.W. and Rodriguez-Arias, J.H. 1958. Equilibrium moisture content of shelled corn. Agricultural Engineering, 39, 466–470.

Haque, E., Chung, D.S., and Foster, G.H. 1981. Analytical solution of the pressure and velocity field in steady-state incompressible axisymmetric Darcy flow through granular materials such as corn. Transactions of the American Society of Agricultural Engineers, 24(6), 1618–1620.

Haque, E., Chung, D.S., and Foster, G.H. 1981. Pressure and velocity field in airflow through a packed bed of corn mixed with fines under non-Darcy flow conditions. Transactions of the American Society of Agricultural Engineers, 24(6), 1595–1599, 1604.

Heldman, D. R. 1975. Food process engineering. Westport, Connecticut, AVI Publishing Company, Inc.

Hukill, W.V. and Schmidt, J.L. 1960. Drying rate of fully exposed grain kernels. Transactions of the American Society of Agricultural Engineers, 3(2), 71–77, 80.

Jayas, D.S., Cenkowski, S., and Muir, W.E. 1988. A discussion of the thin-layer drying equation. American Society of Agricultural Engineers, Paper No. 88-6557.

Jayas, D.S., Cenkowski, S., Pabis, S., and Muir, W.E. 1991. Review of thin-layer drying and wetting. Drying Technology, 9(3), 551–588.

Jindal, V.K. and Siebenmorgen, T.J. 1994. Simulation of low temperature rough rice drying and rewetting in shallow beds. Transactions of the American Society of Agricultural Engineers, 37(3), 863–871.

Kachru, R.P., and Matthes, R.K. 1976. The behavior of rough rice in sorption. Journal of Agricultural Engineering Research, 21(4), 405–416.

Kanujoso, B., Chung, D.S., Song, A., and Erickson, L.E. 1995. Study of desorption and adsorption during grain aeration. Drying Technology, 13(1/2), 183–196.

Lai, F.S., and Fan, L.T. 1976. Excessive pressure drop through a bed of stored grain during aeration. Journal of Agricultural Engineering Research, 21(2), 207–209.

Li, W.Y., Sokhansanj, S., and Gu, D. 1991. The generalized model of bulk grain resistance to airflow. American Society of Agricultural Engineers, Paper No. 91–6529.

Miketinac, M.J., Sokhansanj, S., and Tutek, Z. 1992. Determination of heat and mass transfer coefficients in thin-layer drying of grain. Transactions of the American Society of Agricultural Engineers, 35(6), 1853–1858.

Misra, M.K. and Brooker, D.B. 1978. Thin layer drying of shelled corn. American Society of Agricultural Engineers Paper No. 78-3002.

Mohsenin, N.N. 1965. Physical properties of agricultural products. Transactions of the American Society of Agricultural Engineers, 8(1), 25–29.

Mohsenin, N.N. 1980. Thermal properties of food and agricultural materials. Gordon and Beach Science Publishers.

Noomhorm, A. and Verma, L. R. 1986. Generalized single-layer rice drying model. Transactions of the American Society of Agricultural Engineers, 29(9), 587–591.

Okos, M.R., ed. 1986. Physical and chemical properties of food. St. Joseph, Michigan 49085-9659, USA, American Society of Agricultural Engineers.

Osborne, L.E. 1961. Resistance to airflow of grain and other seeds. Journal of Agricultural Engineering Research, 6(2), 119–122.

Pabis, S. and Hall, C.W. 1962. Temperature distribution and moisture movement while drying an ear corn. Transactions of the American Society of Agricultural Engineers, 5(2), 168–171.

Parti, M. 1993. Selection of mathematical models for drying grain in thin-layers. Journal of Agricultural Engineering Research, 54(4), 339–352.

Parti, M. and Dugmanics, I. 1990. Diffusion coefficient of corn drying. Transactions of the American Society of Agricultural Engineers, 33(5), 1652–1656.

Parti, N.D. 1988. Evaluation of diffusion equation of simulating moisture movement within an individual grain kernel. Drying Technology, 6(1), 21–42.

Pfost, H.B., Maurer, S.G., and Chung. D.S. 1976. Summarizing and reporting equilibrium moisture data for grains. American Society of Agricultural Engineers, Paper No. 76-3520.

Raman, S., ed. 1995. Food properties handbook. New York, CRC Press, Inc.

Robs, I.J. and White, G.M. 1972. Thin layer drying characteristics of white corn. Transactions of the American Society of Agricultural Engineers, 15(1) : 175–176, 179.

Rodriguez-Arias, J.H. 1956. Desorption isotherms and drying rate of shelled corn, 40°F to 140°F. Unpublished Ph.D. Dissertation, Michigan State University.

Sheldon, W.H. 1953. Static pressure drop for low air flows through grain. American Society of Agricultural Engineers, Paper No. 60-302.

Sheldon, W.H., Hall, C.W., and Wang, K.K. 1960. Resistance of shelled corn and wheat to low air flows. Transactions of the American Society of Agricultural Engineers, 3(2), 92–94.

Shove, G.C. 1971. Low temperature drying of shelled corn. Agricultural Engineering, 52(7), 372–373.

Siebenmorgen, T.J. and Banaszek, M.M. 1988. Equilibrium moisture contents of long-grain rough rice. American Society of Agricultural Engineers, Paper No. 88-6067.

Smith, E.A. and Sokhansanj, S. 1990. Natural convection and temperature of stored products—a theoretical analysis. Canadian Agricultural Engineering, 32(1), 91–97.

Smith, S.E. 1947. The sorption water vapor by high polymers. Journal of the Chemical Society, 69, 646–651.

Sokhansanj, S. and Li, W.Y. 1993. Development of a general equation to predict airflow resistance of bulk grain from kernel properties. American Society of Agricultural Engineers, Paper, 93-6541/93-6569.

Strohman, R.D. and Yoeger, R.R. 1967. A new equilibrium moisture content equation. Transactions of the American Society of Agricultural Engineers, 10(5), 675–677.

Wang, C.Y. and Sigh, R.P. 1978. Use of variable equilibrium moisture content in modeling rice drying. American Society of Agricultural Engineers, Paper No. 78-6505.

Weres, J. and Jayas, D.S. 1994. Effects of corn kernel properties on predictions of moisture transport in the thin-layer drying of corn. Transactions of the American Society of Agricultural Engineers, 37(5), 1695–1705.

Westerman, P.W., White, G.M., and Robs, I. J. 1973. Relative humidity effect on the high-temperature drying of shelled corn. Transactions of the American Society of Agricultural Engineers, 16(6), 1136–1139.

Modelling Moisture Migration in Stored Grains

G.R. Thorpe*

Abstract

Moisture migration in stored grains is caused by warm, moisture-laden air rising towards cooler surfaces of a grain store where the relative humidity of the air, hence the moisture content of the grain, increases. The natural convection currents that give rise to moisture migration in the store are driven by temperature gradients that have components in the horizontal direction. This paper presents the equations that govern heat and mass transfer, and buoyancy driven flows, in bulk stored grains. It demonstrates how to formulate the governing equations in finite difference form, and how to solve them numerically using a well established alternating direction implicit method. The rationale of casting the governing equations in dimensionless form is discussed in some detail. Comprehensive data on grain properties, such as sorption isotherms and permeabilities, are presented and these enable the rates of moisture migration in a range of food grain types to be calculated. Phenomena such as dry matter loss arising from respiration, and the rate of pesticide decay are included in the model. Examples are given of typical methodologies that can be used to ensure that the predicted grain temperatures and moisture contents are independent of the size of the computational grid. Reference is made to the modelling of moisture migration in grain bulks that have geometries commonly found in practice, and the need for researchers to study the interaction between phenomena that occur in a bulk of grains and in the air space above is highlighted.

GRIFFITH (1964) observed that when grains with initial moisture contents between 9 and 11% (wet basis) are stored at temperatures of about 40°C the upper surface of the grains becomes caked after 6 months of storage. He also observed that in Australia no such caking occurred in grains that were stored with initial temperatures lower than 15°C, even when the average grain moisture content (m.c.) was 14.4% wet basis (w.b.). Griffith (1964) attributed this to the fact that the temperature gradients in the grain bulk were less severe at the lower temperatures, hence the natural convection currents were less pronounced and, as a consequence, they carried less moisture from warm regions of the grain stores to the cooler surfaces. In the warm central region of the grain bulk, the vapour pressure of water in the intergranular air is high, even though the grain moisture content is low. As the air approaches the cooler regions, its relative humidity, or water activity, increases, thus causing the grain moisture content to increase.

In some circumstances, grain cakes on the walls of silos, and a likely cause for this phenomenon is molecular diffusion of moisture, again resulting from temperature gradients in the direction normal to a cool surface. The grain some distance from the wall is warm, hence the water vapour pressure is high, whereas close to the wall the vapour pressure is low. The vapour pressure gradient gives rise to molecular diffusion. Pixton and Griffith (1971) determined that the apparent diffusion coefficient of moisture through grain is about 10^{-11} m^2/s when the mass transfer driving force on the moisture content of the grain. Thorpe (1980, 1981) recognised that most of the mass diffusion occurs in the intergranular air and he determined an empirical value for the tortuosity of a bulk of grain. The validity of this approach has been confirmed recently by Khankari et al. (1994). This empirical determination of the tortuosity has been complemented by a theoretical study of moisture diffusion through grain carried out by Thorpe et al. (1991a,b) which is based on rigorous expressions for mass conservation in the intergranular air and the grain kernels.

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Moisture migration arising from natural convection currents in two-dimensional systems was initially modelled by Nguyen (1987), and subsequently by Dona and Stewart (1988), Freer et al. (1990) and Khankari et al. (1993a,b). This work was extended to two-dimensional systems with arbitrary shapes by Singh and Thorpe (1993a) and Casada and Young (1994). A method based on the vector potential for quantifying natural convection in three-dimensional grain bulks has been presented by Singh et al. (1993a), and this was generalised to simulate moisture migration in grain bulks of arbitrary shapes by Singh and Thorpe (1993b). Thorpe (1996a) has refined analyses of heat and moisture transfer processes that occur in bulk stored grains to include the implications for the conservation of mass and energy when the grain respires. This analysis has been used to describe phenomena associated with both natural and forced convection in arbitrarily shaped bulks of respiring grains.

The objective of this paper is to present a comprehensive analysis of heat, mass, and momentum transfer in bulk stored grains, and to show in some detail how the equations can be solved numerically.

Analysis

As it is an objective of this work to illustrate in some detail how to solve the equations that govern the rate of moisture migration in stored grains, we shall consider only a two-dimensional system that has a simple geometry as shown in Figure 1. Singh et al. (1993a) have illustrated how this simple approach may be extended to grain bulks that are three-dimensional or that have arbitrary shapes (Singh and Thorpe 1993a,b). The basic heat, mass, and momentum balance equations apply to all bulks of grains, regardless of their shape or size, and it is only the initial and boundary conditions that must be specified to solve particular problems.

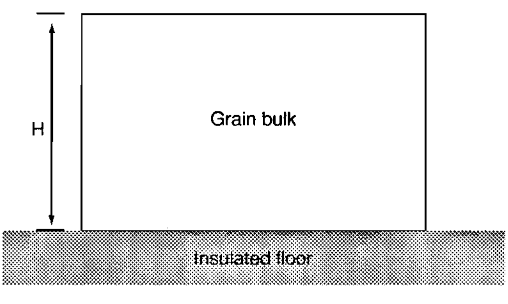

Figure 1. A bulk of grain with a simple geometry.

Thermal energy balance

We shall make use of the thermal energy equation presented by Thorpe (1996a), which may be written as:

$$\rho_\sigma \varepsilon_\sigma \left\{ c_\sigma + W c_1 + \frac{\partial H_w}{\partial T} \right] \frac{\partial T}{\partial t} + \rho_a \varepsilon_\gamma \left\{ c_a + w\left(c_1 + \frac{\partial h_v}{\partial T} \right) \right] \frac{\partial T}{\partial t}$$
$$- h_s \varepsilon_\sigma \rho_\sigma \frac{\partial W}{\partial t} - \rho_\sigma \frac{\partial \varepsilon_\sigma}{\partial t} \int_o^w h_s dW + \rho_a v_a \cdot \nabla T$$
$$+ \rho_a v_a w \left(c_1 + \frac{\partial h_v}{\partial T} \right) \cdot \nabla T = k_{eff} \nabla^2 T + Q_r - h_v S_1 \qquad \textbf{(1)}$$

The first two terms on the left-hand side of the equation represent the rate at which the energy of a region of the grain changes as its temperature varies with time, and the term $\partial H_w / \partial T$ arises from the fact that the integral heat of wetting of grains depends on temperature. Although the presence of this latter term is strictly necessary, the integral heat of wetting is generally difficult to evaluate because it must be calculated from sorption isotherms that are determined over a wide range of grain moisture contents that includes low values. The third term on the left-hand side of equation (1) accounts for the energy that is associated with moisture being adsorbed on or desorbed from the grains. For example, if the grains are being dried, energy must be added to the grains to first remove moisture from the grain substrate to which it is bound, and then to vaporise it. When the grains are consumed by fungi, the grain substrate disappears and as a result the energy associated with binding moisture to the disappearing substrate must be accounted for. This is accomplished by the fourth term in which $\rho_\sigma(\partial \varepsilon_\sigma / \partial t)$ represents the rate of disappearance of the substrate and $\int_o^W h_s dW$ is the energy associated with binding the moisture. The fifth and sixth terms on the left-hand side of equation (1) account for the convection of thermal energy by dry air and moisture vapour, respectively. The first term on the right-hand side of equation (1) governs the rate of heat conduction through the grain bulk, the second term is the heat of respiration, and the final term on the right-hand side is a correction term to the heat of respiration to account for the fact that the water liberated is in the form of vapour, and not as liquid.

Boundary conditions

The temperatures on the exposed surfaces of the grain bulk can be prescribed or calculated, usually from a thermal energy balance that often involves solar radiation (Singh et al. 1993a; Thorpe 1996b). It is usual to assume that the floor of the store is thermally insulated. Along the exposed surfaces of the store, the boundary conditions may be written as:

$$T(0,y)-f_1(y)=0;\quad 0\le y\le H \tag{BC1}$$

$$T(L,y)-f_2(y)=0;\quad 0\le y\le H \tag{BC2}$$

$$T(x,H)-f_3(x)=0;\quad 0<x<L \tag{BC3}$$

$$\frac{\partial T(x,0)}{\partial y}=0;\quad 0<x<L \tag{BC4}$$

The functions $f_1(y)$, $f_2(y)$, and $f_3(x)$ are temperatures that depend essentially on an energy balance carried out at the outer surfaces of the grain. In this study we shall set them as constants, i.e. the surfaces are isothermal.

Moisture balance

The moisture balance may be written as

$$\varepsilon_\sigma \rho_\sigma \frac{\partial W}{\partial t}+\rho_a \mathbf{v}_a\cdot\nabla w = D_{eff}\rho_a\nabla^2 w + S_1(1+1.6W) \tag{2}$$

which accounts not only for moisture being released by respiration but also that arising from water being released from the moisture bound to the grains substrate that is consumed by the respiration of the fungi.

Boundary conditions

In the case studied here it is assumed that the outer surface of the grain store is impermeable to moisture vapour; hence, the boundary conditions may be written as

$$\frac{\partial w(0,y)}{\partial x}=0;\quad 0\le y\le H \tag{BC5}$$

$$\frac{\partial w(L,y)}{\partial x}=0;\quad 0\le y\le H \tag{BC6}$$

$$\frac{\partial w(x,0)}{\partial x}=0;\quad 0\le x\le L \tag{BC7}$$

$$\frac{\partial w(x,H)}{\partial x}=0;\quad 0\le x\le L \tag{BC8}$$

Momentum balance

Buoyancy driven flows that occur in bulks of stored grains are characterised by intergranular air velocities that are sufficiently small that the pressure gradient is directly proportional to the velocity gradient and the 'hydrostatic head'. This may be expressed mathematically as

$$\nabla p = -\frac{\mu}{K}v-\rho g \tag{3}$$

in which μ is the viscosity of the intergranular air, K is the permeability of the bed of grain and the gravity vector is denoted by g. Equation (3) is an expression of Darcy's (1856) law, and we might surmise that the permeability of a bulk of grains decreases as the kernel size decreases because the resistance to flow is lower in beds of larger diameter particles. This is borne out by the data on permeabilities given in Appendix 2. A small rearrangement of equation (3), and expressing the result in component form results in

$$u=-\frac{K}{\mu}\frac{\partial p}{\partial x} \tag{4}$$

$$v=-\frac{K}{\mu}\left(\frac{\partial p}{\partial y}+\rho_a g_y\right) \tag{5}$$

where g_y is the y-component of the gravity vector. Differentiating equation (4) with respect to y and equation (5) with respect to x, and forming the difference of the two yields

$$\frac{\partial u}{\partial y}-\frac{\partial v}{\partial x}=\frac{Kg_y}{\mu}\frac{\partial \rho_a}{\partial x} \tag{6}$$

We now make use of Boussinesq's approximation that implies that the density of the intergranular air, ρ_a, can be taken as being constant in the mass and thermal energy conservation equations, but it varies in the momentum transfer equation. In this way we can account for buoyancy forces by noting that the density of the intergranular air can be approximated by the expression

$$\rho_a=(\rho_a)_o\{1-\beta(T-T_o)\} \tag{7}$$

in which $(\rho_a)_o$ is the density of air at some reference temperature T_o, and β is the volumetric coefficient of expansion of air.

Whitaker (1981) shows that conservation of mass is inherent in the definition of the stream function, ψ, and that one can obtain the following important relationships

$$u=\frac{\partial \psi}{\partial y} \tag{8}$$

and

$$v=-\frac{\partial \psi}{\partial x} \tag{9}$$

Differentiating equations 8 and 9 with respect to y and x respectively, and inserting the results into equation (6), leads to the equation that governs the behaviour of the stream function, namely

$$\frac{\partial^2\psi}{\partial x^2}+\frac{\partial^2\psi}{\partial y^2}=-\frac{Kg_y(\rho_a)_o\beta}{\mu}\frac{\partial T}{\partial x} \tag{10}$$

Because the containing walls and floor of the grain store are impermeable, the stream function is constant along the perimeter of the grain store, and it can be arbitrarily assigned a value of zero, the boundary conditions can be expressed as

$$\psi(0,y)=0;\quad 0\le y\le H \tag{BC9}$$

$$\psi(L,y)=0;\quad 0\le y\le H \tag{BC10}$$

$$\psi(x,0)=0;\quad 0\le x\le L \tag{BC11}$$

$$\psi(x,H)=0;\quad 0\le x\le L \tag{BC12}$$

Non-dimensionalisation

Stored grains technologists are familiar with several dimensionless quantities such as grain moisture content, which is the ratio of the mass of water in a bulk of grains to the total mass of the grains. They are also familiar with other dimensionless variables such as the germination counts of seeds, head rice yield in milling, and so on.

There are good reasons for stored grains technologists *not* working in terms of dimensionless temperatures, air velocities, times, lengths, and so on. These include the fact that stored grains systems are very specific entities, such as a particular silo with a given height, and specific questions are asked about their performance. This contrasts with systems that are often studied for academic research in which variables such as physical dimensions, thermal conductivities of the solid particles and intergranular fluid may vary over several orders of magnitude and generality is highly prized. In addition, the physical and biological behaviour of stored grains are highly temperature dependent, and the reporting of experimental data must refer to actual temperatures as well as dimensionless temperatures — in essence, insects do not respond to dimensionless temperatures. Finally, engineers and technologists are familiar with actual temperatures and velocities, as opposed to dimensionless quantities which may be defined in quite arbitrary manners.

Notwithstanding these reasons for performing computations with real variables, we shall express the heat, mass, and momentum equations in terms of dimensionless quantities. One reason for this is that it enables components of the analysis to be validated against published solutions and experiments carried out on systems in which there is no mass transfer. Having gained confidence that the heat transfer alone analysis is correct, it may be incrementally transformed to account for mass transfer and respiration. In addition, components of the problem may be defined in terms of variables, such as dimensionless temperature, that vary between 0 and 1 (when respiration is negligible) which assists with the detection of errors in the solutions. Another advantage of using dimensionless variables is that they may be defined so that important terms of the governing equations are of similar magnitude, and this generally increases the efficiency of their solution, as noted by de Vahl Davis (1976). Dimensionless quantities are easily reverted to physical quantities.

Denoting the dimensionless variables with primes, we can define dimensionless horizontal and vertical components of velocity, thus

$$u'=\frac{u}{u*} \tag{11}$$

$$v'=\frac{v}{v*} \tag{12}$$

where $u*$ and $v*$ are reference velocities yet to be determined. We similarly define the following dimensionless variables

$$t'=\frac{t}{t*} \tag{13}$$

$$x'=\frac{x}{L} \tag{14}$$

$$y'=\frac{y}{L} \tag{15}$$

$$T'=\frac{T-T_o}{T_1-T_o}=\frac{T-T_o}{\Delta T} \tag{16}$$

where L is the width of the grain store and T_o and T_l are some arbitrarily specified temperatures. The difference, ΔT, between these two temperatures is typically set at a value on the order of magnitude of expected changes in the temperature, T. Inserting these dimensionless variables into the energy balance, equation (1), results in

$$\begin{aligned}
&\rho_\sigma\varepsilon_\sigma\left\{c_\sigma+Wc_1+\frac{\partial H_w}{\partial T}\right\}\frac{\Delta T}{t*}\frac{\partial T'}{\partial t'}\\
&+\rho_a\varepsilon_\gamma\left\{c_a+w\left(c_1+\frac{\partial h_v}{\partial T}\right)\right\}\frac{\Delta T}{t*}\frac{\partial T'}{\partial t'}-\frac{h_s\varepsilon_\sigma\rho_o}{t*}\frac{\partial W}{\partial t'}\\
&-\frac{\rho_\sigma}{t*}\frac{\partial\varepsilon_\sigma}{\partial t'}\int_o^w h_s dW+\frac{\rho_a c_a\Delta T}{L}\left(u'u*\frac{\partial T'}{\partial x'}+v'v*\frac{\partial T'}{\partial y'}\right)\\
&+\frac{\rho_a w\Delta T}{L}\left(c_1+\frac{\partial h_v}{\partial T}\right)\left(u'u*\frac{\partial T'}{\partial x'}+v'v*\frac{\partial T'}{\partial y'}\right)\\
&=\frac{k_{eff}\Delta T}{L^2}\left(\frac{\partial^2 T'}{\partial x'^2}+\frac{\partial^2 T'}{\partial y'^2}\right)+Q_r-h_v S_1
\end{aligned} \tag{17}$$

Multiplying equation (17) by $L^2/K_{eff}\Delta T$ renders it dimensionless with the result

$$\begin{aligned}
&\frac{\langle\rho c_p\rangle L^2}{k_{eff}}\frac{1}{t*}\frac{\partial T'}{\partial t'}-\frac{h_s\varepsilon_\sigma\rho_\sigma L^2}{k_{eff}\Delta Tt*}\frac{\partial W}{\partial t'}-\frac{\rho_\sigma L^2}{k_{eff}\Delta Tt*}\frac{\partial\varepsilon_\sigma}{\partial t'}\int_o^w h_s dW\\
&+\frac{\rho_a c_a L}{k_{eff}}\left(u'u*\frac{\partial T'}{\partial x'}+v'v*\frac{\partial T'}{\partial y'}\right)\\
&+\frac{\rho_a wL}{k_{eff}}\left(c_1+\frac{\partial h_v}{\partial T}\right)\left(u'u*\frac{\partial T'}{\partial x'}+v'v*\frac{\partial T'}{\partial y'}\right)\\
&=\left(\frac{\partial^2 T'}{\partial x'^2}+\frac{\partial^2 T'}{\partial y'^2}\right)+\frac{L^2}{k_{eff\Delta T}}\left(Q_r-h_v S_1\right)
\end{aligned} \tag{18}$$

in which we have defined the mass weighted heat capacitance, $\langle \rho c_p \rangle$,as

$$\langle \rho c_p \rangle = \rho_\sigma \varepsilon_\sigma \left\{ c_\sigma + W c_1 + \frac{\partial H_w}{\partial T} \right\} + \rho_a \varepsilon_\gamma \left\{ c_a + w \left(c_1 + \frac{\partial h_v}{\partial T} \right) \right\} \tag{19}$$

We might be tempted to define t^* as

$$t^* = \frac{k_{eff}}{\langle \rho c_p \rangle L^2} \tag{20}$$

as this makes the leading term on the left-hand side of equation (18) dimensionless. We should note, however, that $\langle \rho c_p \rangle$ depends on the grain moisture content which varies considerably from point to point in the bed and with time. Instead we choose to define

$$t^* = \frac{\rho_a c_a L^2}{k_{eff}} \tag{21}$$

Since the units of u^* and v^* are m/s, it follows that we can define the characteristic velocities as L/t^*, i.e.

$$u^* = v^* = \frac{k_{eff}}{\rho_a c_a L} \tag{22}$$

Inserting these values into equation (18) results in

$$\frac{\langle \rho c_p \rangle}{\rho_a c_a} \frac{\partial T'}{\partial t'} - \frac{h_s \varepsilon_\sigma \rho_\sigma}{\rho_a c_a \Delta T} \frac{\partial W}{\partial t'} - \frac{\rho_\sigma}{\rho_a c_a \Delta T} \frac{\partial \varepsilon_\sigma}{\partial t'} \int_o^w h_s dW + \left(u' \frac{\partial T'}{\partial x'} + v' \frac{\partial T'}{\partial y'} \right) + \frac{w}{c_a} \left(c_1 + \frac{\partial h_v}{\partial T} \right) \left(u' \frac{\partial T'}{\partial x'} + v' \frac{\partial T'}{\partial y'} \right) = \left(\frac{\partial^2 T'}{\partial x'^2} + \frac{\partial^2 T'}{\partial y'^2} \right) + \frac{L^2}{k_{eff\Delta T}} \left(Q_r - h_v S_1 \right) \tag{23}$$

Multiplying equation (23) by $(\rho_a c_a)/\langle \rho c_p \rangle$ results in the desired dimensionless form of the thermal energy balance equation, namely

$$\frac{\partial T'}{\partial t'} - \frac{h_s \varepsilon_\sigma \rho_\sigma}{\langle \rho c_p \rangle \Delta T} \frac{\partial W}{\partial t'} - \frac{\rho_\sigma}{\langle \rho c_p \rangle_a \Delta T} \frac{\partial \varepsilon_\sigma}{\partial t'} \int_o^w h_s dW + \frac{\rho_a c_a}{\langle \rho c_p \rangle} \left(u' \frac{\partial T'}{\partial x'} + v' \frac{\partial T'}{\partial y'^2} \right) + \frac{\rho_a w}{\langle \rho c_p \rangle} \left(c_1 + \frac{\partial h_v}{\partial T} \right) \left(u' \frac{\partial T'}{\partial x'} + v' \frac{\partial T'}{\partial y'} \right) = \frac{\rho_a c_a}{\langle \rho c_p \rangle} \left(\frac{\partial^2 T'}{\partial x'^2} + \frac{\partial^2 T'}{\partial y'^2} \right) + \frac{\rho_a c_a L^2}{\langle \rho c_p \rangle k_{eff} \Delta T} \left(Q_r - h_v S_1 \right) \tag{24}$$

The moisture balance, equation (23), may be expressed as

$$\frac{\varepsilon_\sigma \rho_\sigma}{t^*} \frac{\partial W}{\partial t'} + \frac{\rho_a}{L} \left(u^* u' \frac{\partial w}{\partial x'} + v^* v' \frac{\partial w}{\partial y'} \right) = \frac{D_{eff} \rho_a}{L^2} \left(\frac{\partial^2 w}{\partial x'^2} + \frac{\partial^2 w}{\partial y'^2} \right) + (1 + 1.6W) S_1 \tag{25}$$

Substituting the expressions for t^*, u^*, and v^* in the moisture conservation equation (equation 25), leads to

$$\frac{\varepsilon_\sigma \rho_\sigma k_{eff}}{\rho_a c_a L^2} \frac{\partial W}{\partial t'} + \frac{k_{eff}}{c_a L^2} \left(u' \frac{\partial w}{\partial x'} + v' \frac{\partial w}{\partial y'} \right) = \frac{D_{eff} \rho_a}{L^2} \left(\frac{\partial^2 w}{\partial x'^2} + \frac{\partial^2 w}{\partial y'^2} \right) + (1 + 1.6W) S_1 \tag{26}$$

which may be slightly rearranged into the desired form, thus

$$\frac{\partial W}{\partial t'} + \frac{\rho_a}{\varepsilon_\sigma \rho_\sigma} \left(u' \frac{\partial w}{\partial x'} + v' \frac{\partial w}{\partial y'} \right) = \frac{D_{eff}}{k_{eff}} \frac{\rho_a}{\varepsilon_\sigma \rho \sigma} \left(\frac{\partial^2 w}{\partial x'^2} + \frac{\partial^2 w}{\partial y'^2} \right) + \frac{(1 + 1.6W) L^2 \rho_a c_a S_1}{k_{eff} \varepsilon_\sigma \rho_\sigma} \tag{27}$$

It remains to express the stream function equation in dimensionless terms. We define a dimensionless stream function, ψ', in terms of a characteristic stream function, ψ^*, thus

$$\psi' = \frac{\psi}{\psi^*} \tag{28}$$

and from the definition of the stream function we observe that

$$u' u^* = \frac{\partial \psi'}{\partial x'} \frac{\partial x'}{\partial x} \psi^* \tag{29}$$

When the definitions of u^* and x' are substituted into equation (29) we find that the natural choice of ψ^* is

$$\psi^* = \frac{k_{eff}}{\rho_a c_a} \tag{30}$$

The stream function, equation (10), can now be expressed as

$$\frac{k_{eff}}{\rho_a c_a L^2} \left(\frac{\partial^2 \psi}{\partial x'^2} + \frac{\partial^2 \psi}{\partial x'^2} \right) = \frac{K \rho_a \beta g_y \Delta T}{\mu L} \frac{\partial T'}{\partial x'} \tag{31}$$

which may be rearranged into the form

$$\left(\frac{\partial^2 \psi'}{\partial x'^2} + \frac{\partial^2 \psi'}{\partial x'^2} \right) = Ra^* \frac{\partial T'}{\partial x'} \tag{32}$$

in which

$$Ra^* = \frac{K\rho_a \beta g_y \Delta TL}{\mu k_{eff}} \tag{33}$$

Ra^* is called the *modified* Rayleigh number (to distinguish from the Rayleigh number associated with single-phase fluid flow, such as warm air rising in a room). From this point, we shall omit the superscript primes, ', and all the variables should be taken as being dimensionless unless otherwise stated.

Our goal is to solve equations (24), (27), and (32) subject to the appropriate initial and boundary conditions. This will allow us to calculate how the temperature and moisture content fields within the grain store vary with time, and this in turn enables us to investigate how we can manipulate bulks of stored grains to minimise quality losses.

The numerical solution procedure

For illustrative purposes we are considering a grain store that has a rectangular cross-section. A rectangular mesh can be superimposed on the cross-section such that there are m nodes in the x-direction and n-nodes in the y-direction as shown in Figure 2. As we have set the dimensionless width as unity, the height is A_r, the aspect ratio, and the node spacings are

$$h_x = \frac{1}{m-1} \tag{34}$$

and

$$h_y = \frac{A_r}{n-1} \tag{35}$$

Using this notation we find that the distances x and y are expressed as

$$x = (i-1)h_x \tag{36}$$

and

$$y = (j-1)h_y \tag{37}$$

If the integration time step is h_t, the elapsed time, t, from the start of the solution is $(p-1)h_t$.

The temperatures at the mesh points are denoted by $T_{i,j}^p$, where i and j are the space coordinates and p represents the pth time step from the start of the solution. In order to avoid a plethora of subscripts and superscripts we shall, like de Vahl Davis (1976), let i, j, and p be default values. This allows us to write

$T_{i,j}^p$ as T $\quad T_{i,j+1}^{p+1}$ as T_{j+1}^{p+1} $\quad T_{i-1,j}^p$ as T_{i-1}

and so on.

We are now in a position to define finite difference approximations of derivatives. Time derivatives are written as forward differences, so at the (i,j)th node, the derivative of temperature with respect to time at the pth time step is approximated by

$$\frac{\partial T}{\partial t} = \frac{T^{p+1} - T^p}{h_t} \tag{38}$$

Spatial derivatives are approximated by central differences, hence we have, for example,

$$\frac{\partial T}{\partial x} = \frac{T_{i+1} - T_{i-1}}{2h_x} \tag{39}$$

and

$$\frac{\partial^2 T}{\partial x^2} = \frac{T_{i+1} - 2T + T_{i-1}}{h_x^2} \tag{40}$$

We now substitute the finite difference forms of the derivatives, such as those defined by equations (38), (39), and (40) into the heat, mass, and momentum balances and we solve them using the Peaceman-Rachford (1955) alternating direction implicit (ADI) method, described in detail in the following section. The method enables the temperatures, moisture contents, air velocities, and so on to be calculated at the end of each time step, and the method involves the solution of simultaneous linear equations. A very simple method for doing this has been described by Carnahan et al. (1969) and Thomas (1949) and the method is detailed in Appendix 1.

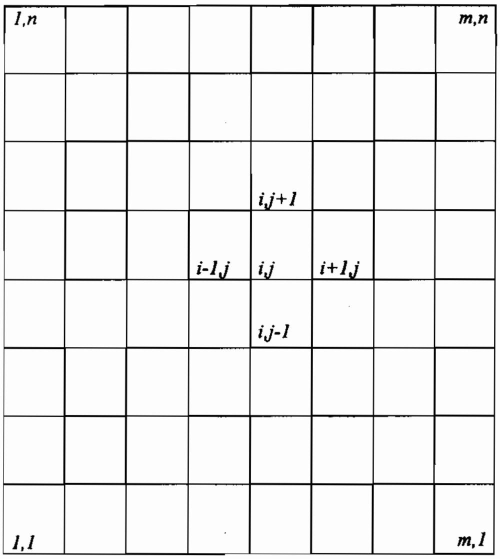

Figure 2. The finite difference mesh used to discretise the governing equations.

Solution of the thermal energy equation

The thermal energy equation may be written in the form

$$\frac{\partial T}{\partial t}+t_{pi}\left(\frac{\partial(uT)}{\partial x}+\frac{\partial(vT)}{\partial y}\right)+\left(t_{mx}\frac{\partial T}{\partial x}+t_{my}\frac{\partial T}{\partial y}\right)$$
$$=t_{pd}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)+t_r+t_\ell \tag{41}$$

in which

$$t_{pi}=\frac{\rho_a c_a}{\langle\rho c_p\rangle}$$

$$t_{mx}=\frac{\rho_a wu}{\langle\rho c_p\rangle}\left(c_1+\frac{\partial h_v}{\partial T}\right)$$

$$t_{my}=\frac{\rho_a wv}{\langle\rho c_p\rangle}\left(c_1+\frac{\partial h_v}{\partial T}\right)$$

$$t_r=\frac{\rho_a c_a L^2}{\langle\rho c_p\rangle k_{eff}\Delta T}\left(Q_r-h_v S_1\right)$$

$$t_\ell=\frac{\varepsilon_\sigma\rho_\sigma h_s}{\langle\rho c_p\rangle\Delta T}+\frac{\rho_\sigma}{\langle\rho c_p\rangle\Delta T}\frac{\partial\varepsilon_\sigma}{\partial T}\int_o^w h_s dW$$

and in which we have written the discretised dominant convective term with the t_{pi} multiplier in the conservative form; that is, we have discretised $\partial(uT)/\partial x$, for example, as opposed to $u(\partial T/\partial x)$ (see Roache 1972). We shall solve the discretised form of this equation (41) by the Peaceman-Rachford (1955) method which treats the problem as being implicit in the direction of one coordinate, the x-coordinate say, during half of a time increment. The integration in the orthogonal direction, the y-coordinate, is carried out explicitly. During the second half of the time step the y-components of gradients and laplacians are advanced implicitly, whilst the x-components are treated explicitly. An example will illustrate the method.

Implicit in the x-direction

We let T^* represent the notional values of the temperature after the first half time step, in which case the discretised form of the thermal energy balance equation for the internal mesh points is

$$\frac{T^*-T}{h_t/2}+t_{pi}\left(\frac{u_{i+1}T^*_{i+1}-u_{i-1}T^*_{i-1}}{2h_x}\right)+t_{pi}\left(\frac{v_{i+1}T_{i+1}-v_{i-1}T_{i-1}}{2h_v}\right)$$
$$+t_{mx}\left(\frac{T^*_{i+1}-T^*_{i-1}}{2h_x}\right)+t_{my}\left(\frac{T_{j+1}-T_{j-1}}{2h_y}\right) \tag{42}$$
$$=t_{pd}\left(\frac{T^*_{i+1}-2T^*+T^*_{i-1}}{h_x^2}\right)+t_{pd}\left(\frac{T_{j+1}-2T+T_{j-1}}{h_y^2}\right)+t_r+t_i$$

Collecting terms results in

$$\left(-\frac{t_{pi}}{2h_x}u_{i-1}-\frac{t_{pd}}{h_x^2}-\frac{t_{mx}}{2h_x}\right)T^*_{i-1}+\left(\frac{2}{h_t}+\frac{2t_{pd}}{h_x^2}\right)T^*$$
$$+\left(\frac{t_{pi}}{2h_x}u_{i-1}-\frac{t_{pd}}{h_x^2}+\frac{t_{mx}}{2h_x}\right)T^*_{i+1}$$
$$=\left(\frac{t_{pi}}{2h_y}v_{j-1}+\frac{t_{pd}}{h_y^2}+\frac{t_{my}}{2h_y}\right)T_{j-1}+\left(\frac{2}{h_t}-\frac{2t_{pd}}{h_y^2}\right)T \tag{43}$$
$$+\left(-\frac{t_{pi}}{2h_y}v_{j-1}+\frac{t_{pd}}{h_y^2}-\frac{t_{my}}{2h_y}\right)T_{j+1}+t_\ell+t_r$$

The important thing to note about equation (43) is that all of the unknowns are on the left-hand side of the equation, and the right-hand side contains only temperatures that are known (because they are those that occurred at the start of the time step). Equation (43) can be written in a more compact form by defining the following variables

$c_1=2/h_t$
$c_{tp1}=t_{pi}/2h_x$
$c_{tp2}=t_{pd}/h_x^2$
$c_{tp3}=c_1+2c_{tp2}$
$c_{tp4}=t_{pi}/2h_y$
$c_{tp5}=t_{pd}/h_y^2$
$c_{tp6}=c_1-2c_{tp5}$
$c_{tp7}=c_1+2c_{tp5}$
$c_{tp8}=c_1-2c_{tp1}$
$c_{tm1}=t_{mx}/2h_x$
$c_{tm2}=t_{my}/2h_y$

which enables the discretised equation to be written as

$$\left(-c_{tp1}u_{i-1}-c_{tp2}-c_{tm1}\right)T^*_{i-1}+c_{tp3}T^*$$
$$+\left(c_{tp1}u_{i+1}-c_{tp2}+c_{tm1}\right)T^*_{i+1}$$
$$=\left(c_{tp4}v_{j-1}+c_{tp5}\right)T_{j-1}+c_{tp6}T \tag{44}$$
$$+\left(-c_{tp4}v_{j+1}+c_{tp5}\right)T_{j+1}+t_i+t_r$$

Now at the start of the first time step, the values of all the multipliers, t_{pi}, t_{mx}, t_{my} and so on can be calculated because the initial values of the temperatures, T, and grain moisture contents, W, have been declared. We must therefore calculate the values of T^* at the interior mesh points. This is done by incrementing j from 2 to j-1, and for each value of j we have a system of (m-2) linear equations written thus

$$a_{i-1}T^*_{i-1}+b_{i-1}T^*+c_{i-1}T^*_{i+1}=d_{i-1} \tag{45}$$

in which

$$a_{i-1} = -c_{tp1}u_{i-1} - c_{tp2} - c_{tml}$$

$$b_{i-1} = c_{tp3}$$

$$c_{i-1} = c_{tp1}u_{i+1} - c_{tp2} + c_{tm1}$$

$$d_{i-1} = \left(c_{tp4}v_{j-1} + c_{tp5}\right)T_{j-1} + c_{tp6}T$$

$$+\left(-c_{tp4}v_{j+1} + c_{tp5}\right)T_{j+1} + t_\ell + t_r$$

for which $i = 2, 3, 4, \ldots, m, m-1$.

We note that when $i = 2$ the first equation becomes

$$b_1 T_2^* + c_1 T_3^* = d_1 - a_1 T_1 \tag{46}$$

and when $i = (m-1)$ we have

$$a_{m-2}T_{m-2}^* + b_{m-2}T_{m-1}^* = d_{m-2} - c_{m-2}T_m \tag{47}$$

in which T_l and T_m are the values of the temperature on the boundaries of the store at the start of the *p*th time step. The values of these boundary temperatures are known, or they can be calculated from interior nodes. The algorithm is encoded in FORTRAN, and listed in Figure 3.

```
      mm1=m-1
      nm1=n-1
      nm2=m-2
      do 1 j=2,nm1
      do 2 i=2,mm1
*
*
*      Update values of coefficients in thermal energy equation
*
      call constte(i,j)
*
*
      a(i-1)=-ctp1*u(i-1,j)-ctp2-ctm1(i,j)
      b(i-1)=ctp3
      c(i-1)=ctp1*u(i+1,j)-ctp2+ctm1(i,j)
      d(i-1)=(ctp4*v(i,j-1)+ctp5)*told(i,j-1)+ctp6*told(i,j)
     1    +(-ctp4*v(i,j+1)+ctp5)*told(i,j+1)
     2    -ctm2(i,j)*(told(i,j+1)-told(i,j-1))+tl(i,j)+tr(i,j)
      if(i.eq.2) d(1)=d(1)-a(1)*told(1,j)
    2 if(i.eq.mm1) d(mm2)=d(mm2)-c(mm2)*told(m,j)
*
*      At this point we have computed the coefficients in the tridiagonal system
*      of equations that govern the temperatures, thalf(i,j), that obtain at the end
*      of a notional half time step.
*
      call thomas(mm2)
      do 3 i=2,mm1
      jj=i-1
    3 thalf(i,j)=xx(jj)
    1 continue
```

Figure 3. The Peaceman-Rachford alternating direction implicit method encoded in FORTRAN for the step that is implicit in the *x*-direction.

It will be noted that the coefficients ctp1, ctp2, ctp3, etc. are functions of temperature and grain moisture content and they are computed for each of the interior mesh points in subroutine constte. The initial temperature at the start of the time step is designated as told(i,j) because at the start of the integration time step they are 'old' temperatures, as opposed to the new, updated temperatures that occur at the end of the time step. Having calculated the coefficients, the tridiagonal system of *m*-2 (mm) equations is solved by subroutine thomas to yield the temperatures *T** (thalf(i,j) in the program) at the end of the notional half time step.

As we noted when defining the boundary conditions, the temperatures on the side of the store are prescribed at each time step, i.e. T_l and T_m are known at the start (and also at the end) of the time step because we have specified what they are. They could be set at the same temperature as the temperature of the ambient air around the grain store, but more generally we have to account for effects such as solar radiation.

Implicit in the y-direction

The next step is to solve the discretised thermal energy equation implicitly in the *y*-direction to obtain the updated values of the temperatures, *T***, at the end of the integration time step, whilst the values, *T**, obtained at the end of the half time step are treated explicitly. This is clarified by

$$\begin{aligned}
&\frac{T^{**} - T^*}{h_t/2} + t_{pi}\left(\frac{u_{i+1}T_{i+1}^* - u_{i-1}T_{i-1}^*}{2h_x}\right) \\
&+t_{pi}\left(\frac{v_{i+1}T_{i+1}^{**} - v_{i-1}T_{i-1}^{**}}{2h_y}\right) + t_{mx}\left(\frac{T_{i+1}^* - T_{i-1}^*}{2h_x}\right) \\
&+t_{my}\left(\frac{T_{j+1}^{**} - T_{j-1}^{**}}{2h_y}\right) = t_{pd}\left(\frac{T_{i+1}^* - 2T^* - T_{i-1}^*}{h_x^2}\right) \\
&+t_{pd}\left(\frac{T_{j+1}^* - 2T^{**} - T_{j-1}^{**}}{h_y^2}\right) + t_r + t_\ell
\end{aligned} \tag{48}$$

Again this equation can be simplified by collecting terms in the unknowns on the left-hand side, and the known values on the right-hand side, thus

$$\begin{aligned}
&\left(-c_{tp4}v_{j-1} - c_{pt5} - c_{tm2}\right)T_{j-1}^{**} + c_{tp7}T^{**} \\
&+\left(c_{tp4}v_{j+1} - c_{tp5} - c_{tm2}\right)T_{j+1}^{**} \\
&= \left(c_{tp1}u_{i-1} + c_{tp2}\right)T_{i-1}^* + c_{tp8}T^* \\
&+\left(-c_{tp1}u_{i+1} + c_{tp2}\right)T_{i+1}^* + t_\ell + t_r
\end{aligned} \tag{49}$$

In this case we have (*n*–2) linear equations for each of the (*m*–2) interior columns which are readily solved for *T***, which of course are the required updated temperatures, T^{p+1}, at the end of the integration time step. This algorithm is encoded in FORTRAN as shown in Figure 4.

In this element of the program *n*–2 (nm2) equations are solved for each of the (*m*–2) interior columns of interior nodes. In this case we have designated the updated temperatures T^{p+1} or T** as tnew(i,j).

Although not shown in the excerpts of computer code we next set told(i,j) to tnew(i,j), i.e. the 'new', or updated, temperatures become the 'old', or initial, temperatures at the start of the next iteration.

```
      nm2=n-2
c
c     Implicit in y-direction
c

      do 4 i=2,mm1
      do 5 j=2,nm1
      a(j-1)=-ctp4*v(i,j-1)-ctp5-ctm2(i,j)
      b(j-1)=ctp7
      c(j-1)=ctp4*v(i,j+1)-ctp5+ctm2(i,j)
      d(j-1)=(ctp1*u(i-1,j)+ctp2)*thalf(i-1,j)+ctp8*thalf(i,j)
     1      +(-ctp1*u(i+1,j)+ctp2)*thalf(i+1,j)+add(i,j)
     2    -ctm1(i,j)*(thalf(i+1,j)-thalf(i-1,j))+resheat(i,j)
      if(j.eq.nm1) d(j-1)=d(j-1)-c(j-1)*thalf(i,n)
      if(j.eq.2) d(1)=d(1)-a(1)*thalf(i,1)
    5 continue
      call thomas(nm2)
      do 6 j=2,nm1
      jj=j-1
    6 tnew(i,j)=xx(jj)
    4 continue
```

Figure 4. The second half time step in the Peaceman-Rachford alternating direction implicit method encoded in FORTRAN when implicit in the *y*-direction.

Time step

As an approximate guide, the time step to guarantee stability of numerical solutions is proportional to the square of the internodal distance, h_x^2 and h_y^2. We define the minimum of these values as *dmin* and since we wish to choose time steps that correspond to times that are multiples of 3600 seconds (one hour), say, we define using FORTRAN notation

$$dtreal = stabr * d\,min * *2 * 1.44E8 \tag{50}$$

We note that when *stabr* = 0.25 and *dmin* = 0.1, for example, dtreal is 360 000 seconds or 100 hours. By making use of the definition of dimensionless time, equation (21), the dimensionless time step, h_t, is written as

$$h_t = \frac{dtreal * k_{eff}}{\rho_a c_a L^2} \tag{51}$$

Temperature boundary conditions

The numerical method described above is used to determine the temperatures at the $(m{-}2) \times (n{-}2)$ internal nodes of the grain store, and we either impose temperatures at the surface, or if a surface is adiabatic (perfectly thermally insulated) we estimate the surface temperatures from temperatures of the interior nodes. When the surface is adiabatic, i.e. there is no heat flow, q, through the surface, this condition is represented by

$$q = -k_{eff} \left.\frac{\partial T}{\partial y}\right|_{y=0} = 0 \tag{52}$$

In the case studied here, the floor is thermally insulated and we estimate the temperatures on the floor of the store by extrapolating from the known temperatures of the interior nodes. A second-order forward differences approximation of the temperature gradient is

$$\frac{\partial T}{\partial y} = \frac{-3T_1 + 4T_2 - T_3}{2h_y} \tag{53}$$

At an adiabatic surface, $\partial T/\partial y = 0$, hence we are able to find the surface temperature T_1 from the interior values T_2 and T_3 by the expression

$$T_1 = \frac{4T_2 - T_3}{3} \tag{54}$$

This is programmed as follows:

```
*
*    Floor at y=0 is adiabatic
*
      do 2 i=1,m
    2 tnew(i,1)=(4.0*tnew(i,2)-tnew(i,3))/3.0
```

Solution of the stream function equation

Having advanced the temperature field through one time step, we have effectively set up temperature gradients within the grain bulk. Hence, we are now in a position to evaluate the stream function from equation (32). Our approach to solving this elliptic partial differential equation is to introduce a false transient term so that the equation is transformed into parabolic form, i.e. we may write

$$\frac{1}{\alpha_p}\frac{\partial \psi}{\partial t} = \nabla^2 \psi + Ra * \frac{\partial T}{\partial x} \tag{55}$$

where α_p is a multiplier with an arbitrary value determined by numerical experiment. After each real time step in which the temperatures, T, are advanced, equation (55) is solved until a steady state has been approached, in which case it closely approximates equation (32). At this point the components of the air velocity in the grain bulk can be obtained from equations (8) and (9). When equation (55) is discretised, and we express it implicitly in the x-direction, it takes the form

$$\frac{1}{\alpha_p}\frac{\psi^*-\psi}{h_t/2}=\left(\frac{\overset{*}{\psi}_{i-1}-2\psi^*+\overset{*}{\psi}_{i+1}}{h_x^2}\right)+\left(\frac{\psi_{j-1}-2\psi+\psi_{j+1}}{h_y^2}\right)+Ra*\frac{(T_{i+1}-T_{i-1})}{2h_x} \qquad \textbf{(56)}$$

which may be expressed more compactly

$$\begin{aligned}&-c_{p1}\overset{*}{\psi}_{i-1}+c_{p2}\psi^*-c_{p1}\overset{*}{\psi}_{i+1}\\&=c_{p3}\psi_{j-1}+c_{p4}\psi+c_{p3}\psi_{j+1}+c_{p7}(T_{i+1}-T_{i-1})\end{aligned} \qquad \textbf{(57)}$$

This equation is solved for ψ^* for each of the interior points. For this we set j to 2,3,4,...., m-1, and for each value of j we are able to make use of the Thomas (1949) algorithm to solve equation (56) for $\psi^*_{2,j}$, $\psi^*_{3,j}$, $\psi^*_{4,j}$, $\psi^*_{5,j}$,......., $\psi^*_{m-2,j}$, $\psi^*_{m-1,j}$. The boundary values of the stream function, i.e. $\psi^*_{1,j}$, $\psi^*_{m,j}$, $\psi^*_{i,1}$, and $\psi^*_{i,m}$ are all set to zero.

Having determined the values of ψ^* at the end of the half time step, the values ψ^{**} of the stream function at the end of the time step are determined by means of the equation

$$\frac{1}{\alpha_p}\frac{\psi^{**}-\psi^*}{h_t/2}=\left(\frac{\overset{*}{\psi}_{i-1}-2\psi^*+\overset{*}{\psi}_{i+1}}{h_x^2}\right)+\left(\frac{\overset{**}{\psi}_{j-1}-2\psi^{**}+\overset{**}{\psi}_{j+1}}{h_y^2}\right)+\frac{Ra*(T_{i+1}-T_{i-1})}{2h_x} \qquad \textbf{(58)}$$

which may be rearranged and expressed compactly as

$$\begin{aligned}&-c_{p3}\overset{*}{\psi}_{j-1}+c_{p5}\psi^{**}-c_{p3}\overset{**}{\psi}_{j+1}\\&=c_{p1}\overset{*}{\psi}_{i-1}+c_{p6}\psi^*+c_{p1}\overset{*}{\psi}_{i+1}+c_{p7}(T_{i+1}-T_{i-1})\end{aligned} \qquad \textbf{(59)}$$

where, for conformity with the nomenclature of de Vahl Davis (1976), we have defined the coefficients as

$$\begin{aligned}c_{p1}&=\alpha_p/h_x^2 & c_{p5}&=c_1+2c_{p3}\\c_{p2}&=c_1+2c_{p1} & c_{p6}&=c_1-2c_{p1}\\c_{p3}&=\alpha_p/h_y^2 & c_{p7}&=\alpha_p/2h_x\\c_{p4}&=c_1-2c_{p3}\end{aligned}$$

As noted above, we wish the false transient equation (55) to approach the steady state, hence during each time step we advance the equation through successive integration steps, $\alpha_p h_t$, until some criterion such as

$$\sum_{\substack{i=2\\j=2}}^{\substack{j=n-1\\i=m-1}}\left|\psi^{p+1}-\psi^p\right|<\psi_{err} \qquad \textbf{(60)}$$

is satisfied, in which ψ_{err} is some predetermined maximum permissible error. The velocity field is determined more accurately as ψ_{err} is made smaller.

For completeness, we indicate that algorithm used to solve the stream function is programmed as detailed in Figure 5.

```
c
c    solves for stream function in stored grains
c
c    This outer loop iterates the stream function equation
c    to the steady state.
c
      do 100 ii=1,50
c
c       implicit in x-direction
c

      do 1 j=2,nm1
      do 2 i=2,mm1
      a(i-1)=-cp1
      b(i-1)=cp2
      c(i-1)=-cp1
      d(i-1)=cp3*phiold(i,j-1)+cp4*phiold(i,j)
     1       +cp3*phiold(i,j+1)+cp7*(tnew(i+1,j)-tnew(i-1,j))
         if(i.eq.2) d(1)=d(1)-a(1)*phiold(1,j)
    2 if(i.eq.mm1) d(mm2)=d(mm2)-c(mm2)*phiold(m,j)
      call thomas(mm2)
      do 3 i=2,mm1
      jj=i-1
    3 phihalf(i,j)=xx(jj)
    1 continue
c
c       implicit in y-direction
c
      do 4 i=2,mm1
      do 5 j=2,nm1
      iarg=j-1
      a(iarg)=-cp3
      b(iarg)=cp5
      c(iarg)=-cp3
      d(iarg)=cp1*phihalf(i-1,j)+cp6*phihalf(i,j)
     1       +cp1*phihalf(i+1,j)+cp7*(tnew(i+1,j)-tnew(i-1,j))
         if(j.eq.2) d(1)=d(1)-a(1)*phihalf(i,1)
    5 if(j.eq.nm1) d(iarg)=d(iarg)-c(iarg)*phihalf(i,n)
      call thomas(nm2)
      do 6 j=2,nm1
      jj=j-1
    6 phinew(i,j)=xx(jj)
    4 continue
c
c    Here we check if the stream function is approaching
c    a steady state.
c
      sum=0.0

      do 110 i=1,m
      do 110 j=1,n
      sum=sum+abs(phiold(i,j)-phinew(i,j))
      phiold(i,j)=phinew(i,j)
  110 phihalf(i,j)=phinew(i,j)
      if(sum.lt.phierr) goto 120
  100 continue
  120 continue
```

Figure 5. The Peaceman-Rachford ADI algorithm used to solve the stream function equation to the steady-state.

The outer do loop with the counter ii and terminating on statement '100 continue' is the iterative loop invoked to drive the stream function towards a steady state, i.e. the inequality 60 is satisfied in which we have denoted ψ_{err} in the program by phierr. The value of the stream function, ψ, at the start of the integration time step is designated in the program as phiold, ψ^* is designated as phihalf, and ψ^{**} is designated as phinew.

The horizontal and vertical components of the velocities, u and v, are calculated from the stream function as indicated in equations (8) and (9) which are discretised to yield

$$u = \frac{\psi_{j+1} - \psi_{j-1}}{2h_y} \tag{61}$$

and

$$v = -\frac{\psi_{i+1} - \psi_{i-1}}{2h_x} \tag{62}$$

Determination of the intergranular moisture content

Before updating the grain moisture contents at each point in the bed of grain it is necessary to calculate the moisture content of the intergranular air at the new temperature. Now, the vapour pressure, p_v, of the water in the intergranular air is given as

$$p_v = rp_s \tag{63}$$

in which the relative humidity, r, of the intergranular air is given by an expression presented by Hunter (1987), thus

$$r = \left(\frac{p_s}{p_o}\right)^{\frac{h_s}{h_v}-1} \tag{64}$$

p_s is the saturated vapour pressure of which may be obtained from Hunter's (1987) equation

$$p_s = \frac{6\times10^{25}}{(T+273.15)^5}\exp\left(\frac{-6800}{\mathrm{T}+273.15}\right) \tag{65}$$

and p_o is an empirical constant that depends on the grain type being considered. The latent heat of vaporisation, h_v, in the range of interest may be taken to depend linearly on the temperature, T, of the grain thus

$$h_v = 2502.39 - 2.3768T \tag{66}$$

As noted above, h_s, is the differential heat of sorption of moisture on grains which has been fitted by Hunter (1987) to the following empirical function of grain moisture content, W

$$\frac{h_s}{h_v} - 1 = \frac{c_{w1}\,\ell\mathrm{n}(c_{w2}W) - (W/W_o)^{cw5}\,c_{w3}\,\ell\mathrm{n}(c_{w4}W)}{1-(W/W_o)^{cw5}} \tag{67}$$

in which

$$W_o = \left(\frac{c_{c_{w2}}^{c_{w1}}}{c_{c_{w4}}^{c_{w5}}}\right)^{\frac{1}{c_{w3}-c_{w1}}} \tag{68}$$

Equations (63) to (68) enable us to calculate the dependency of the moisture content, w, of the intergranular air on the temperature, T, and moisture content, W, of the grains by means of the expression

$$w = \frac{0.622p_v}{P - p_v} \tag{69}$$

in which P is atmospheric pressure, and the constant 0.622 is the ratio of the molecular weights of water and air.

Updating the grain moisture content at the interior nodes

Before we are able to solve the moisture conservation equation (equation 27) we are required to use equation (69) to determine the humidity of the intergranular air as a function of grain moisture content and temperature. The moisture content of the grain changes very slowly, and it has been found that it may be updated using a simple explicit method. Hence, at each interior node we have

$$W^{p+1} = W^p + \frac{D_{eff}}{k_{eff}}\frac{\rho_a}{\varepsilon_\sigma\rho_\sigma}\left(\frac{w_{i-1}^{p+1} - 2w^{p+1} + w_{i+1}^{p+1}}{h_x^2} + \frac{w_{j-1}^{p+1} - 2w^{p+1} + w_{j+1}^{p+1}}{h_y^2}\right)$$
$$+\frac{\rho_a}{\varepsilon_\sigma\rho_\sigma}\left(\frac{u_{i+1}w_{i+1}^{p+1} - u_{i-1}w_{i-1}^{p+1}}{2h_x} + \frac{v_{i+1}w_{i+1}^{p+1} - v_{i-1}w_{i-1}^{p+1}}{2h_y}\right) - \frac{\left(1+1.6W^p\right)L^2\rho_a c_a S_1}{k_{eff}\varepsilon_\sigma\rho_\sigma} \tag{70}$$

and the grain moisture contents are thus updated from W^p at the pth time step to W^{p+1} one time step later.

Moisture contents at the periphery of the grain bulk

At the boundaries of the grain store the temperature and humidity of the intergranular air have been determined by the foregoing analysis. The grain moisture content at the boundaries is therefore a dependent variable, and it must be expressed as a function of the moisture content and temperature of the intergranular air. Hunter (1987) has given the approximate reversion formula for equation (67), thus

$$W = \frac{\frac{1}{c_{w4}}\exp\left(h / c_{w3}\right) - \left(\frac{h}{h_o}\right)^{m_f} \frac{1}{c_{w2}}\exp\left(h / c_{w1}\right)}{1 - \left(h / h_o\right)^{m_f}} \qquad (71)$$

in which we have written h for h_s/h_v-1, m_f is an empirical parameter and h_o is the intercept of the two exponential terms in equation and it is given by

$$h_o = \frac{c_{w1}c_{w3}}{c_{w3} - c_{w1}} \ell\text{n}\left(c_{w2} / c_{w4}\right) \qquad (72)$$

Whilst use of the reversion formula, equation (71), is mathematically consistent, its use can give rise to a practical numerical difficulty. This occurs particularly during the initial stages of the simulation when the temperature gradients close to the wall are very steep, whilst the air humidity gradient is *computed* to be very shallow. In the case in which the walls of the grain store are cooled, the result of these phenomena is a prediction of very high grain moisture contents at the cool surfaces. In this situation the reversion formula may exceed its range, and a numerical overflow may result. Fortunately, peripheral values of the grain moisture content are not strongly involved in the computations if the humidity of the air is extrapolated to the boundaries by means of the analogue of equation (54) in which temperature, T, is replaced by humidity, w. As an expediency, the grain moisture contents at the boundaries may be estimated by means of linear extrapolation of the interior values. Since we have chosen to work with grid points that are uniformly spaced the boundary moisture contents are found from an equation of the form

$$W_1 = 2W_2 - W_3 \qquad (73)$$

Whilst this is a pragmatically reasonable procedure, it should be borne in mind that the grain moisture content at the boundaries has been over specified, i.e. we have set the boundary temperatures, moisture content, and intergranular humidities independently, whereas they are of course related by means of equations (65) and (67).

Effects of respiration

When grains are stored damp, such that the relative humidity of the intergranular air is greater than about 70%, the respiration of moulds results in the production of heat and moisture. Because grain is a good thermal insulator, the rate of heat production may be so great that hot spots form because the heat cannot escape fast enough. When this happens, the grain can be ruined within a day or so. Even under less catastrophic conditions, the loss of dry matter resulting from respiration is nonetheless associated with a reduction in quality indices, and the possible development of mycotoxins.

Respiration may be regarded as the complete combustion of carbohydrates to form carbon dioxide and water, along with the liberation of heat. The oxidation of 1 kg of the grain substrate liberates 15 778 kJ of heat, and forms 1.47 kg of carbon dioxide and 0.6 kg of water. Several workers (Thompson 1972; Seib et al. 1980; Lacey et al. 1994) have quantified the factors that affect the rate of respiration, and in this work we make use of Thompson's (1972) work on the respiration of maize. He has determined that the dry matter loss is time dependent, and after a time t seconds the fractional loss, dm, of dry matter is given by

$$dm = 8.83 \times 10^{-4}\left(\exp\left(1.667 \times 10^{-6} \times t\right) - 1\right) + 2.833 \times 10^{-9} t \qquad (74)$$

Equation (74) applies to shelled maize at 15.5°C and 25% m.c. (w.b.) with 30% damage. Because the temperature and moisture content of the grains vary with location in the grain store it is necessary to map the value of the real time, t, into some physiological time, t_p Real time and physiological time are related by

$$t_p = \frac{t}{M_M M_T} \qquad (75)$$

in which M_M and M_T modify the elapsed time, or 'life' of the grains depending on their moisture content and temperature. Converting Thompson's (1972) expression to SI Units results in the following:

(a) Temperature modifier

When T ≤ 15.5°C or M ≤ 19%

$$M_T = 32.2\,exp(-0.1044T - 1.856) \qquad (76)$$

When T > 15.5°C and 19 < M < 28%

$$M_T = 32.2\exp(-0.1044T - 1.856) + \{(M - 19)/100\}\exp(0.0183T - 0.2847) \qquad (77)$$

When T > 15.5°C and M> 28%

$$M_T = 32.2\exp(-0.1044T - 1.856) \\ +0.09\exp(0.0183T - 0.2847) \tag{78}$$

(b) Moisture modifier

The moisture modifier, Mm, is given by the expression:

$$M_M = 0.103\left(\exp\left(455 / M_{DB}^{1.53}\right) - 0.00845 M_{DB} + 1.558\right) \tag{79}$$

in which M_{DB} is the grain moisture content, % dry basis.

Equations (74) to (79) are used to calculate the dry matter loss, *dm*, after the physiological time, t_p, by means of the expression

$$dm = 8.83 \times 10^4 \left\{\exp\left(1.667 \times 10^6 t_p - 1\right)\right\} + 2.833 \times 10^{-9} t_p \tag{80}$$

from which it is readily determined that the rate of dry matter loss is given by

$$\frac{ddm}{dt} = 14.72 \times 10^{-10}\left\{\exp\left(1.667 \times 10^{-6} t_p\right) - 1\right\} \\ +2.833 \times 10^{-9} / \left(M_M M_T\right) \tag{81}$$

The rate of pesticide decay

The rates at which contact pesticides decay when applied to stored grains are strongly dependent on temperature and the relative humidity of the intergranular air. Desmarchelier and Bengston (1979) have elucidated the chemical kinetics of pesticide decay, and found them to be pseudo first-order, thus

$$\frac{\partial C}{\partial t} = -k_r C \tag{82}$$

where *C* is the concentration of the pesticide on the grains, k_r is a reaction rate constant, and *r* is the fractional relative humidity of the intergranular air. When the relative humidity of the intergranular air is 0.5, the half-life, $t_{1/2}$, of a typical pesticide at a temperature *T* is given by Desmarchelier and Bengston (1979) as

$$t_{1/2} = t_{1/2}^{*} 10^{-B(T-30)} \tag{83}$$

where $t^*_{1/2}$ is the half-life at 30°C and *B* is a parameter that depends on the pesticide being considered. Values of $t^*_{1/2}$ and *B* for eleven pesticides are listed in Table A2.3. After a little manipulation of equations (82) and (83) it is readily shown that the concentration, C^{p+1}, of the pesticide at the (*p*+1)th integration step is given by

$$C^{p+1} \approx C^p \, exp\left(-1.386 r^p h_t \times 10^{B\left(T^p - 30\right)} / t_{1/2}^{*}\right) \tag{84}$$

The approximation sign has been introduced because the kinetics of pesticide decay have been calculated using the values of *r* and *T* that occur at the beginning of the time step, as indicated by the superscript *p*. Provided that h_t is sufficiently small, the error is negligible.

Results

The results of the simulations should be independent of the grid spacings, h_x and h_y, and the time step, h_t, used in the solution of the heat, moisture, and momentum equations. Phenomena that occur within the grain bulk are of course completely independent of such considerations. However, as a general rule, as the grid spacings and time steps are made smaller the errors resulting from discretisation of the governing equations become smaller, and the original continuous equations are approached. We should therefore perform numerical experiments to investigate the convergence of the simulations. In the case considered here we have used mesh sizes of 0.1, 0.05, and 0.025, and 2000 hours of real time were simulated. When the mesh size is reduced, the time steps should be reduced to ensure that the solutions do not become numerically unstable. This is accounted for by equation (50), and in this case we further set stabr to 0.25, 0.125, and 0.0625 when the mesh sizes were 0.1, 0.05, and 0.025, respectively. When $m=n=11$ and stabr = 0.25, the total number of iterations is 20, whereas when $m=n=41$ and stabr = 0.0625, the total number of iterations is 1240. It should be noted that the solutions presented here are of the heat and moisture transfer equations, equations (1) and (2) respectively, but without the terms $\partial H_w / \partial T$ and $\rho_\sigma\left(\partial \varepsilon_\sigma / \partial t\right)\int_o^W h_s dW$, the existence of which has been discerned by the author since the numerical computations were concluded. The equations that are solved are those presented by Singh and Thorpe (1993a).

The work simulates the transient response of the various fields, hence it is important that the false transient stream function equation is iterated to a steady state during each true time step, h_t. In this way we are able to calculate the velocity of the intergranular air after each time step. We must therefore select, by trial and error, values of ψ_{err} that render the solution independent of the error criterion. This is illustrated in Table 1 which shows the influence of ψ_{err} on midpoint values of the grain temperature, moisture content, and pesticide concentration after simulating 2000 hours of storage when $h_x = h_y = 0.05$ and stabr = 0.25. In the numerical experiments described in this work, the initial grain temperature is set at 30°C and the temperatures of the upper surface and the two vertical walls are set at 20°C. The initial moisture content of the grains is set at 18% dry basis, and it is on this basis that all the moisture contents are reported.

Table 1. Values of $T(11,11)$, $W(11,11)$ and $C(11,11)$ for values of $\psi_{err} = 5.0 \times 10^{-2}$, 5.0×10^{-3} and 5.0×10^{-4}.

	5.0×10^{-2}	5.0×10^{-3}	5.0×10^{-4}
$T(11,11)$	0.70365	0.070364	0.070364
$W(11,11)$	0.17909	0.17909	0.17909
$C(11,11)$	0.41706	0.41705	0.41705

It can be seen that $\psi_{err} = 5.0 \times 10^{-3}$ is a satisfactory choice. A further check showed that convergence with respect to ψ_{err} was obtained when $h_x = h_y = 0.1$ and stabr = 0.0625 when $\psi_{err} = 5.0 \times 10^{-3}$.

Results of the numerical experiments are summarised in Table 2 which shows the mid-point values of the quantities of interest to stored grains technologists. They are the grain temperature and moisture content, the dry matter loss, and the concentration of fenitrothion ($C = 1$ when $t = 0$).

The Richardson extrapolation (see de Vahl Davis 1986) was used to estimate the variables as $h_x \to 0$ and $h_y \to 0$ and the results are shown in Table 3.

Spatial distributions

The fields of the key variables, i.e. temperature, grain moisture content, pesticide concentration, and so on, are examined after simulating 2000 hours of storage. Figure 6 shows the stream function which, as would be expected in this example, is symmetrical about the centreline of the grain bulk. The air velocity within the grain bulk is tangent to the streamlines, i.e. those lines along which the stream function is constant, and Figure 6 therefore gives us a qualitative picture of the velocity distributions. For example, near the midpoints of the vertical walls the horizontal component of the velocity is low, whereas the vertical component is relatively large because the stream lines are close together. From equations (8) and (9) we note that $u = \partial\psi/\partial y$ and $v = -\partial\psi/\partial x$, and it can be seen that in the top left of Figure 6 $\partial\psi/\partial y$ is negative, hence we would expect the horizontal component of the velocity to be negative in this region. Indeed it is, as the intergranular air near the upper surface of the grains flows from the central region to the left-hand wall. In the vicinity of the left-hand wall $\partial\psi/\partial y$ is positive, hence the vertical component of the velocity is negative, and the air flows down the inside of the wall, exactly as would be expected.

Equations 8 and 9 are readily exploited to yield quantitative information on the flow, as indicated in Figures 7 and 8 which clearly conform to our qualitative predictions. It is significant to note that the velocity of the air is predicted to be non-zero at the boundaries of the stores, which differs from the typical no-slip boundary condition that applies to single-phase fluids such as air flowing adjacent to the roof of a grain silo. The reason for the slip boundary condition is that we are not in actual fact considering the very complicated flow of the air around individual grains, but the average velocity in some small region of the grain bulk. Even at the walls, the average velocity of the air in a region of grain close to the wall is different from zero.

Table 2. Effect of the number of nodes and *stabr* on convergence.

Mesh	Mid-point values	stabr		
		0.25	0.125	0.0625
11×11	$T(6,6)$	0.75399	0.73762	0.73132
	$W(6,6)$	0.17945	0.17932	0.17927
	$C(6,6)$	0.41255	0.41493	0.41617
	$dm(6,6)$	0.98068E-2	0.95819E-2	0.94642E-2
21×21	$T(11,11)$	0.70364	0.69963	0.69775
	$W(11,11)$	0.17909	0.17906	0.17904
	$C(11,11)$	0.41800	0.41800	0.41847
	$dm(11,11)$	0.93186E-2	0.93186E-2	0.92779E-2
41×41	$T(21,21)$	0.6891	0.68536	0.68458
	$W(21,21)$	0.17898	0.17896	0.17896
	$C(21,21)$	0.41922	0.41955	0.41971
	$dm(21,21)$	0.92279E-2	0.92016E-2	0.91885E-2

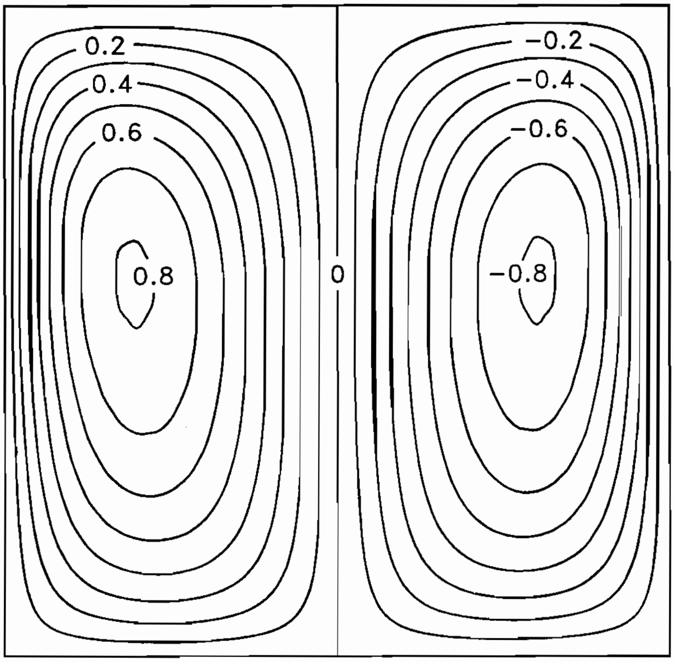

Figure 6. The stream function field.

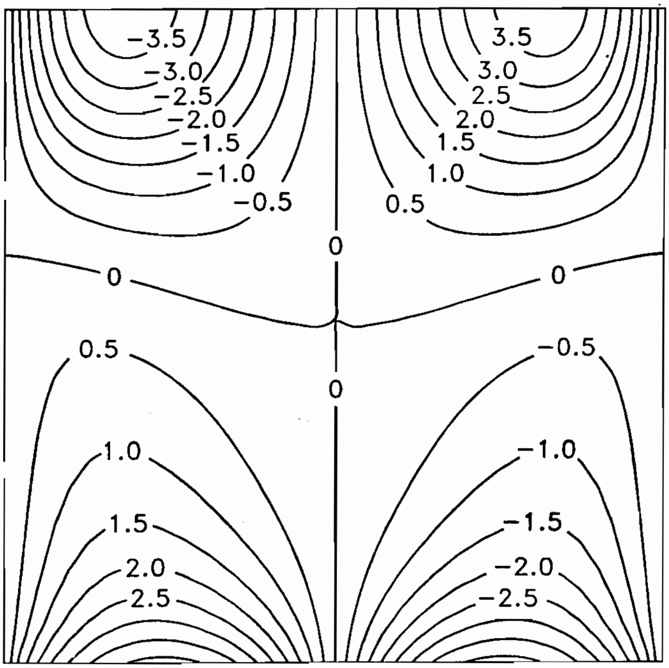

Figure 7. Horizontal component of velocity.

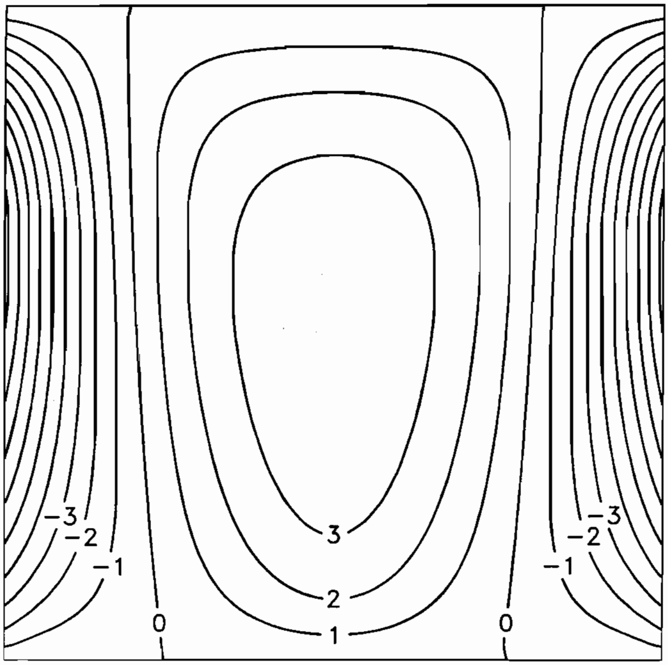

Figure 8. Vertical component of velocity.

Table 3. Values of variables at the mid-point of the store determined by the Richardson extrapolation.

Temperature, T	0.680
Moisture content, W	0.179
Pesticide concentration, C	0.420
Dry matter loss, dm	0.916E-2

The temperature distribution, shown in Figure 9, reflects in part the air flow field, in that the maximum temperature is displaced somewhat above the centre of the grain bulk. This is because heat is convected vertically upward by the flowing air stream.

The grain moisture distribution (Fig. 10) also reflects the effects of the flow field and the temperature field. We see, for example, that as air rises from the warm central region of the bulk to the upper surface the grain moisture content increases. We also see that the grain at the periphery of the bulk assumes a high moisture content. The peripheral grain moisture contents are calculated by linear extrapolation of the internal values as given by equation (73). Values of the grain moisture contents at the mid-points of the vertical sides and horizontal top of the store are given in Table 4.

It can be seen that the moisture content at the edges does not appear to converge when linear extrapolation is used. However, it should be observed that very small changes in the predicted moisture contents of the intergranular air give rise to very large changes in grain moisture content. When the reversion formula is used to calculate the peripheral moisture contents, the results are somewhat different but they appear to converge as shown in Table 5.

One method of ensuring that the peripheral values of the moisture contents are found more accurately is to make use of a non-uniform mesh, and to ensure that the grid points are very closely spaced near the boundaries. When a variable mesh size is used it must be realised that the discretisation of the spatial derivatives, such as those illustrated by equations (39) and (40), must be expressed in a different form as described by Thorpe (1996b).

Figures 11 and 12 show that the rates of pesticide decay and dry matter loss are the highest where the grain temperature is highest.

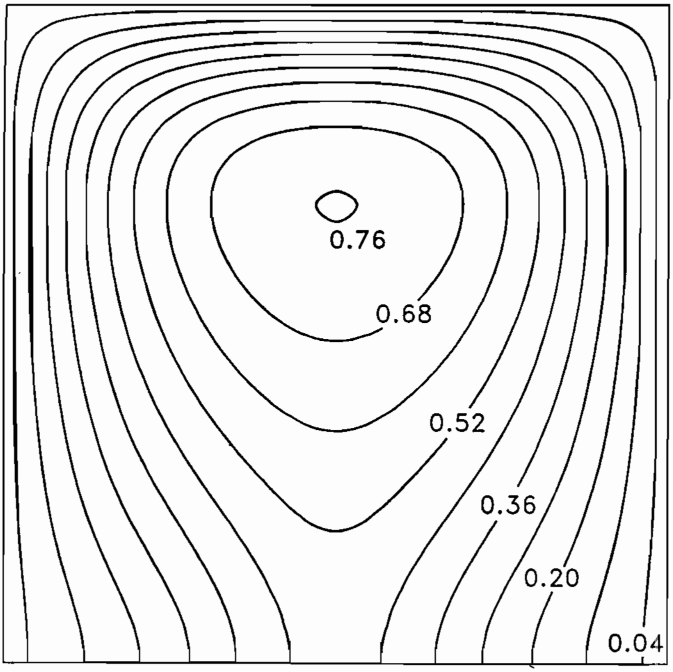

Figure 9. Temperature distribution in the bulk of grain.

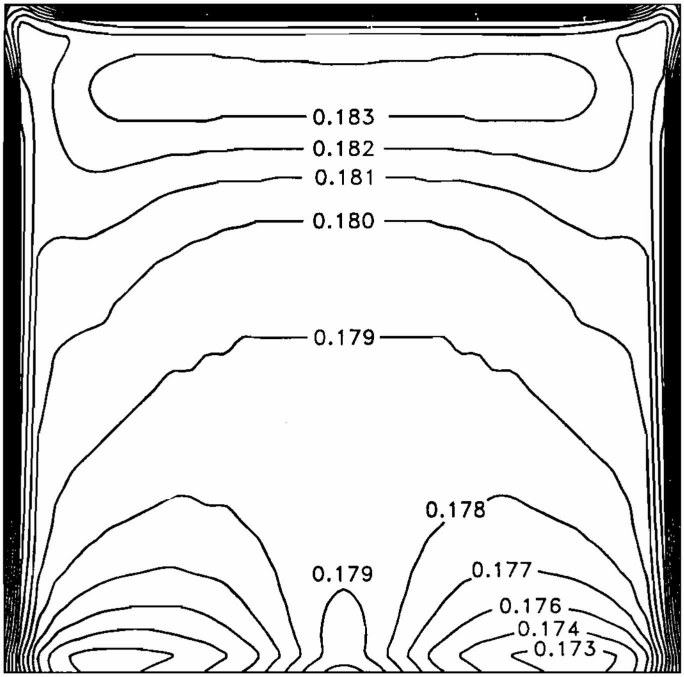

Figure 10. Moisture distribution in the grain.

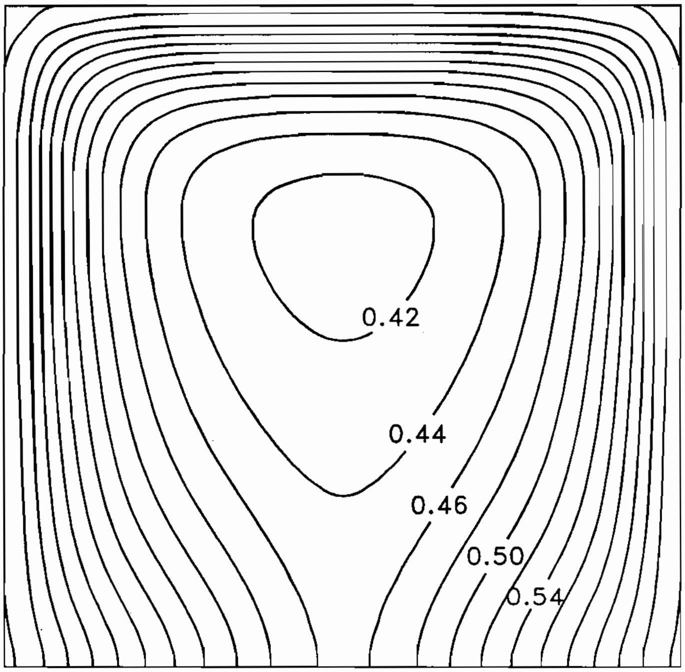

Figure 11. Normalised concentration of fenitrothion

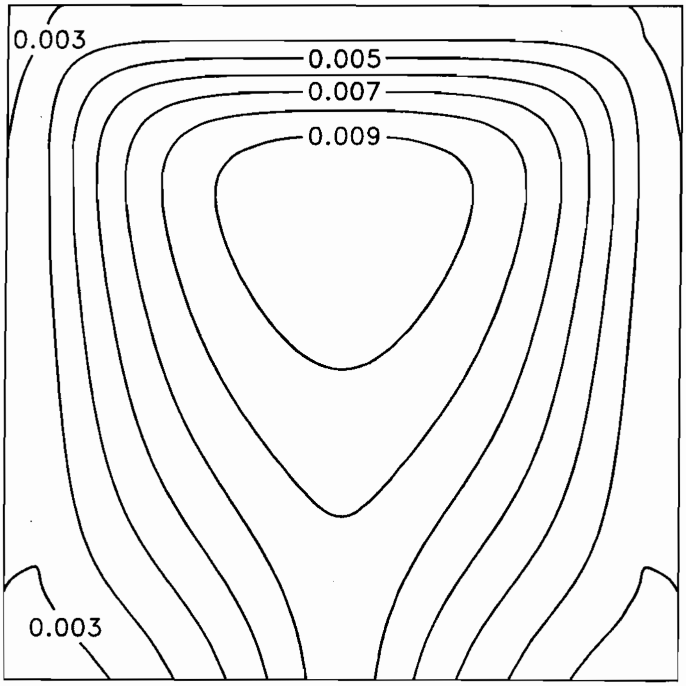

Figure 12. The distribution of dry matter loss.

Table 4. Mid-point peripheral values of grain moisture content, W, estimated by linear extrapolation.

	Mid-point values of W	
	Vertical sides	Horizontal top
$h_x = h_y = 0.1$	0.1819	0.1827
$h_x = h_y = 0.05$	0.1838	0.1838
$h_x = h_y = 0.025$	0.1866	0.1877

Table 5. Mid-point peripheral values of grain moisture content, W, calculated by the reversion formula, equation 71.

	Mid-point values of W	
	Vertical sides	Horizontal top
$h_x = h_y = 0.1$	0.2338	0.3011
$h_x = h_y = 0.05$	0.2046	0.2285
$h_x = h_y = 0.025$	0.2057	0.2087

Contemporary developments

The main purpose of this work is to illustrate the basic tools required to model moisture migration in bulks of respiring food grains. As a result, the geometry and boundary conditions have been kept very simple. In reality, grain bulks are three-dimensional entities, such as those found in circular silos or rectangular grain storage sheds. The stream function approach used in this paper cannot be applied directly to three-dimensional systems, but an analogous approach based on the vector potential may be used as outlined by Singh et al. (1993a) and Singh and Thorpe (1993b).

In the simple system treated in this paper the nodes at the boundary coincided with the physical boundary, and the mesh remain orthogonal; that is, the grid lines in the x and y directions remain at right angles to each other. This is not generally the case, but one way of approaching this problem is to retain an orthogonal mesh, and give special treatment to the boundary conditions. Carnahan et al. (1969) describe in some detail how this is accomplished. A second approach is that adopted by Singh and Thorpe (1993a,b) and Thorpe (1996b) in which the boundary nodes coincide with the physical periphery of the grain bulk, and a mathematical technique is used to transform the nonorthogonal mesh into one that is orthogonal. This method is effective in systems in which the grain rests against retaining walls on all sides of the grain bulk, as often occurs in grain storage sheds, and in some bunkers. It has also been used with some success by Thorpe (1996b) to simulate heat and moisture transfer in hopper bottomed grain silos. However, the method breaks down when there is no retaining wall, as occurs in the case when grain is simply heaped on the floor.

There is still a need to simulate the interaction of a grain bulk and the air space above it. This is important when fumigant is liberated in the headspace, say, where is likely to be mixed by turbulent buoyancy driven flows and then enter the grain bulk. Questions arise concerning the rate at which the fumigant enters the grain, and the distribution of the fumigant in the grains. Similar questions concerning moisture migration in grain stores containing a headspace also arise. To date, this problem has not been approached by stored grains technologists, although the generic problem of the interaction of heat and buoyancy driven fluid flows between a fluid layer and a porous medium has been addressed, mainly in the heat and mass transfer literature. Furthermore, these have generally been restricted to laminar flows. Two-dimensional systems have been studied by Singh et al. (1994) and Singh and Thorpe (1995), and the three- dimensional analogue has been investigated by Singh et al. (1993b). It is clear that there is a need to carry out both theoretical and applied studies on the interaction of phenomena that occur in the headspace and in the grain bulk.

Conclusions

This paper has presented equations that govern heat and moisture transfer in bulk stored grains, and a method of calculating the air flows that result from temperature gradients is described. The governing equations are expressed in dimensionless form and discretised on a uniform finite difference mesh. The discretised equations are solved by an established alternating direction implicit method which is described in detail. Procedures required to test the convergence of the solution are outlined, and the stream function, velocity, temperature, moisture content, pesticide concentration, and dry matter loss fields are presented. It is noted that slightly different approaches are required when grain bulks assume arbitrary shapes, and it is pointed out that the interaction of the air space above the grain and the bulk remains an outstanding problem.

Acknowledgments

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Nomenclature

$a_i, b_i, c_i, d_i,$	Coefficients in equation 47.
A_r	Aspect ratio, *L/H*
B	Pesticide specific constant in equation 83.
c	Specific heat, J/kg/K.
C	Concentration of pesticide, kg/m^3
c_l	Specific heat of water, kg/m^3
c_a	Specific heat of air, J/kg/K.
$\mathrm{C_{tp1}, C_{tp2}, C_{tp3}, \ldots}$	Coefficients in equation 49.
$\mathrm{C_{p1}, C_{p2}, C_{p3}, \ldots}$	Coefficients in equation 59.
$\mathrm{C_{w1}, C_{w2}, C_{w3}, \ldots}$	Coefficients in the isotherm equation, 67.
D_{eff}	Effective diffusivity of water vapour through grain, m^2/s.
dm	Dry matter loss.
$dmin$	Minimum grid spacing.
$dtreal$	Integration time step in real time, s.
$f_1(y), f_2(y)$	Spatial functions of temperature, *T*.
g	Gravity vector, m/s^2
g_y	Vertical component of gravity vector, m/s^2
H	Height of grain bulk, m.
h	Defined by h_s/h_v-1
h_o	A grain specific constant defined by equation 72.
h_s	Differential heat of sorption, J/kg.
h_t	Integration time step, s.
h_v	Heat of vaporisation of free water, J/kg
H_W	Integral heat of wetting of grain, J/kg
h_x	Internodal distance in the *x*-direction, m.
h_y	Internodal distance in the *y*-direction, m.
i,j	The (i,j)th node.
K	Permeability of grain bulk, m.
K_{eff}	Effective thermal conductivity of grain bulk, W/m/K
k_r	Reaction rate coefficient, 1/s.
L	Width of grain bulk, m.
M	Moisture content, % wet basis.
m,n	Number of nodes in *x* and *y* directions.
m_f	A grain specific constant in the isotherm reversion equation 71.
M_M	Moisture modifier in equation 75
M_T	Temperature modifier in equation 75
p	Pressure, Pa.
p_o	A constant in relative humidity equation 64, Pa.
p_v	Vapour pressure of water, Pa.
p_s	Saturation vapour pressure of water, Pa.
q	Heat flux, W/m^2
q_o	Heat of respiration of grain, J/kg
Q_r	Volumetric heat of respiration, W/m^3

r	Relative humidity.
Ra^*	Modified Rayleigh number, defined by equation 33.
S_i	Volumetric rate of mass generation, kg/s/m^3
$stabr$	A stability factor.
T	Temperature, K.
T_o	A temperature imposed on one wall of the grain store, K.
t	Time, s.
$t_l, t_{mx}, t_{my}, \ldots$	Coefficients in equations 42.
t_p	Physiological time, s.
t^*	A reference time, s.
$t^*_{1/2}$	Pesticide specific constant in equation 87, s.
u	Horizontal component of velocity, m/s
u^*	Reference horizontal velocity, m/s.
v_a	Velocity vector, m/s
v	Vertical component of velocity, m/s.
v^*	Reference vertical velocity, m/s.
w	Humidity of air, kg/kg
W	Grain moisture content, kg/kg
W_o	A grain specific constant.
x,y	Space coordinates, m.

Greek symbols

β	Volumetric coefficient expansion of air, 1/K.
β_i	Leading coefficient of *i*th equation in the Thomas algorithm.
γ	Refers to the intergranular air.
δ_i	Right hand side of ith equation in the Thomas algorithm.
ε	Volume fraction.
μ	Viscosity of air, Pa s/m
σ	Refers to the grains.
ψ	Stream function, m^2/s.
ψ_{err}	Error bound on dimensionless stream function.
ψ^*	Reference stream function, m^2/s.
ρ	Density, kg/m^3.
ρ_a	Density of air, kg/m^3
$\langle \rho c_p \rangle_a$	Mass weighted specific heat, J/K/m^3
ΔT	Temperature difference across the grain bulk, K.

Superscripts

*	Refers to values after a notional half time step.
**	Refers to values at the end of an integration time step.
p	Refers to the *p*th time step.
'	Denotes dimensionless values.

References

Carnahan, B., Luther, H.A., and Wilkes, J.O. 1969. Applied numerical methods. New York, Wiley.

Casada, M.E. and Young, J.H. 1994. Model for heat and moisture transfer in arbitrarily shaped two-dimensional porous media. Transactions of the American Society of Agricultural Engineers, 37, 1927–1938.

Darcy, H.P.G. 1856. Les fontaines publique de la ville de Dijon. Exposition et application a suivre et des formules a employer dans les questions de distribution d'eau. Victor Delamont.

Desmarchelier, J.M. and Bengston, M. 1979. Chemical residues of newer grain protectants. In: Evans, D.E., ed., Australian contributions to the symposium on the protection of grain against damage during storage, Moscow 1978. Canberra, CSIRO Division of Entomology, 108–115.

de Vahl Davis, G. 1976. Program FRECON for the numerical solution of free convection in a rectangular cavity. Sydney, University of New South Wales, School of Mechanical and Industrial Engineering, Report 1976/FMT/1.

— 1986. Numerical methods in engineering and science. London, Allen and Unwin..

Dona, C.L.G. and Stewart, W.E. 1988. Numerical analysis of natural convection heat transfer in stored high moisture corn. Journal of Agricultural Engineering Research, 40, 275–284.

Freer, M.W., Siebenmorgan, T.J., Couvillion, R.R., and Loewer, O.J. 1990. Modeling temperature and moisture content changes in bunker-stored rice. Transactions of the American Society of Agricultural Engineers, 33, 211–220.

Griffith, H.J. 1964. Bulk storage of grain: a summary of factors governing control of deterioration. Melbourne, Australia, CSIRO Division of Mechanical Engineering, Report ED8.

Hunter, A.J. 1983. Pressure difference across an aerated seed bulk for some common duct and store cross-sections. Journal of Agricultural Engineering Research, 28, 437–450.

— 1987. An isostere equation for some common seeds. Journal of Agricultural Engineering Research, 24, 219–232.

Khankari, K.K., Morey, R.V. and Patankar, S.V. 1993a. Application of a numerical model for prediction of moisture migration in stored grains. St Joseph, Michigan, American Society of Agricultural Engineers, ASAE Paper No. 93-6018.

— 1994. Mathematical model for moisture diffusion in stored grain due to temperature gradients. Transactions of the American Society of Agricultural Engineers, 37, 1591–1604.

Khankari, K.K., Patankar, S.V., and Morey, R.V. 1993b. A mathematical model for natural convection moisture migration in stored grain. St Joseph, Michigan, American Society of Agricultural Engineers, ASAE Paper No. 93-6017.

Lacey, J., Hamer, A., and Magan, N. 1994. Respiration and losses in stored wheat under different environmental conditions. In: Highley, E., Wright, E.J., Banks, H.J. and Champ, B.R., ed., Stored Product Protection. Proceedings of the 6th International Working Conference on Stored-product Protection. Wallingford, U.K., CAB International, 1007–1013.

Nguyen, T.V. 1987. Natural convection in stored grains—a simulation study. Drying Technology, 5, 541–560.

Peaceman, D.W. and Rachford, H.H. 1955. The numerical solution of parabolic and elliptic differential equations. Journal of the Society for Industrial and Applied Mathematics, 3, 28–41.

Pixton, S.W. and Griffith, H.J. 1971. Diffusion of moisture through grain. Journal of Stored Products Research, 7, 133–152.

Roache, P.J. 1972. Computational fluid dynamics. Albuquerque, New Mexico, Hermosa.

Seib, P.A., Pfost, H.B., Sukaboi, A., Rao, V.S., and Burroughs, R.B. 1980. Spoilage of rough rice as measured by carbon dioxide evolution. Proceedings of the Third ASEAN Technical Seminar on Grain Post-Harvest Technology, Kuala Lumpur.

Singh, A.K. and Thorpe, G.R. 1993a. The application of a grid generation technique to the numerical modelling of heat and moisture movement in peaked bulks of grain. Journal of Food Process Engineering, 16, 127–145.

— 1993b. A solution procedure for three-dimensional free convective flow in peaked bulks of grain. Journal of Stored Products Research, 28, 221–235.

— 1995. Natural convection in a confined fluid overlying a porous layer—a comparison study of different models. Indian Journal of Pure and Applied Mathematics, 26, 81–95.

Singh, A.K., Leonardi, E and Thorpe, G.R. 1993a. A solution procedure for the equations governing three-dimensional free convection in bulk stored grains. Transactions of the American Society of Agricultural Engineers, 36, 1159–1173.

— 1993b. Three-dimensional natural convection in a confined fluid overlying a porous layer. Journal of Heat Transfer, 115, 631–638

Singh, A.K., Moore, G.A., and Thorpe, G.R. 1994. Effect of the ratio of the depths of fluid and porous layers on free convective flow in a tall rectangular cavity. Paper 3/35-G presented at the 12th National Heat and Mass Transfer Conference, Bombay 1994.

Thomas, L.H 1949. Elliptic problems in linear equations over a network. Watson Scientific Computing Laboratory, Columbia University.

Thompson, T.L. 1972. Temporary storage of high moisture shelled corn using continuous aeration. Transactions of the American Society of Agricultural Engineers, 15, 333–337.

Thorpe, G.R. 1980. Moisture diffusion through bulk grain. Journal of Stored Products Research, 17, 39–42.

— 1981. Moisture diffusion through bulk grain subjected to a temperature gradient. Journal of Stored Products Research, 18, 9–12.

— 1996a. More complete mathematical descriptions of heat and moisture transfer in ventilated bulks of respiring grains. Agricultural Engineering Australia, Journal of the Society for Engineering in Agriculture, in press.

— 1996b. Modelling ecosystems in conical bottomed farm grain silos. Ecological Modelling, in press.

Thorpe, G.R., Ochoa, J.A., and Whitaker, S. 1991a. The diffusion of moisture in food grains. I The development of a mass transfer equation. Journal of Stored Products Research, 27, 1–9.

— 1991b. The diffusion of moisture in food grains. II Estimation of the effective thermal diffusivity. Journal of Stored Products Research, 27, 11–30.

Whitaker, S. 1981. Introduction to fluid mechanics. Malabar, Florida, R.E. Krieger Publishing Co.

Appendix 1 Solution of a set of linear equations that has a tridiagonal coefficient matrix

When we solved the thermal energy balance and stream function equations we had to solve sets of simultaneous equations that have a tridiagonal coefficient matrix. For example, when we are solving equation (57) for the intermediate values of ψ^* implicitly in the x-direction we have for values of $j = 2,3,4,\ldots, n-2, n-1$.

$$\begin{pmatrix} b_1 & c_1 & & & & & \\ a_2 & b_2 & c_2 & & & & \\ & a_3 & b_3 & c_3 & & & \\ & & & & & & \\ & & a_i & b_i & c_i & & \\ & & & & & & \\ & & & & a_{M-3} & b_{M-3} & c_{M-3} \\ & & & & & a_{M-2} & b_{M-2} \end{pmatrix} \begin{pmatrix} \psi_2^* \\ \psi_3^* \\ \psi_4^* \\ \\ \psi_{i+1}^* \\ \\ \psi_{M-2}^* \\ \psi_{M-1}^* \end{pmatrix} = \begin{pmatrix} d_1 \\ d_2 \\ d_3 \\ \\ d_i \\ \\ d_{M-3} \\ d_{M-2} \end{pmatrix} \tag{A1.1}$$

in which

$$a_i = -cp1; \quad i = 2, M-2$$
$$b_i = cp2; \quad i = 1, M-2$$
$$c_i = -cp1; \quad i = 1, M-3$$
$$d_i = cp3 * \psi_{i+1,j-1} + cp4 * \psi_{i+1,j} + cp3 * \psi_{i+1,j+1} + cp7 * \left(T_{i+2}^{p+1} - T_i^{p+1}\right)$$
$$d_1 = d_1 + cp1 * \psi_1$$
$$d_{M-2} = d_{M-2} + cp1 * \psi_M$$

The equations are solved by manipulating the above matrix so that it has only two bands of coefficients, thus

$$\begin{bmatrix} \beta_1 & c_1 & & & & \\ & \beta_2 & c_2 & & & \\ & & & & & \\ & & \beta_i & c_i & & \\ & & & & & \\ & & & & \beta_{M-3} & c_{M-3} \\ & & & & & \beta_{M-2} \end{bmatrix} \begin{bmatrix} \psi_2 \\ \psi_3 \\ \\ \psi_{i+1} \\ \\ \psi_{M-2} \\ \psi_{M-1} \end{bmatrix} = \begin{bmatrix} \delta_1 \\ \delta_2 \\ \\ \delta_i \\ \\ \delta_{M-3} \\ \delta M-2 \end{bmatrix} \tag{A1.2}$$

in which we have omitted the asterisk denoting the value at the half time step. After we have transformed the equations into the above form it is a simple matter to determine all of the updated stream functions by back substitution, i.e.

$$\psi_{M-1} = \delta_{M-2} / \beta_{M-2} \tag{A1.3}$$

Using this value of ψ_{M-1} in the penultimate equation enables us to find ψ_{M-2} thus

$$\psi_{M-2} = \left(\delta_{M-3} - c_{M-3}\psi_{M-1}\right) / \beta_{M-3} \tag{A1.4}$$

In general the stream function, ψ_i, of the ith node is given by

$$\psi_i = \left(\delta_{i-1} - c_{i-1}\psi_{i+1}\right) / \beta_{i-1} \tag{A1.5}$$

Examination of the original set of equations indicates that the first equation is already in the desired form with

$$\beta_1 = b_1 \text{ and } \delta_1 = d_1 \tag{A1.6}$$

The first two equations may then be written as

$$\beta_1\psi_2 + c_1\psi_3 = \delta_1 \tag{A1.7}$$
$$a_2\psi_2 + b_2\psi_3 + c_2\psi_4 = d_2 \tag{A1.8}$$

The second equation may be manipulated into the desired form by eliminating the term involving a_2 which is accomplished by multiplying the first equation by a_2/β_1 and subtracting the result from the second equation, i.e.

$$\left(b_2 - \frac{c_1 a_2}{\beta_1}\right)\psi_2 + c_2\psi_3 = d_2 - \frac{\delta_1 a_2}{\beta_1} \tag{A1.9}$$

Hence, if we define

$$\beta_2 = b_2 - \frac{c_1 a_2}{\beta_1} \tag{A1.10}$$

and

$$\delta_2 = d_2 - \frac{\delta_1 a_2}{\beta_1} \tag{A1.11}$$

the second equation becomes

$$\beta_2 x_2 + c_2 x_3 = \delta_2 \tag{A1.12}$$

which is of the desired form. We can now proceed to eliminate the remaining leading coefficients in an exactly analogous manner. For example,

$$\beta_3 = b_3 - \frac{c_2 a_3}{\beta_2} \tag{A1.13}$$

and

$$\delta_3 = d_3 - \frac{\delta_2 a_3}{\beta_2} \tag{A1.14}$$

For the general *i*th node these equations are

$$\beta_1 = b_i - \frac{c_{i-1} a_i}{\beta_{i-1}} \tag{A1.15}$$

and

$$\delta_i = d_i - \frac{\delta_{i-1} a_i}{\beta_{i-1}} \tag{A1.16}$$

We have developed the algorithm, which is sometimes known as the Thomas algorithm after Thomas (1949), specifically to solve for the interior stream function $\psi_2, \psi_3, \ldots, \psi_{M-2}, \psi_{M-1}$. In general we may wish to solve for the NN unknowns $x_1, x_2, \ldots, x_{NN-1}, x_{NN}$. In this case the system of equations to be solved is

$$\begin{bmatrix} \beta_1 & c_1 & & & \\ & \beta_2 & c_2 & & \\ & & \beta_i & ci & \\ & & & \beta_{NN-1} & c_{NN-1} \\ & & & & \beta_{NN} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_i \\ x_{NN-1} \\ x_{NN} \end{bmatrix} = \begin{bmatrix} \delta_1 \\ \delta_2 \\ \delta_i \\ \delta_{NX-3} \\ \delta_{NN} \end{bmatrix} \tag{A1.17}$$

The Thomas algorithm may be formulated in the form shown in Figure A1.1

A FORTRAN equivalent of the Thomas algorithm is given in Figure A1.2.

```
ALGORITHM THOMAS
This algorithm represents a scheme to solve a set of linear equations, the
coefficients of which form a tridiagonal matrix.

INPUT: Number of equations, NN.
       Coefficients $a_i, b_i$ and $c_i$
       Values on right hand side of equation, $d_i$
           For $i=2,3,\ldots,NN$, do:
               $\varepsilon = a_i/\beta_{i-1}$
               $\beta_i = b_i - \varepsilon c_{i-1}$
               $\delta_i = d_i - \varepsilon\delta_{i-1}$
           End
               $x_{NN} = \delta_{NN}/\beta_{NN}$
           For $i=2,3,\ldots,NN$, do:
               $j=NN+1-i$
               $x_j = (\delta_j - c_j x_{j+1})/\beta_j$
           End
           OUTPUT: $x_j$. Stop
END THOMAS
```

Figure A1.1. The Thomas (1949) algorithm

```
      Subroutine thomas(nn)
*
*     This subroutine solves tridiagonal system of equations
*
*     There are nn equations and the coefficients are
*                   a(2),a(3),.......,a(nn-1),a(nn)
*                   b(1),b(2),.......,b(nn-1),b(nn)
*                   c(1),c(2),.......,c(nn-2),c(nn-1)
*
*     The right hand side of the equations is
*                   d(1),d(2),.......,d(nn-1),d(nn)
*
*     The nn unknowns are
*                   xx(1),xx(2),....xx(nn-1),xx(nn).
*
*
*     Note that the dimension and common statements are
*     contained in the include statement.
*
      include 'mm.inc'
      beta(1)=b(1)
      delta(1)=d(1)
      do 10 i=2,nn
      eps=a(i)/beta(i-1)
      beta(i)=b(i)-eps*c(i-1)
   10 delta(i)=d(i)-eps*delta(i-1)
      xx(nn)=delta(nn)/beta(nn)
      do 20 i=2,nn
      j=nn+1-i
   20 xx(j)=(delta(j)-c(j)*xx(j+1))/beta(j)
      return
      end
```

Figure A1.2. A FORTRAN listing of the Thomas (1949) algorithm.

Appendix 2 Physical and chemical properties required in the simulations

In this appendix, the permeabilities of grains and constants associated with Hunter's (1987) isotherm equation are presented, together with constants used in Desmarchelier and Bengston's (1979) rate of decay of pesticide equations.

Table A2.1. The permeabilities of cereal and other grains (multiply by 10^{-8}). Calculated from data presented by Hunter (1983).

Alfalfa, 7%	0.111	Oats, 13%	0.997
Barley, 12%	1.08	Pea beans, 15%	4.16
Clover, alsike, dry	0.0663	Peanuts in shell, 4.4%	62.4
Clover, crimson, 8%	0.173	Popcorn, shelled, yellow pearl type, 12%	1.73
Clover, red, dry	0.103	Popcorn, white rice type, 14%	1.02
Corn, clean ear, lot 2, 16%	292.0	Rice, rough, 13%	0.927
Corn, ear, lot 1, as harvested, 20%	14.1	Sericea Lespedeza, 13%	0.111
Corn, shelled, 12.4%	2.52	Sorghum, grain, 13%	0.679
Fescue, 11%	0.383	Soybeans, 10%	2.80
Flax, 11%	0.174	Wheat, 11%	0.578
Grass seed, broome, 10.5%	1.18	Linseed, glenelg, 7.9%	0.121
Grass seed, rescue, 13%	2.55	Rapeseed, tower, 5.7%	0.255
Kobe, Lespedeza, 15.5%	0.572	Safflower, gila, 5.9%	1.50
Lupin seed, blue, 7.5%	3.54	Sunflower, commercial crushing, 7.9%	1.14

Table A2.2. Parameters for use in the isostere equations 67 and 68 (after Hunter 1987).

Commodity	c_{w1}	c_{w2}	c_{w3}	c_{w4}	c_{w5}	p_o	m_f
Barley	-0.26249	4.6097	-0.00910	1.2485	8.4783	6.9176×10^5	1.7788
Corn	-0.50160	5.6323	-0.09832	3.1041	11.4758	1.1584×10^5	3.7880
Peanuts	-0.30395	7.4899	-0.07120	3.9970	11.2951	1.2119×10^5	4.4464
Rapeseed	-0.22976	10.5894	-0.01706	2.4461	7.3356	6.5175×10^6	2.6469
Rice	-0.29907	5.1427	-0.14485	3.8106	12.0556	9.7481×10^5	4.9670
Sorghum	-0.17662	5.1872	-0.06118	4.2819	56.3811	7.4031×10^7	9.7154
Soybeans	-0.22297	8.1659	-0.04524	2.8957	10.3580	8.5377×10^6	5.6651
Sunflower	-0.27797	12.6731	-0.04931	4.4794	6.0718	5.0304×10^6	3.0445
Wheat	-0.21133	4.7403	-0.03483	2.2610	17.6706	4.4571×10^6	4.9682

Table A2.3. Chemical reaction constants for the decay of chemical pesticides applied to stored grains (after Desmarchelier and Bengston 1979).

Pesticide	$t^*_{1/2}$ (weeks)	B (per degree C)	Pesticide	$t^*_{1/2}$ (weeks)	B (per degree C)
Fenitrothion	14	0.036	Methacrifos	8	0.055
Bioresmethrin	24	0.033	Malathion	12	0.05
Bioresmethrin*	38	0.031	Chlorpyrifos-methyl	19	0.04
d-Fenothrin	38	0.029	Carbaryl	21	0.031
d-Fenothrin*	40	0.029	Pirimiphos-methyl	70	small
Pyrethrum*	55	0.022	Pyrethrum	34	not known

*Plus the antioxidant piperonyl butoxide at 20 mg/kg.

Analysis of Continuous-flow Grain Dryers

F.W. Bakker-Arkema*, M.D. Montross*, Liu Qiang* and D.E. Maier†

Abstract

The high-temperature continuous-flow dryer is the prevalent dryer type in the major grain-producing countries. The choice of a particular model is frequently based on the initial cost, rather than on technical factors such as energy efficiency and grain quality. This has led at times to the employment of low-quality dryers, and to the production of inferior-grade grain and the consumption of excessive fossil-fuel energy. This paper shows that the dryer-manufacturing industry currently markets reasonably-priced, energy-efficient dryers which are able to produce excellent quality grain.

Crossflow, mixed-flow, and concurrent-flow are at present the primary high-temperature dryer types. Simulation modelling is routinely used today in the industry for analysis and design, resulting in their improved grain-quality and energy-efficiency characteristics.

The modern crossflow dryer is suitable for drying maize as feed; it is less expensive than mixed-flow and concurrent-flow dryers. For the drying of rice (and food maize), mixed-flow and concurrent-flow dryers are recommended because of their superior grain-quality characteristics. Of these, the concurrent-flow models have, in general, the best energy efficiency.

Several unconventional high-temperature dryers are occasionally used commercially for the drying of grains. Included in this group are the steam, the rotary, and the fluidised-bed dryers. Although each of these dryer types has certain advantages, their high initial and operating costs have thus far prevented market penetration.

DRYING is one of the essential steps in the postharvest technology of grains, especially of maize and rice which almost always require mechanical drying. Grains are dried on the farm and off the farm, depending mainly on the country of production. For instance, in the USA the bulk of the maize is farm-dried; in France, almost all the maize is dried off the farm at local grain depots. This paper assesses the state-of-the-art of off-farm grain drying, and its specific needs for design improvement.

Off-farm dryers are considered to be of the high-temperature continuous-flow type, and to have a capacity of at least 12.5 t/hour. Usually, this excludes all but the largest in-bin drying systems.

The main off-farm dryer types are: (1) the *crossflow* dryer, (2) the *mixed-flow* dryer, and (3) the *concurrent-flow/counterflow* dryer (see Fig. 1). Each dryer type is able to dry maize rice and other grains. Each type has specific advantages and disadvantages. The dryer-selection criteria differ somewhat from country to country, and from crop to crop. For instance, a 1995 Chinese tender for the purchase of a series of high-temperature maize dryers ranks and weights the dryer-characteristics as follows (CNIIEC 1995): (1) initial price—60%, (2) energy consumption—5%, (3) kernel breakage—5%, (4) moisture gradient at dryer exit—5%, (5) life expectancy—4%, (6) dryer type—3%, (7) increase in stress-cracked kernels—3%, (8) level of automatic control—3%, (9) kernel-temperature at dryer exit—2%, (10) service record— 10%. Thus, the price factor (60%) far outweighs the technical factors (30%) and the service factor (10%), and the least expensive dryer is likely to be selected for the drying of maize in northeastern China, regardless of the model's grain-quality and energy-efficiency characteristics. In general, the *weighting scale* of the various economic/technical/service factors is decisive in the selection of the high-temperature dryer at a grain facility.

Analyses of dryer designs are today routinely conducted by computer simulation; models of the major dryer types have been available in the literature for a decade (Brooker et al. 1992). Simulation modelling has not led to revolutionary new dryer designs but has resulted in evolutionary improvement of existing dryer types. This is best illustrated by comparing the energy-efficiency and grain-quality characteristics of

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1970-vintage crossflow dryers and 1990 models: significant improvement has occurred with respect to both dryer-quality parameters.

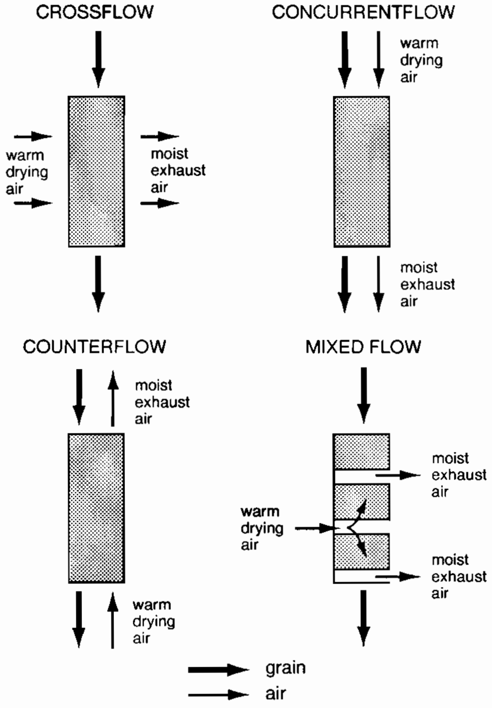

Figure 1. Schematics of the four major types of high-temperature grain dryers: crossflow, concurrent-flow, counterflow and mixed flow.

Grain Moisture Content

High-temperature grain dryers are commonly rated for capacity on the basis of 10-point moisture removal from maize, i.e. from 25 to 15% moisture content (wet basis). No mention is made that the quoted moistures are *average* moisture contents. It is assumed that the variation in moisture content of the maize kernels entering a dryer is small. However, this is not the case, as is shown in Table 1 in which the average moisture content, the moisture content range, and the standard deviation of 50 kernels on an ear are tabulated for the tip/middle/butt kernels of an early and a late maize variety. The difference in the moisture content of the wettest and driest kernels is 27.5% for the early variety, and 32.0% for the late variety. The tip kernels are on average about 5% drier than the butt kernels. Just after high-temperature drying, the difference in moisture content between the kernels is still large, as the data in Table 2 show.

The moisture range narrows and the standard deviation diminishes during storage (see Tables 3 and 4).

Dryer Types

Crossflow dryers

Crossflow dryers are the most popular dryer type in North America. They have a plenum surrounded by a relatively thin grain column; hot air traverses the grain perpendicular to the downward flow of the grain. Cooling of grain takes place in the bottom section of the grain column. Crossflow dryers are often called tower or column dryers.

Crossflow dryers do not dry grain uniformly. Significant moisture and temperature gradients exist across the grain column at the moment the drying process is discontinued. During the cooling cycle the degree of non-uniformity decreases, but a definite moisture differential among the kernels still exists when the grain leaves the dryer, notwithstanding the fact that the average moisture content may have reached the desired level.

Recent design advances in crossflow dryers have improved the grain-quality characteristics of this model type. *Airflow reversal* has been incorporated in some crossflow dryers in order to offset the moisture and temperature differentials in the grain column. *Grain inverters* turn the overheated grain at the air-inlet side to the air-exhaust side of the column, and thus reduce overdrying/overheating. A new feature added recently to the basic crossflow design—tempering—improves the quality of crossflow-dried grain.

Modern crossflow dryers with air recycle, grain tempering, and grain inverting are able to dry wet grain at high throughput and moderate energy efficiency, and can produce dried grain with moderate moisture differentials among the kernels. For feed grain, the crossflow dryer is a good choice.

In-depth analyses of crossflow-dryer designs can be made by employing a differential-equation-based model of the following type (Brooker et al. 1992):

$$\frac{\partial T}{\partial x} = \frac{-h'a}{G_a c_a + G_a c_v W}(T-\theta) \qquad \textbf{(1)}$$

$$\frac{\partial \theta}{\partial y} = \frac{h'a}{G_p c_p + G_p c_w \overline{M}}(T-\theta) + \frac{h_{fg} + c_v(T-\theta)}{G_p c_p + G_p c_w \overline{M}} G_a \frac{\partial W}{\partial x} \qquad \textbf{(2)}$$

$$\frac{\partial W}{\partial x} = -\frac{G_p}{G_a}\frac{\partial \overline{M}}{\partial y} \qquad \textbf{(3)}$$

$$\frac{\partial \overline{M}}{\partial t} = \text{a single-kernel drying equation} \qquad \textbf{(4)}$$

Table 1. Average kernel moisture content (%), moisture content range, and standard deviation of 50 kernels on an ear of an early and late variety maize in the midwestern USA.

Location	Late variety			Early variety		
	Average moisture content	Moisture content range	Standard deviation	Average moisture content.	Moisture content range	Standard deviation
Tip	25.0	8.5–36.5	6.20	20.8	15.5–32.0	3.40
Middle	28.3	10.5–38.0	6.44	24.3	15.5–35.0	5.04
Butt	30.4	12.5–40.5	9.03	26.1	10.0–37.5	6.88

Table 2. Standard deviation and moisture content (%) range of maize dried in a commercial crossflow dryer.

Inlet			Outlet		
Average moisture content	Standard deviation	Moisture content range	Average moisture content	Standard deviation	Moisture content range
22.7	4.51	12.5–34.5	14.5	3.17	8.5–24.5
21.8	3.80	12.0–33.0	13.9	3.44	8.0–28.5
21.0	3.13	14.0–31.0	12.7	4.23	7.0–31.0

Table 3. Short-term change in the moisture content (%) range and standard deviation of maize after crossflow drying (average m.c. = 14.5%).

Time (hours)	Moisture content range	Standard deviation
0	9.0–30.5	3.75
3	10.0–21.5	2.63
20	10.0–24.5	2.38
27	10.0–18.5	2.08
45	11.0–17.5	1.74
50	9.5–16.5	1.63
68	10.0–17.5	1.50
92	11.0–17.0	1.38
114	10.5–16.0	1.21
122	11.5–16.5	1.24
450	11.5–16.5	1.03

Table 4. Long-term change in the average moisture content (%), moisture content range, and standard deviation of maize stored in a 1500 t bin under Michigan conditions.

Date	Average moisture content	Moisture content range	Standard deviation
1 Nov. 93–30 Nov. 93	14.5	9.0–30.5	3.75
10 Jan. 94	16.4	11.0–18.5	1.30
17 Feb. 94	15.2	11.0–17.5	1.06
22 Mar. 94	13.6	10.0–15.0	1.15
25 Apr. 94	13.2	10.5–15.5	1.07

Solution of the model for a specific crossflow dryer establishes the approximate values of such parameters as: (1) the grain retention time, (2) the minimum and maximum kernel temperatures, (3) the minimum and maximum kernel moistures, and (4) the energy efficiency.

Airflow reversal, tempering, and grain inverting were first investigated by simulation (Pierce and Thompson 1981), and have subsequently been applied successfully to commercial crossflow dryer designs (FFI Corporation, Indianapolis, Indiana, personal communication, 1995).

Concurrent-flow dryers

The *concurrent-flow* dryer design is relatively new; it has one or more concurrent-flow drying sections, and one counterflow cooling section. In a concurrent-flow section, the grain and drying air flow in the same direction, in the counterflow cooler in the opposite direction.

With the exception of a small, one-stage on-farm concurrent-flow model, concurrent-flow dryers have two or three concurrent-flow drying zones. A tempering zone is located between successive drying sections. The ability to employ different air temperatures in the different stages is an inherent advantage of this dryer type.

A concurrent-flow/counterflow dryer has alternate concurrent-flow and counterflow drying sections. Dryers of this type are of Chinese design, and usually are multi-tower units. Because of the relatively poor grain-quality characteristics of this dryer, it is not further discussed.

The most distinguishing feature of the concurrent-flow dryer is the *uniformity of the drying process.* Every kernel undergoes the same heating/drying/tempering/cooling treatment, unlike in crossflow and mixed-flow dryers. The temperature of the drying air is much higher than in the other dryers because the wet grain is subjected to the hot drying air not for hours (crossflow dryers) or minutes (mixed-flow dryers), but only seconds. Therefore, the grain does not approach the temperature of the drying air, as it does in the other dryer types.

The uniform, relatively gentle drying and cooling processes in concurrent-flow dryers, and the built-in tempering treatment(s), result in dried grain of superior quality. The percentage of stress-cracked kernels in concurrent-flow dryers is less than in mixed-flow dried and in crossflow-dried grain.

A characteristic feature of the concurrent-flow dryer is its use of *ultra high drying-air temperatures,* as high as 200–285°C for maize. The high evaporative and sensible heat loads at the inlet of each drying section prevent the grain kernels from reaching temperatures above 60–80°C (depending on the type of grain).

Precleaning of the wet grain (recommended for all high-temperature dryers) is essential for concurrent-flow dryers because of the high operating temperatures.

Most dryer experts agree that concurrent-flow grain dryers are theoretically, technically, and operationally superior to crossflow and mixed-flow dryers, with respect to grain-quality characteristics and fuel efficiency. However, the high-technology aspects, general misunderstanding, and relatively-high initial cost are definite disadvantages of this dryer type.

The equations for the concurrent-flow and crossflow drying models appear superficially to be similar but close scrutiny reveals significant differences (Brooker et al. 1992). The crossflow model consists of a set of partial differential equations, while the concurrent-flow dryer is represented by a set of ordinary differential equations:

$$\frac{dT}{dx} = \frac{-h'a}{G_a c_a + G_a c_v W}(T-\theta) \tag{5}$$

$$\frac{d\theta}{dx} = \frac{h'a}{G_p c_p + G_p c_w \overline{M}}(T-\theta) - \frac{h_{fg} + c_v(T-\theta)}{G_p c_p + G_p c_w \overline{M}} G_a \frac{dW}{dx} \tag{6}$$

$$\frac{dW}{dx} = -\frac{G_p}{G_a}\frac{d\overline{M}}{dx} \tag{7}$$

$$\frac{d\overline{M}}{dt} = \text{a single-kernel drying equation} \tag{8}$$

Standard mathematical techniques (e.g. Runga-Kutta) can be used to solve the system of equations (5)–(8).

The grain in a concurrent-flow dryer is cooled in a counterflow cooler. The concurrent- and counterflow drying/cooling models are similar except for some of the signs in the equations (Brooker et al. 1992). However, the solution of the counterflow model is more complex because it is a two-point boundary value problem (instead of a one-point boundary problem as is the case for the concurrent-flow model). Montross (1995) recently developed a stable method of solving the model of a counterflow grain cooler.

Computer simulation has contributed extensively to the design of multi-stage concurrent-flow dryers, in particular of optimum grain-bed depths and optimal air-recycle patterns (Bakker-Arkema et al. 1992).

Mixed-flow dryers

Mixed-flow dryers are the predominant dryer type in western Europe and Latin America. Grain is dried in mixed-flow dryers by a mixture of crossflow, concurrent-flow, and counterflow processes. The grain flows over a series of alternate inlet and exhaust air ducts. This results in fairly uniform drying, and therefore in relatively uniform grain moisture content and quality. The drying temperature in mixed flow dryers is higher than in crossflow dryers because the grain is not subjected to the high temperature for as long.

It has recently been shown that there is a significant difference in the retention time and grain-temperature history between the kernels as they pass through a mixed-flow dryer (Liu 1993). This leads to a higher than expected spread in the moisture content and temperature of the grain exiting the dryer.

The difference in design between different mixed-flow dryer models centres around the *duct size/spacing/pattern specifications.* No comparative studies have been published on these design modifications with respect to fuel consumption, grain-quality characteristics, and capacity (i.e. throughput per unit of dryer volume). Therefore, claims by manufacturers of 'best duct design' are impossible to verify.

Mixed-flow dryers are more expensive to manufacture and require more extensive air-pollution equipment than crossflow dryers.

During the mixed-flow drying process, the grain kernels are subjected to a continuously-changing pattern of repeated crossflow concurrent-flow and counterflow drying treatments. Therefore, a mixed-flow dryer simulation model consists of a combination of these three submodels (Liu 1993).

The mixed-flow drying model has recently been utilised for the design of tapered airducts in a mixed-flow maize dryer (Cao 1993).

Miscellaneous dryer types

In addition to the three major grain dryer types, i.e. crossflow, mixed-flow, and concurrent-flow, several other dryers are used occasionally for grains, often only at the research level. Spouted-bed, fluidised bed, and microwave dryers are examples; they have not (yet) proven to be economical as high-temperature dehydration devices for grains.

Rotary dryers are employed successfully in drying rice, mainly parboiled rice. The uniform drying treatment of the kernels is an advantage. However, the initial and maintenance costs of these dryers are high, and thus they do not compete with the more conventional grain-dryer types.

The *steam* dryer is a recent Chinese invention, and is popular in certain regions of northeastern China. A steam dryer usually consists of 3 to 4 towers in series. Each tower contains in its upper section a series of steam pipes, and in its lower section a number of inlet/outlet airducts. The grain is heated by conduction as it flows over the steam-heated pipes, and is subsequently treated with ambient or slightly-heated recycled drying-air. The grain retention time is long (4–6 hours for 10-point moisture removal) due to the relatively low grain temperatures, resulting in superior grain quality. The high initial cost of a steam dryer is likely to prevent adoption of this dryer type outside of China.

Rotary-dryer models have been developed in the chemical engineering industry (Kelly 1987). However, they have not been applied to the design and analysis of rotary grain-dryers.

The authors have not been able to find a steam-dryer model for grain in the literature.

Dryer Comparison

Drying temperatures

The *drying-air temperatures* employed in high-temperature grain dryers depend on the dryer type and the grain variety. Table 5 contains values of the temperatures measured recently in maize dryers at elevator/grain-depot sites in the USA and China (Montross et al. 1994; Liu et al. 1994). Clearly, the concurrent-flow dryers operate at the highest temperature, the crossflow dryers at the lowest temperature. The disparity in operating temperatures between those measured in the USA and China is due to the different heat sources used in the two countries: natural gas in the USA, coal in China.

Table 5. Typical drying-air temperatures employed in different maize-dryer types in the USA and China.

Dryer type	USA (°C)	China (°C)
Concurrent-flow	205–290	150–160
Mixed-flow	130–140	120–150
Crossflow	85–120	90–120
Steam dryer	—	130–140

The *grain-kernel temperature,* not the drying-air temperatures, determines the drying rate of the grain in a dryer. Figure 2 shows the distribution of the kernel temperature in the crossflow, concurrent-flow, mixed-flow, and counterflow dryers. The variation in temperature (and in moisture content) between the kernels in the crossflow dryer is large, in the mixed-flow dryer relatively small, and in the concurrent/counterflow dryer non-existent. Also, in the crossflow dryer the grain kernels are subjected to the high inlet-air temperature for a period of hours, in the mixed-flow dryer for minutes, and in the concurrent-flow dryer for (only) seconds. Therefore, there are different high-level limitations on the drying-air temperature in the three dryer types.

Maize quality

The authors have recently investigated the effect of dryer type on maize quality (Montross et al. 1994; Liu et al. 1994). In the USA, three dryer types were tested, i.e. crossflow, concurrent-flow and mixed-flow models. In China, the same three types were investigated, along with steam-drying and sun-drying installations. Tables 6 and 7 show the results of both studies.

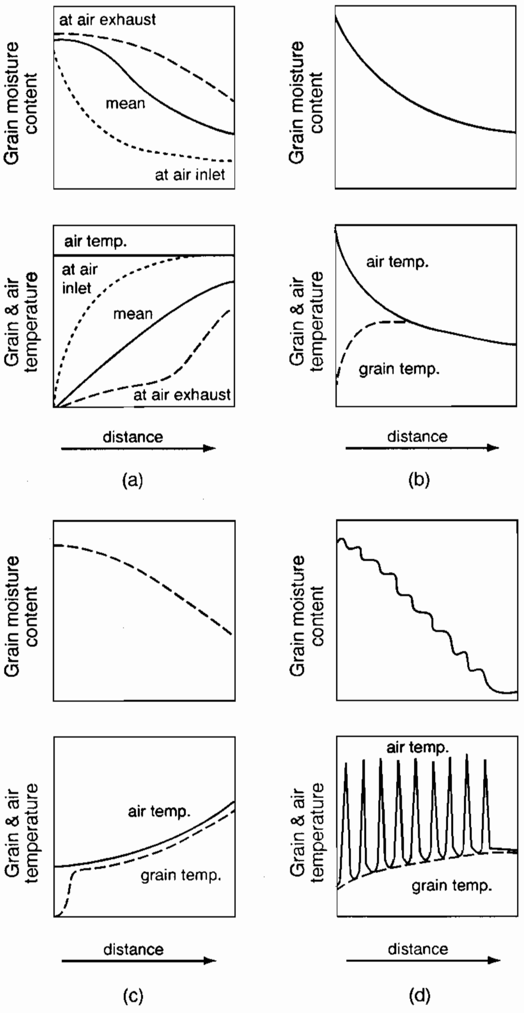

Figure 2. Moisture and temperature changes during: (a) crossflow drying; (b) concurrent-flow drying; (c) counterflow drying; and (d) mixed-flow drying.

Several conclusions can be drawn from the data in Tables 6 and 7:

1. Sun drying is able to produce maize with a minimum number of stress cracks *if properly implemented.*
2. Steam-dried maize usually has only a small number of stress cracks.
3. Of the three major high-temperature dryer types, concurrent-flow dryers cause the smallest increase in the number of stress cracks in maize kernels while crossflow dryers generate the largest increase.
4. Mixed-flow dryers fall between the concurrent-flow and crossflow dryer types with respect to the stress-cracking of maize.

Comparing the data in Tables 6 and 7 shows that the number of stress cracks recorded for the three major dryer types in China is lower than in the USA. This could be due to variety differences but is likely to be caused by the higher drying temperatures used in the USA than in China, i.e. concurrent-flow dryers usually operate at 250–275°C in the USA, but at 125–150°C in China.

A comparison between four dryer types is given in Table 8 with respect to the drying-air temperature, the maximum temperature reached by the grain, and the expected increase in stress-cracked kernels, in drying maize by ten percentage points of moisture.

Dryer rating

High-temperature dryers are usually rated for capacity only. In some cases the energy efficiency is given. A buyer has difficulty interpreting the dryer manufacturer's data due to the lack of a standard rating scheme.

The International Standards Organization (ISO) has proposed the standard 'Agricultural Grain Dryers—Determination of Drying Performance.' Until this standard has been approved, and accepted worldwide by grain-dryer manufacturers, it is impossible to draw objective conclusions from a comparison of different dryer types and dryer models.

Dryer Control

The moisture content of wet grain reaching a high-temperature continuous-flow dryer over a 24-hour period can vary greatly. This is due to the different harvest-procedure preferences, soil types, and variety selections of individual farmers. At commercial elevators it is not unusual to encounter moisture content differences of 10–15% in lots of maize received from different growers. Yet all the grain must be dried to approximately the same average moisture content. The challenge presented to the dryer operator, or the automatic controller, is to properly vary the speed of the unload auger and thus the residence time of the grain in the dryer.

Manual control of continuous-flow dryers often leads to significant overdrying or underdrying. Automatic control of continuous-flow dryers is usually designed to minimise these occurrences. Secondary objectives are minimising energy consumption and optimising dryer capacity, both necessarily subject to grain quality constraints (Eltigani and Bakker-Arkema 1987).

Table 6. Average type of stress cracks, stress-cracked percentage and stress-crack index of maize dried in three dryer types in the USA.

	Stress cracks					
Dryer type	None (%)	Single (%)	Multiple (%)	**Checked (%)**	**Stress-cracked (%)**	SCI[a]
Three-stage concurrent-flow	47.4	5.8	27.1	19.7	52.6	185.6
Mixed-flow	34.5	8.0	32.5	25.0	65.5	230.5
Crossflow	12.2	3.4	38.6	45.8	87.8	348.3

[a] SCI =1* (% single) + 3* (% multiple) + 5* (% checked) (Gunasekaran et al. 1985).

Table 7. Average type of stress cracks, stress-cracked percentage and stress-crack index of maize dried in five dryer types in China.

Dryer type	None (%)	Single (%)	Multiple (%)	Checked (%)	Stress-cracked (%)	SCI[a]
Concurrent-flow/crossflow	71.6	10.0	14.7	1.0	28.4	72.6
Mixed-flow	70.7	11.0	15.7	0.7	29.3	70.9
Crossflow	55.5	15.7	21.6	9.2	44.5	107.6
Steam	89.7	6.3	1.0	3.0	10.3	24.3
Sundrying	93.3	3.5	1.5	0	6.7	16.4

[a] SCI =1* (% single) + 3* (% multiple) + 5* (% checked) (Gunasekaran et al. 1985).

Table 8. The average effect of dryer type on the drying-air temperature, the maximum grain temperature, and the percentage of stress-cracked kernels in maize.

Dryer type	Drying air temperature (°C)	Maximum grain temperature (°C)	Stress-cracked kernels (%)
Crossflow	80–110	80–110	70–85
Mixed-flow	100–130	70–100	40–55
Concurrent-flow	200–285	60–80	30–45
Steam	Ambient	40–50	10–20

Continuous-flow dryer control is of the classical or the adaptive type. Either the exhaust-air temperature or the inlet and outlet moisture contents of the grain are measured, and the speed of the metering roles is adjusted according to a specific control law. Temperature-based controllers are adequate for small inlet moisture variations; moisture-based control is recommended for large swings in moisture content.

A classical feedback controller reacts slowly when the residence time of the grain in the dryer is long. An optimal feedback control system requires a well-defined objective function, which is difficult to obtain mathematically. A classical feed-forward controller needs an accurate dynamic model of the drying process, which requires long computation time for on-line calculations (Marchant 1985).

An adaptive controller has been shown to offer the best technique for adequately controlling continuous-flow grain drying (Moreira 1989). Adaptive feedback and feed-forward control is able to minimise the fluctuation of the outlet moisture content even for large variations in the inlet and ambient conditions.

Fuzzy or expert control is used when the objective function is difficult to express mathematically. It employs a set of heuristic rules based on experimental knowledge and operator expertise (Zhang et al. 1990).

Two quality-control measures have been proposed to evaluate different control performances. One is based on the standard deviation of the grain moisture content and the other on the percentage of off-specification product. By employing these control measures, the success or the failure of a particular controller type can be quantified.

Considerable computing power is required for continuous-flow dryer controllers. The required continuous or intermittent sensing of the grain moisture needs sophisticated instrumentation. Therefore, the cost of a control system for a continuous-flow grain dryer is relatively high.

Notwithstanding the substantial costs, dryer control systems are economically justified on many grain dryers.

Dryer Economics

The analysis of profitability of the purchase of a particular dryer is an essential part of the evaluation of different dryer types. Analyses commonly used, such as the payback period and rate of return, do not adequately express the economics in the dryer-selection process. The *capital-budgeting* (also called *life-cycle costing)* analysis does allow the buyer to analyse the cash-flows over time resulting from the purchase of a specific dryer model. The capital-budgeting procedure requires values of a series of parameters—including the fixed and operating costs, the energy consumption, the grain quality change, the fuel and maintenance costs, the service life, the time value of money (i.e. the interest to be paid on the loan), and so forth.

The capital-budgeting analysis provides a realistic comparison of dryer types. For instance, the initially costly dryer may in the long run be the better buy because it may produce better quality grain at lower operating costs and lower environmental pollution. A payback-period analysis may not reveal these advantages; a capital-budgeting analysis, spanning a 3–10 year planning horizon, will.

A capital-budgeting analysis of the purchase of a dryer requires knowledge, or accurate estimates, of a number of dryer-related parameters such as the dryer capacity, energy efficiency, salvage value, etc. Many of these parameter values are inadequately known, and thus have to be researched by engineers and economists.

As an example, the capital-budgeting costs of adding a grain-preheater to an existing concurrent-flow dryer are analysed (Montross 1995). [The preheater increases the capacity of high-temperature dryers by 10–15%.] The parameters used in the analysis are listed in Table 9. The drying costs in the table refer to the drying charges at a local grain elevator, and would be incurred if no preheater had been installed.

Table 10 shows the tonnage to be dried and the number of drying-operations to be required for the net present value (NPV) to be zero, for three levels of elevator income-tax rate. Thus, at a tax rate of 17%, and drying maize from 25 to 15%, at least 584 t of maize have to be dried per year for the addition of the preheater to the dryer to be economical, or the dryer has to be operated at least 255 hours.

Table 9. Parameters used in the capital budgeting analysis (in US$) of a concurrent-flow dryer to be fitted with a preheater.

Input parameters	
Discount rate	15%
Life of preheater	10
Federal income tax	0, 17, 34%
Depreciation method	straight-line
Capital costs	
Preheater cost (fans/burners)	$10,590
Dealer profit and miscellaneous costs	$2,650
Installation labor ($23/hour)	$3,680
Crane time ($75/hour)	$1,200
Salvage value	$2,000
Operating costs	
Natural gas	$2.83/m^3 ($0.40/100 ft^3)
Electricity (kWh)	$0.075
Drying costs	
5 percentage points of moisture removed	$3.93/t ($0.10/bu)
Capacity increase at 5 points	6.2 t/br (245 bu/hour)
10 percentage points of moisture removed	$9.82/t ($0.25/bu)
Capacity increase at 10 points	2.3 t/br (90 bu/hour)

Table 10. Maize to be dried (t/year) and annual operating time (hours) required for the net present value (NPV) of the preheater to be zero at a variable tax rate.

Tax rate and time required	Drying 20 to 15%	Drying 25 to 15%
Maize dried at 17% tax, t/year	1,411	584
Time required, hours	226	255
Maize dried at 34% tax, t/year	1,682	696
Time required, hours	270	304

A capital-budgeting analysis of a high-temperature dryer provides quick answers to the effect on the net present value of: (1) the discount rate, (2) the fuel-inflation rate, (3) the loan policy, (4) the local drying cost, (5) the grain-quality premium and (6) the dryer energy-efficiency. In short, a capital-budgeting analysis provides for better economic information on a dryer, or on the add-on to a dryer, than can be obtained from an initial-cost or payback-period comparison.

References

Bakker-Arkema, F.W., Maier, D.E., Raifsnider, R. and Westelaken, C. M. 1992. Commercial dehydration of soybeans. St. Joseph, Michigan, American Society of Agricultural Engineers, Paper Number 92-6532.

Brooker, D.B., Bakker-Arkema, F.W. and Hall, C.W. 1992. Drying and storage of grains and oilseeds. New York, Van Nostrand Reinhold.

Cao, C.W. 1993. Experimental investigation of hot air drying mechanism of corn. In: Proceedings of the 1993 International Symposium of Grain Drying and Storage Technology, Beijing, China, 15–18 September 1993.

CNIIEC (China National Instruments Import and Export Corporation) 1995. Bid Number CICW956014: China Grain Distribution and Marketing Project. Ministry of Internal Trade, Beijing, China.

Eltigani, A.Y. and Bakker-Armena, F.W. 1987. Automatic control of commercial crossflow grain dryers. Drying Technology, 5, 561–575.

Gunasekaran, S., Deshpande, S., Paulsen, M.R. and Shove, G. C. 1985. Size characterization of stress cracks in corn kernels. Transactions of the American Society of Agricultural Engineers, 28, 1668–1672.

Kelly, J.J. 1987. Rotary drying. In: Mujumdar, A.S., ed., Handbook of industrial drying. New York, Dekker Incorporated.

Liu, Q. 1993. Study on the drying mechanism, simulation and test of mixed flow grain dryers. Ph.D. Thesis, Beijing Agricultural Engineering University, Beijing, China.

Liu, Q., Bakker-Arkema, F.W. and Hines, R. E. 1994. Effect of dryer type on maize quality in China. St. Joseph, Michigan, American Society of Agricultural Engineers, Paper Number 94-6589.

Marchant, J.A. 1985. Control of high temperature continuous flow grain driers. Agricultural Engineering, 40, 145–149.

Montross, M.D. 1995. Dryer performance enhancement through grain pre-heating. M.S. thesis, Michigan State University, East Lansing, Michigan.

Montross, M.D., Bakker-Arkema, F. W., Leppanen, C. L. and Hines, R. E. 1994. Moisture content variation and grain quality of corn dried in different high temperature dryers. St. Joseph, Michigan, American Society of Agricultural Engineers, Paper Number 94-6590.

Moreira, R.G. 1989. Adaptive control of continuous flow grain dryers. Ph.D. thesis, Michigan State University, East Lansing, Michigan.

Pierce, R. O. and Thompson, T. L. 1981. Energy use and performance related to crossflow dryer design. Transactions of the American Society of Agricultural Engineers, 24, 216–220.

Zhang, Q., Litchfield, J.B. and Bentsman, J. 1990. Fuzzy predictive control system for corn quality during drying. In: Food processing automation. Proceedings of the 1990 Conference, American Society of Agricultural Engineers. St. Joseph, Michigan, American Society of Agricultural Engineers, Publication 02-90.

In-store Drying and Grain Psychrometrics

Robert Driscoll*

Abstract

Product drying, though conceptually simple, is the least understood postharvest operation. Successful drying produces a safe product, but drying problems can cause massive quality and actual losses. The interaction of a product with air can be represented on a psychrometric chart, a basic tool of the drying engineer, and this allows estimates of drying performance to be made. Interaction of the product with the air also will affect its chemical structure, microbial flora, and storage stability. A current trend in dryer models research is towards quality models which can be incorporated in deterministic models of grain drying, and are conveniently expressed in terms of the temperature and moisture histories of the product. Such models allow predictions of safe and optimal drying from simulated or historical weather data, as well as development of appropriate control algorithms. The trend in Southeast Asia is towards mechanisation and increased collection of grain in bulk, allowing technologies on a more efficient scale to be introduced.

DRYING is one of the most common and least understood postharvest operations. Banga and Singh (1994) stated that drying is too complex to fully analyse in a rigorous mathematical sense, and that dryer design still mainly depends on experimental data. Although true, the application of basic science to situations such as drying of agricultural crops has led to a revolution in our understanding of drying equipment and strategies, but that revolution is only now starting to impact on the massive postharvest grain drying problem of Southeast Asia.

Grain drying in Southeast Asia

The wet season harvests originated through the development of high yielding, fertiliser-dependent varieties of grain. Hybrid varieties, due to their greater initial vigour, have helped to increase yields at a time when land, labour, and water are decreasing (Virmani and Dedolph 1994), and so have increased pressure on the postharvest system. Drying the grain became a major problem in the region, as sun drying proved insufficient for wet season tropical climates.

Thus, mechanical dryers have been investigated as an alternative. New types of dryers are now being developed at a great rate; for example, spouted and fluidised-bed dryers, and conduction drum dryers (Noomhorm et al. 1994). Soponronnarit and Prachayawarakorn (1993) have developed fluidised bed dryers for first stage drying of paddy, predicting a cost of about US$80 per tonne water evaporated, and studying energy, quality and throughput rates of the fluidised-bed drying system. This has now been commercialised in Thailand.

I worked on the dryer for the model grain depot at Jilin in China (Newman 1992), and so was able to observe developments there. China shows a slow trend towards mechanisation, the main delay being that the displaced labour force does not attract competitive wages compared with agricultural employment, which is currently 70% of employment. As the Chinese GNP rises, this trend towards urban society and 10% rural work force will accelerate (Schrock 1994). But all countries in Southeast Asia reflect this trend.

Interaction of grain with air

Drying inhibits product degradation by control of water activity only. Water activity determines the rates of most biological and chemical reactions of relevance to food systems. Thus, the design objective in drying is not to control moisture but to control water activity. Yet most dryer objectives are stated in terms of moisture.

The most common technique for dehydration is to allow interaction between low moisture air and the product, moisture being transferred to the air and then carried out of the grain mass in solution.

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Other interactions between the grain and the air occur, many related to quality. A secondary interaction is a thermal interaction between the air and the grain, often referred to under constant aeration conditions as the initial transient. Some related effects are:

- Grain can be preserved cheaply by cooling (Barth 1993), giving independence of weather conditions and dryer delays, and at a low cost as cooling fronts propagate rapidly through a grain mass. Few have attempted to simulate more than the immediate dryer, with the exception of Chung et al. (1991), who simulated an on-farm grain storage system for American conditions, finding that gas-modulated burners gave a potential saving over on/off burner control. Recirculation of air was also studied in this simulation. My own work in simulating Malaysian mills as a drying system demonstrated dramatically the quality benefits that would result from cooling grain in an aeration bin at receival, so that the effect of dryer delays or bottlenecks within the complex would be alleviated. A reduction of dry matter loss from 0.8 to 0.5% was observed using typical harvest data, this being the difference between accepting and rejecting the grain for export. The cost would have been that of a receival bin (bulk), aeration equipment and a small fan. No cooling system was required.
- Grain kept in bags absorbs moisture at a rate of about 0.5% per month in tropical climates (Guritno et al. 1991).
- If grain is sealed inside a plastic bag, gases build up due to respiration which are self-limiting, allowing long term storage (several months) by this simple technique (Kawashima and Siriacha 1990).

Relevance of isotherms

Drying is a two-phase dual component system. The two phases are vapour and liquid, and the two components are water and water vapour. At equilibrium, the number of degrees of freedom F is:

$$F = 2 \text{ (phases)} - 2 \text{ (components)} + 2$$
$$= 2$$

Since we have two degrees of freedom, if we define two state variables of the system we have defined the system state precisely. Choosing relative humidity (RH) and temperature (T) as our state variables, we can then write:

$$M = f(T, RH)$$

where f is a function, and M is the dry basis moisture content. For a particular temperature, the relation between M and RH is called an isotherm, and is product dependent. In turn, relative humidity is defined as a partial pressure ratio:

$$RH = p_v / p_s$$

where p_v is the vapour pressure exerted by moisture in the air, and p_s is the vapour pressure of moisture in saturated air at the same temperature. This definition identifies RH with water activity a_w, although relative humidity is generally expressed as a percentage whereas water activity never is.

Recent research has suggested that there are criteria other than water activity and temperature which determine reaction rates, and these alternatives will be discussed briefly in a later section.

The result of the above identification is that we can plot lines of constant moisture (isosteres) on a psychrometric chart, by holding moisture constant and using the function f to calculate the relative humidity as temperature varies. For most agricultural products, temperature has less effect than moisture on the relative humidity, so that the isosteres tend to follow the relative humidity lines. This accounts for the use of moisture content for a particular product as the commercial determinant of the end point of drying.

Work has continued internationally on building up a comprehensive library of product properties, with individual researchers continuing to collect basic thermophysical data.

Psychrometrics

Definitions

Air is used as the transport medium for moisture in the dryer. So as far as the dryer is concerned, air is a two component mixture of a gas (primarily O_2 and N_2) and a vapour (water). A limited volume of air above a free water surface becomes saturated, the amount of moisture present in the air depending on the temperature only, and independent of the pressure of the dry air. Relative humidity is a measure of the proportion of vapour present to the maximum amount the air can hold (at saturation). Absolute humidity is the mass of moisture in the air relative to the mass of the gas component of the air (called dry basis). Plots of air state variables are called psychrometric charts (Fig. 1), of which the most important is a plot of temperature against absolute humidity.

The example chart shown also demonstrates relative humidity lines, enthalpy lines, and density lines. All of these are important in grain drying. Air enthalpy is a measure of the heat content of the air and its contained vapour:

$$h = m_a \, [c_a T + H \, (c_v T + \lambda_0)]$$

where h is the air enthalpy (kJ), m_a is the mass flow rate of the air on a dry basis (gas component only), c_a and c_v are specific heats of the air and water vapour, respectively, (kJ/kg.K) and λ_0 is the latent heat of water at 0°C.

Enthalpy is important in drying because for an adiabatic, constant pressure system, enthalpy is conserved. Many dryers approximate this situation. Thus on our psychrometric chart, drying can be represented using lines of constant enthalpy. In general, the inlet air will start at a different enthalpy from the initial product, and thus for the product to come to equilibrium with the air, two balances are required, a moisture balance and a thermal or enthalpy balance. In general, thermal balances occur quickly (typically more than 30 times faster than moisture balances).

Drying on a psychrometric chart

Thin-layer drying of a product can be represented on a psychrometric chart using this information. First the product (P) and inlet air (A) points are plotted (Fig. 2). If the product is high in moisture, the product point will be close to the 100% relative humidity (saturation) line. Construct a line from the air point along its enthalpy line to intersect the 100% saturation line. Construct a second line at constant moisture from the initial product state to intersect the air enthalpy line, and call this point B. The line PB represents the enthalpy 'front' moving across the product, while the line BA represents the product drying.

This graphical method is a good way of explaining the drying process, but is not as accurate as an equation-based solution method. In practice there is some moisture change in the product in the enthalpy front and some change in enthalpy in the moisture front for both the air and the product. These changes are generally small enough to be neglected.

Many researchers have developed models of thin-layer drying. Some recent work is that of:

- Parti (1990), who studied diffusion with a temperature and moisture-dependent diffusion coefficient;
- Bala and Woods (1992), who combined internal diffusion with surface evaporation for malt;
- Weres and Jayas (1994), who in a recent evaluation comparing a range of popular models found that the two-term exponential model was superior for describing the thin-layer drying rate of maize;
- Martinez-Vera et al. (1995), who developed a thin-layer drying model of corn based on diffusion, using finite element analysis.

Extension of this concept to deep bed dryers is discussed in the next section.

Other types of dryers

Practically all dryers are systems for interacting air with the product. Although only in-store dryers were considered, the principles can be extended. Some examples showing specific aspects of grain/air interaction are given below.

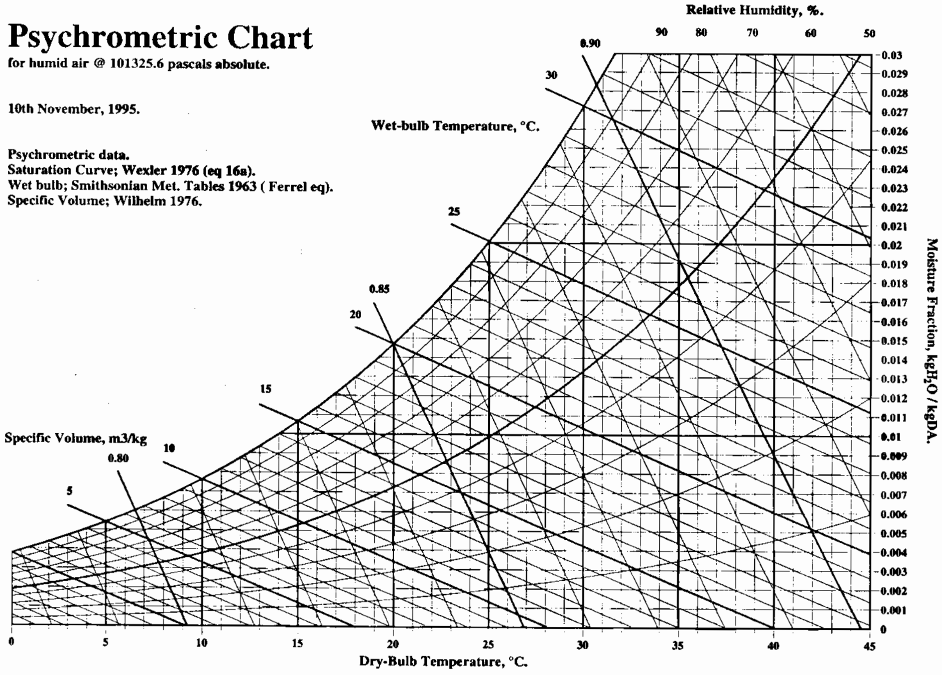

Figure 1. An example of a psychrometric chart (courtesy James Darby, Stored Grain Research Laboratory, CSIRO Division of Entomology, Canberra).

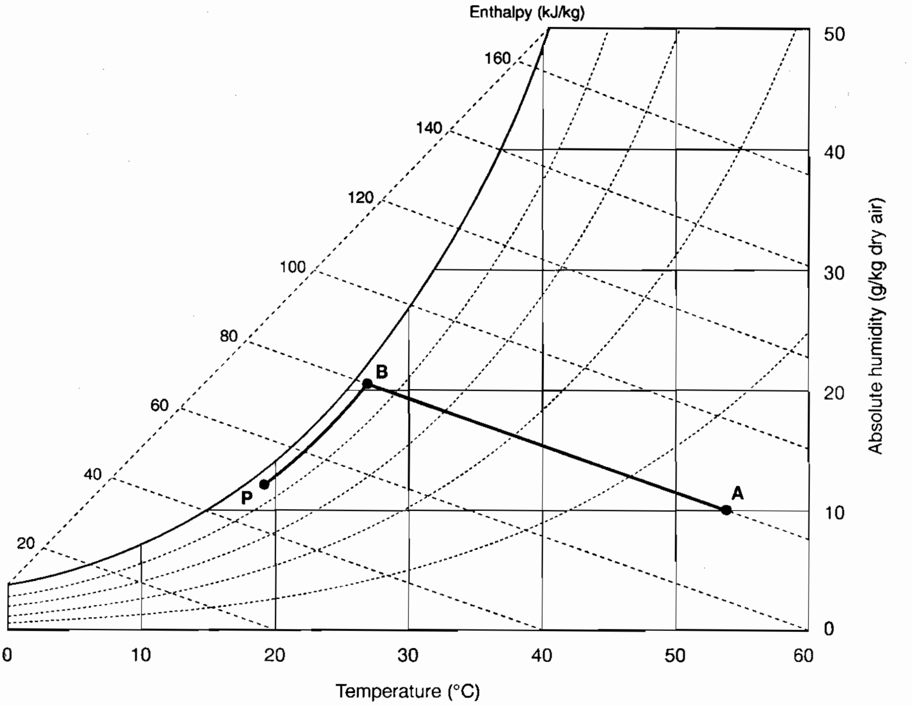

Figure 2. Graphical representation of grain drying on a psychrometric chart. See text for explanation.

One aspect of air properties of great interest in dryer design is solar energy, which can be used to partially heat the air and so dry the grain (Oosthuizen 1992). Although technically possible and achieved by, for example, Somchart Soponronnarit in ACIAR Project 8308, it has not proven to be a commercially successful approach.

Spouted-bed dryer dynamics are complex, especially when it comes to scale up, and hence simplified arrangements are being tested such as two-dimensional spouted beds (Kalwar and Raghaven 1993). Both spouted-bed and fluidised-bed dryers use high airflow rates to fluidise all (or a part) of the granular product mass, allowing rapid heat transfer.

In-store drying

A deep bed of product can be represented as a number of thin layers superimposed, and so can also be represented by points A, B, and P on a psychrometric chart. The first layer acts as a true thin layer for constant inlet conditions. The second layer is affected by the outlet conditions of the first layer, resulting in a time delay before it is exposed to drying air. In this way, there will be a time delay dependent on depth in the bed before layers deep within the grain will be exposed to the same conditions as the first layer.

Thus, two fronts are generated for constant inlet conditions to a deep bed of material. The first is an enthalpy front, generated at the air inlet and propagating relatively rapidly through the grain mass. The second front is the moisture front, which is a drying front. In predicting the rate of moisture removal, the difference between the absolute humidities of the air inlet and zone B conditions determines the rate of drying.

The advantage of drying a deep bed rather than a thin layer is that the drying air is exposed to a large amount of product, and so has more time to come to equilibrium with the product. The wettest product is at the air exit. This gives high moisture efficiency without the need to recirculate the air or stir the grain. In contrast, thin-layer dryers give limited time for contact between the air and the product, so that the air leaves the product with unused moisture capacity.

Deep-bed drying has been modelled extensively over the past three decades. In a recent review of theories (Cenkowski et al. 1993), only three types of drying models were recognised: the equilibrium, non-equilibrium, and logarithmic. In practice this classification neglects by far the most successful model, the so-called near-equilibrium model, which is actually the assumption of thermal equilibrium without also assuming moisture equilibrium. At low temperatures, near equilibrium models were found to perform better in practice than non-equilibrium models, even for fast air situations such as fluidised-bed drying (Nathakaranakule and Soponronnarit 1993). Earlier reviews (e.g. Parry 1985) were perhaps a little more comprehensive.

The drying time can be estimated by equating the moisture removal rate with the amount of moisture in the bed above equilibrium (Bowrey and Driscoll 1986).

Work to develop and improve models of deep-bed drying continues, for example, on:

- optimising integration step size—the work of Jindal and Seibenmorgen (1994) on the importance of the mass ratio of grain to air in a control volume;
- respiration—the heat and water generated by respiration were found to have a significant effect on drying predictions for a deep bed (Soponronnarit and Chinsakolthanakorn 1990), with heat increasing the drying rate and the moisture produced retarding it;
- volume shrinkage—an example of a real bed effect is volume shrinkage, for many years not included in dryer models as being too difficult. Work on collecting empirical data on bed shrinkage is rare. An example is Lang and Sokhansanj (1993) for wheat and canola;
- complexity—some aeration models are of great complexity, covering three-dimensional flow using volume averaging theory. Van Graver (1992) reviews work by Thorpe, Wilson, and others.

The main *problems* with deep bed drying are:

- creation of a moisture gradient between the top of the bed and the inlet;
- lost opportunity cost, as product is held up in the dryer for long periods, so tying up capital.
- compaction of lower layers at high moistures, resulting in increased pressure drop, higher costs and slower drying rates; and
- loading and unloading times are comparatively long.

The main *advantages* are:

- reduced quality deterioration;
- low energy costs for drying under the right conditions; and
- reduced grain losses.

Psychrometrics and quality

There are three parameters for assessing any process equipment: cost of operation (including capital and equipment costs), throughput, and product quality. In this section quality is considered. Dryer models need to include quality models to allow the model to be used for strategy development. For example, in the in-store drying model developed by the University of New South Wales (Srzednicki and Driscoll 1995), four quality models are included, dry matter loss, ergosterol increase, yellowing and seed viability. In most cases, it is the interaction of the product with its psychrometric environment which causes changes in quality.

Recent studies of microflora in milled grain samples of rice from Southeast Asia have shown a predominance of field fungi, with few observations of storage fungi (Pitt et al. 1994), indicating that the milling process removes most of the microflora.

Great progress in dryer design has been achieved with the discovery that fluidised-bed drying of paddy does not necessarily result in poor quality grain, and that fact, coupled with the ability to economically recirculate the air inside a fluidised-bed dryer has led to a rebirth of this technology in southeast Asia (Ghaly et al. 1984; Tumambing 1992; Magampon and Elepano 1993). This success was due to the discovery that high temperature drying does not damage grain provided that the grain is initially at a high moisture content (Tallada et al. 1994). Rather it is the steepness of the moisture gradient within the grain which correlates to head rice yield (Siebenmorgen 1992), with the greatest reduction occurring during the first 8 hours of exposure to an absorption environment.

The results have come from studies on causes of fissuring and breakage during milling of rice. Reduction in head rice yield is caused by moisture readsorption (Banaszek and Siebenmorgen 1990). Although Japanese researchers in the 1930s had established that fissure generation is due to adsorption rather than drying, this information was not disseminated until rediscovered by Kunze over a long series of careful experiments (see Kunze 1991). This has resulted in major rethinking of drying methodologies, with the result that grains are now frequently dried under much harsher conditions, yet with less loss of quality.

More generally, Siebenmorgen (1992) confirmed that moisture reduction gradients caused fissuring, the majority of fissuring occurring during the first 8 hours after exposure to an adsorption environment. This suggested that maize could be dried using high temperatures and high relative humidities (Estrada and Litchfield 1993).

More detailed research on moisture distributions led to the disturbing discovery that individual rice grains vary widely in moisture content with their growth stage, and that even position on the panicle can have extreme effects. Did this matter? Unfortunately, the answer is yes. High moisture rice releases its moisture to low moisture rice, causing that rice to fissure, and hence reducing head rice yield (Siebenmorgen et al. 1992).

We have come to understand more about the chemistry of grain drying as well; for example, the effects on nutrients (Barrier-Guillot et al. 1993), enzymes (Chrastil 1990, 1993), and the location and causes of fissuring in the grain structure (Juliano et al. 1993; Juliano and Perez 1993; Peplinski et al. 1994). Theoretical calculations of fissure development have been attempted by several researchers, one of the most successful being a finite element approach for maize and soybeans by Irudayara et al. (1993), using van Mises' failure criterion, and including thermal and moisture expansion effects and a viscoelastic model of the internal grain structure. Their model predicted fissuring at high temperatures (>70°C), due to stresses of the order of 20 atmospheres being generated near the grain surface.

Thus, we seem to have come full circle, with fissuring due to drying, not readsorption, being indicated by the models. Studies at the University of New South Wales, on moisture gradients in rice grains (Driscoll 1995) suggested that the gradients during drying are not as steep as the gradients that are created by exposure of a dried grain to a humid environment. This suggests that most fissuring could be prevented by controlling the relative humidity of the air to which the grain is exposed after drying to below 40%, until moisture diffusion within the grain has allowed re-equilibration to occur (at least 2 hours for paddy).

Other important quality models include the following:

- A storage quality indicator developed for wheat and rice was yellowing, which is discoloration during storage due to long-term chemical reactions (Bason et al. 1990).
- Several models exist for seed viability [e.g. Giner et al. (1991), for wheat].
- Pinto et al. (1991) and Gibson et al. (1994) have modelled aflatoxin production in terms of water activity and temperature.
- Evranaz (1993) has modelled oxidation of fats in peanuts, expressing it as a function of temperature and moisture.
- Many grain storage pests were found to be dependent on wet-bulb temperature [Desmarchelier (1988) with species of beetles]. Other researchers found that this was not always true [Beckett et al. (1994), with insect pests].

Some efforts are now being made to correlate quality measures with physically measurable characteristics, as a guide to breeding.

Psychrometrics and dryer control

Control of a grain store, whether for drying or aeration, depends critically on the interaction between the product and the air. Criteria for an aeration control system are that it should be accurate, quick to react, stable, and tolerant of changes. Specific points to consider in aeration control are (Moreira and Bakker-Arkema 1992):

- prevention of overdrying is a major concern;
- feedback and adaptive feedforward can be successfully applied, and a recent work even combines these two approaches;
- there is a wide choice for control objectives, for example, uniform drying, safety, lowest cost in one year, lowest cost over 20 years, maximum throughput, etc.;
- there is always a trade-off with deep-bed drying between reduced costs and increased dry matter loss.

In a detailed study of control and aeration strategies for near ambient systems for Canadian wheat, Ryniecki (1991) analysed humidistat control, time clocks, varying airflow rates, and burner strategies using a stochastic (probability) model of weather and drying. The drying model was based on Parti's formulation (Parti 1990) of the differential drying rate across a layer, converted to stochastic form by expressing temperature in the equation as a randomly fluctuating variable linked to weather conditions (Ryniecki et al. 1993; Ryniecki and Jayas 1992). This allows a probabilistic analysis of 20 years of weather data so that strategies which both guarantee and optimise aeration could be developed.

They found that varying the airflow rate and controlling the relative humidity by air selection worked best with time-varying humidity limits, where the band of acceptable air was increased if weather conditions continue unfavourable, to ensure enough hours of aeration (Ryniecki et al. 1993). This uses the same principle as the Australian CSIRO's proportional controller, a mechanical device for ensuring sufficient aeration hours.

Banga and Singh (1994) have also developed a technique for optimising aeration conditions, based on optimal control theory. What is especially interesting about their work is that instead of optimising from the perspective of achievement of technical goals (such as least cost, final moisture), they have also optimised on quality, including maximum nutrient/enzyme retention, minimum process time, and maximum energy efficiency as their control objectives. This emphasis on final product quality is a growing trend in grain storage research.

A further advance in modelling has been through the association of expert systems with dryer models (Kawamoto et al. 1992). In this case a simulation of harvest moistures based on weather data is coupled with an expert system which predicts likely pest outbreaks and suggests solutions.

The area of aeration control is expanding rapidly as new techniques are developed for reducing the major cost of drying of grains. This is possible through psychrometrics.

Conclusions

Three points should be emphasised.

We have not yet reached the stage where a mechanical dryer is the only solution. In most areas in Southeast Asia, sun drying is the preferred option, not just for the sake of tradition but in terms of pure economics.

As Asian countries move towards increased GNP and a resulting increased wage level, the trend will be away from rural employment towards mechanisation, and the current research on dryer design, control, and optimisation will bear increasing fruit.

Reducing costs and optimising dryer performance depends heavily on operators understanding their product and its interaction with air. This is the realm of psychrometry. High-temperature dryers are less dependent on operator skills, at the cost of reduced thermal efficiency at low moisture contents, whilst near ambient systems such as in-store dryers are heavily dependent on operator skills. For a large scale drying complex, massive savings are possible through a deeper understanding of the drying process, for example, cooling the grain at receival, two-stage drying, and prevention of drying delays.

References

Bala, B.K. and Woods, J.L. 1992. Thin layer drying models for malt. Food Engineering, 16, 239–249.

Banaszek, M.M. and Siebenmorgen, T.J. 1990. Head rice yield reduction rates caused by moisture adsorption. Transactions of the American Society of Agricultural Engineers, 33, 1263–1269.

Banga, J.R. and Singh, R.P. 1994. Optimization of air drying of foods. Journal of Food Engineering, 23, 189–211.

Barrier-Guillot, B., Zuprizal, Jondreville C., Chagneau, A.M., Larbier, M., and Leuillet M. 1993. Effect of heat drying temperature on the nutritive value of corn in chickens and pigs. Animal Feed Science and Technology, 41, 149–159.

Barth, F. 1993. Cold Preservation of Grain. In: Naewbanÿ, J.O. ed., State of the art of the grain industry in ASEAN: a focus on grain handling and processing. Proceedings of the 15th ASEAN Technical Seminar on Grain Post Harvest Technology, Singapore, 1992.

Bason, M.L., Gras, P.W., Banks, H.J. and Esteves, L.A. 1990. A quantitative study of the influence of temperature, water activity and storage atmosphere on the yellowing of paddy endosperm. Cereal Science, 12, 193–201.

Beckett, S.J., Longstaff, B.C., and Evans, D.E. 1994. A comparison of the demography of four major stored grain coleopteran pest species and its implications for pest management. In: Highley, E., Wright, E.J., Banks, H.J., and Champ, B.R., ed., 1994. Stored-product protection. Procerdings of the 6th International Working Conference on Stored-product Protection, Wallingford, U.K., CAB International, 491–497.

Bowrey, R.G. and Driscoll, R.H. 1986. A procedure to estimate the supplemental heating needs for in-store paddy drying. In: Champ, B.R. and Highley, E., ed., Preserving grain quality by aeration and in-store drying. ACIAR Proceedings, No. 15, 114–117.

Cenkowski, S., Jayas, D.S., and Pabis S. 1993. Deep-bed grain drying—a review of particular theories. Drying Technology, 11, 1553–1581.

Chrastil, J. 1990. Influence of storage on enzymes in rice grains. Agricultural and Food Chemistry, 38, 1198–1202.

— 1993. Changes of oryzenin and starch during preharvest maturation of rice grains. Agricultural and Food Chemistry, 41, 2242–2244.

Chung, J.H., Verma L.R., and Mailander M.P. 1991. Simulation of a rice drying system. Transactions of the American Society of Agricultural Engineers, 34, 2065–2072.

Desmarchelier, J.M. 1988. The relationship between wet-bulb temperature and the intrinsic rate of increase of eight species of stored product Coleoptera. Journal of Stored Products Research, 24, 107–113.

Driscoll, R.H. 1995. Energy efficiency in dryers and ovens. Food Australia, 47, 310–314.

Estrada, J.A. and Litchfield, J.B. 1993. High humidity drying of corn: effect on drying rate and product quality. Drying Technology, 11, 65–84.

Evranuz, E.O. 1993. The effects of temperature and moisture content on lipid peroxidation during storage of unblanched salted roasted peanuts: shelf life studies for unblanched salted roasted peanuts. International Journal of Food Science and Technology, 28, 193–199.

Ghaly, T., Sutherland, J.W., Ghaffar, R.A., and Hassan, A. 1984. Journal of Agricultural Engineering Research, 30, 337–345.

Gibson, A.M., Baranyi, J., Pitt J.I., Eyles, M.J., and Roberts, T.A. 1994. Predicting fungal growth: the effect of water activity on *Aspergillus flavus* and related species. International Food Microbiology, 23, 419–431.

Giner, S.A., Lupano, C.E., and Anon, M.C. 1991. A model for estimating loss of wheat seed viability during hot-air drying. Cereal Chemistry, 68, 77–80.

Graver, J. van S. 1992. Aeration computer programs. World Grain, 10, 28–29.

Guritno, P., Haque, E., and Chung, D.S. 1991. Moisture adsorption of bagged grain under tropical conditions. Transactions of the American Society of Agricultural Engineers, 34, 2131–2134.

Irudayara, J., Haghighi, K., and Stroshine, R. 1993. Stress analysis of viscoelastic materials during drying: II Application to grain kernels. Drying Technology, 11, 929–959.

Jindal, V.K. and Siebenmorgen, T.J. 1994. Simulation of low temperature rough rice drying and rewetting in shallow beds. Transactions of the American Society of Agricultural Engineers, 37, 863–871.

Juliano, B.O. and Perez, C.M. 1993. Critical moisture content for fissures in rough rice. American Association of Cereal Chemists, 70, 613–615.

Juliano, B.O., Perez, C.M., and Cuevas-Perez, F. 1993. Screening for stable high head rice yields in rough rice. American Association of Cereal Chemists, 70, 650–655.

Kalwar, M.I. and Raghavan, G.S.V. 1993. Batch drying of shelled corn in two-dimensional spouted beds with draft plates. Drying Technology, 11, 339–354.

Kawamoto, H., Sinha, R.N., and Muir, W.E. 1992. Computer simulation modelling for stored-grain pest management. Journal of Stored Products Research, 28, 139–145.

Kawashima, K. and Siriacha, P. 1990. Prevention of aflatoxin contamination in maize grains with high moisture content by using plastic bags. TARC Research Highlights, 13–15.

Kunze, O.R. 1991. Moisture adsorption in cereal grain-technology: a review with emphasis on rice. Transactions of the American Society of Agricultural Engineers, 7, 717–723.

Lang, W. and Sokhansanj, S. 1993. Bulk volume shrinkage during drying of wheat and canola. Food Process Engineering, 16, 305–314.

Magampon. M.T.C. and Elepano. A.R. 1993. A laboratory study of fluidized bed drying of high moisture paddy. Philippine Agricultural Mechanization Bulletin, 1, 15–19.

Martinez-Vera, C., Vizcarra-Mendoza, O., Galan-Domingo, O., Ruiz-Martinez, R., and Maurer, S.G. 1995. Natural-air grain drying modelling and validation. Drying Technology, 13, 333–350.

Moreira, R.G. and Bakker-Arkema, F.W. 1992. Grain dryer controls: a review. Cereal Chemistry, 69, 390–396.

Nathakaranakule, A. and Soponronnarit, S. 1993. Computer application in grain drying simulation. In: Naewbanỹ, J.O. and Mamlay, A.A. Proceedings of the 14th ASEAN Technical Seminar on Grain Post-Harvest Technology, 5–8 November 1991, 1–22.

Newman, C. 1992. China, Australia develop model grain depot. World Grain, 10, 17–18.

Noomhorm, A., Premakumar, K., and Sabarez, H.T. 1994. Design and development of a conduction drier for accelerated drying of peanuts. Food Engineering, 21, 411–419.

Oosthuizen, P.H. 1992. The selection of simple indirect solar rice dryers. Proceedings of the 8th International Drying Symposium, Montreal, 1992, 1465–1474.

Parry, J.L. 1985. Mathematical modelling and computer simulation of heat and mass transfer in agricultural grain drying: a review. Journal of Agricultural Engineering, 32, 1–29.

Parti, M. 1990. A theoretical model for thin-layer grain drying. Drying Technology, 8, 101–113.

Peplinski, A.J., Paulis, J.W., Bietz, J.A., and Pratt, R.C. 1994. Drying of high-moisture corn: changes in properties and physical quality. Cereal Chemistry, 71, 129–133.

Pinto, V.E.F., Vaamonde, G., and Montani, M.L. 1991. Influence of water activity, temperature and incubation time on the accumulation of aflatoxin B_1 in soybeans. Food Microbiology, 8, 195–201.

Pitt, J.I., Hocking, A.D., Bhudhasamai, K., Miscamble, B.F., Wheeler, K.A., and Tanboon-Ek, P. 1994. The normal mycoflora of commodities from Thailand. 2. Beans, rice, small grains and other commodities. International Journal of Food Microbiology, 23, 35–53.

Ryniecki, A. 1991. Control systems for near-ambient grain drying. In: Cereal grain – mycotoxins, fungi and quality in drying and storage. Cereal Grain, 499-511.

Ryniecki, A. and Jayas, D.S. 1992. Stochastic modeling of grain temperature in near-ambient drying. Drying Technology, 10, 123–137.

Ryniecki, A., Jayas, D.S., and Muir, W.E. 1993. A generalized control-strategy for near-ambient drying of wheat under Canadian-prairie climate. Transactions of the American Society of Agricultural Engineers, 36, 1175–1183.

Schrock, M.D. 1994. Grain harvesting in China as an example of the mechanization process. Agricultural Mechanization in Asia, Africa and Latin America, 25, 54–60.

Siebenmorgen. T.J. 1992. Relating moisture transfer rate in rice to kernel quality. Proceedings of the 8th International Drying Symposium, Montreal, 1992, 58–73.

Soponronnarit, S. and Chinsakolthanakorn, S. 1990. Effect of heat and water from respiration on drying rate and energy consumption. ASEAN Journal on Science and Technology for Development, 7, 65–83.

Soponronnarit, S. and Prachayawarakorn, S. 1993. Maintaining quality, maximizing throughput and minimizing energy consumption in fluidized bed paddy drying. In: Naewbanỹ, J.O. ed., State of the art of the grain industry in ASEAN: a focus on grain handling and processing. Proceedings of the 15th ASEAN Technical Seminar on Grain Post-Harvest Technology, Singapore, 8–11 September 1992.

Srzednicki, G.S. and Driscoll, R.H. 1995. In-store drying and quality maintenance in grain. In: Champ, B.R. and Highley, E., ed., Postharvest technology for agricultural products in Vietnam. ACIAR Proceedings, No. 60, 42–49.

Tallada, J.G., Elepano, A.R., and Quick, G.R. 1994. Some effects of high temperature drying on rice milling quality. Paper presented at the PSAE Annual Convention, Manila. Philippine Agricultural Mechanization Bulletin, 1, 11–15.

Tumambing, J. 1992. Fluidised-bed drying. Unpublished masters thesis, University of New South Wales, Australia.

Virmani, S.S. and Dedolph, C. 1994. Reaping the benefits of hybrid rice in the tropics. World Agriculture, 1994, 17–20.

Weres, J. and Jayas, D.S. 1994. Thin-layer drying of corn: experimental validation of a new numerical structural model. Canadian Agricultural Engineering, 36, 85–91.

Design of Aeration and Drying Systems

Design Parameters for Aeration and In-store Drying Systems

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Abstract

This paper summarises some of the main engineering considerations and parameters for the design of aeration and in-store drying systems.

Both aeration and in-store dryers operate on the principle of forcing ambient air through a mass of stored grain and, in many respects, the engineering design principles are much the same. Drying simply requires a larger volume of air, and in some cases the addition of some low-temperature heat.

The paper covers the main aspects of designing systems for moving air through grain, most of which have been well documented in the past. The paper covers methods for determining:

- the fan operation time fraction;
- specific airflow rates for aeration and drying;
- selection of airflow direction;
- selection of air-duct distribution pattern;
- airflow resistance in ducts;
- airflow resistance in grain;
- selection of fans;

The paper presents some new ideas for aeration of large volume 'squat' silos, but generally offers a guide to designers based on well known practices and past experience.

IN-STORE drying and aeration both involve forcing ambient (or near ambient) air through a grain mass.

It is well known that the forced movement of air through grain sets up both temperature and moisture fronts which move through the grain in the direction of the airflow—the temperature front moving very much faster than the moisture front. Thus, grain aeration is likely to result in some moisture change, and in-store drying will cause changes in grain temperature.

However, while similar in principle, the two practices have very different aims:

- In-store drying is carried out on relatively high moisture grain, and its purpose is to remove moisture from the grain to make it 'safe' for storage before fungal activity begins. Temperature control is a secondary consideration, except in high humidity conditions when it may be necessary to increase the air temperature with supplementary heat to reduce its relative humidity to a level where it will remove moisture.
- Aeration is normally performed on relatively low moisture grain with the purpose of cooling the grain in order to preserve it by maintaining its 'condition'. Drying of grain is not a consideration when aerating, since the airflow rates are normally too low to have much influence on moisture content.

Cooling of grain by aeration significantly reduces insect population growth, mould growth, and loss of viability (or germination potential). In addition, aeration can prevent the occurrence of temperature differentials within the grain which can lead to moisture migration; it can also inhibit the development of odours and grain discoloration.

This paper summarises the basic design parameters for in-store aeration and drying systems. The design of hot air continuous-flow dryers is beyond its scope.

From an engineering designer's point of view, aeration and in-store drying systems differ principally in the quantity of air that is required, and the possible addition of supplementary heating (for drying). Other engineering factors come into play when con-

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sidering some of the more sophisticated options for in-store drying, but the principal design parameters remain the same, and involve selection of:

- fan operation time fraction;
- specific airflow rate;
- airflow direction;
- air-duct distribution pattern;
- air-duct sizes; and
- fan or fans.

The selection of the specific airflow rate is the most significant of these design considerations. Compared with this, the selection of duct configuration, duct size, and fan type are relatively routine design matters. However, before the airflow rate is determined, it is important to select the fan operation time fraction.

Fan Operation Time Fraction

The fan operation time fraction is the percentage of time that fans operate when blowing air through a grain mass.

In the case of an in-store drying system, the need for controlling fan operation is relevant only when the grain moisture has reached a level that is close to equilibrium with the average daily relative humidity. In normal drying operations, the fans are run 100% of the time (even during periods of rain) in order to minimise the drying period.

In aeration systems, the fans are normally switched on and off for the purpose of selecting only the coolest air in order to reduce the temperature of the grain. Various control systems are used—including manual controls, fixed time settings, time proportional controls, and more sophisticated systems which monitor both air and grain temperature and/or relative humidity. Automated systems are far more efficient than manual ones, both in terms of minimising fan-hours and grain damage.

The most commonly used controller in Australia is the time-proportioning controller (developed by CSIRO), which automatically turns the fans on when ambient air temperatures go below a set point, and turns them off when it goes above it. The controller automatically adjusts the set-point to ensure that the fans operate for a set proportion of time. By reducing the proportion of time that an aeration system operates, the *slower* will be the rate of cooling of the grain (because less air is being used), but because it selects only the coldest air of the day, the controller ensures that the average temperature of the selected air will become lower as the aeration time fraction gets smaller. Hence, a time-proportioning controller has the effect of reducing the grain temperature as the time fraction is reduced.

Common practice (in Australia) is to select a fan operation time fraction of 50% for initial cooling of newly harvested grain (to speed up the cooling process), and to reduce this to 15% for 'maintaining' the grain and for further reducing its temperature, once the initial cooling has been achieved.

Specific Airflow Rates

General

The 'specific' airflow rate is the quantity of air passing through a grain mass divided by the volume of grain it passes through (e.g. measured in litres of air per second per tonne of grain, or $m^3/min/m^3$). Adjacent to an air duct (i.e. before the air passes through any grain) the specific airflow rate is infinitely large. As the air passes through the grain mass, the specific airflow rate becomes smaller and smaller, until it reaches a minimum value at the surface of the grain. It is this minimum value of specific flow rate that governs the cooling or drying performance of a system, since it defines the time that it takes for cooling and/or drying the grain mass.

Thus, the minimum specific airflow rate governs the speed of the 'temperature front' in the case of aeration, and the 'moisture front' in the case of grain drying. Estimating the speeds of both these fronts depends on a number of factors, the principal factors being—apart from the physical properties of the grain—the temperature and moisture of the grain and of the air being passed through it. Air temperature and moisture are highly variable factors, and the design engineer must often rely on the work of the research scientist to assist in determining the airflow rates applicable for aeration and in-store drying, especially in subtropical and tropical regions in which ambient conditions may often be only marginally useful for either purpose.

Aeration

Ideally, the airflow rate should be sufficient to allow cooling of a newly harvested grain mass within a period of about 4–5 weeks in temperate areas. The cooling period needs to be much less than this in subtropical and tropical areas unless the grain moisture is uniformly below an equilibrium relative humidity level of around 70%. A value for the cooling period can be estimated from equation (1) (from Hunter 1986):

$$q = \frac{\varepsilon}{GA\theta f_\rho} \qquad (1)$$

where q is the airflow rate in $m^3/kg/sec$;
ε is the porosity of the grain bed (say 0.41 for wheat);

A is the cooling front velocity ratio (i.e. cooling front speed/interstitial air velocity) (say 0.75×10^{-3} as a conservative figure);
θ is the desired cooling time (in seconds—say 3×10^6 for five weeks);
G is the flow distribution factor (say 0.8 for vertical storages and 0.5 for horizontal storages);
f is the fan operation time fraction (say 50% for initial cooling); and
ρ is the bulk grain density.

The above equation may give airflow rates that are slightly lower than those commonly recommended. Airflow rates commonly recommended for cooling aeration vary according to the climatic conditions and storage type, and these are summarised in Table 1 (from Foster and Tuite 1982).

Table 1. Recommended airflow rates for aeration.

Storage type	Temperate climate	Subtropical climate
Horizontal	0.8–1.6 L/sec/t	1.6 –3.2 L/sec/t
Vertical	0.4–0.8 L/sec/t	0.8–1.6 L/sec/t

The need for higher rates in horizontal storages is to allow for the fact that air distribution is less uniform. Higher airflow rates are recommended for warmer subtropical climates to provide more rapid cooling during the short periods when air temperatures are low enough to be used for aeration.

Ambient aeration effectively brings the wet-bulb temperature of the grain into equilibrium with the wet-bulb temperature of the air. All the benefits achieved through cooling of the grain through aeration (viz reduced insect activity, reduced moulding, etc.) are directly related to reduction in the *wet-bulb* temperature of the grain (or more specifically, the wet-bulb temperature of the interstitial air which is in equilibrium with the grain).

In order to evaluate the effectiveness of aeration on a grain mass, dry-bulb temperature readings of the grain should be taken regularly and converted to wet-bulb readings using a psychrometric chart or conversion tables (such as Table 2 which applies to wheat and maize). For optimum results, grain should (where possible) be cooled to around 10–15°C.

It should be clearly understood that the airflow rates which are useful for aeration of grain are quite insufficient to dry the grain other than to a very superficial extent. The benefits of aeration result only from the cooling of the grain and in equalising temperatures within the grain mass.

Drying

In the case of in-store drying, the critical requirement is not to preserve the condition of the grain, but to change its moisture content. The requirement is to dry it quickly enough that deterioration by moulding is prevented, and this may often require airflow rates 50 to 100 times those used for aeration.

The rate of moulding of grain is linked to its temperature and moisture content. Some species of moulds are active even at very low temperatures, and high moisture grain stored at or below freezing point may experience moulding if left long enough in storage. At high temperatures and high moisture, moulding takes place very quickly as can be seen from Table 3 (from Brooker et al. 1992).

The rate of drying—and hence the rate of airflow—must be such that the drying front passes through the grain mass before moulding starts.

The drying time can be roughly estimated from a heat balance equation such as equation (2) (from Brooker et al. 1992):

$$t = \frac{v h_{fg} (DM)(M_o - M_c)}{60 Q c_a (T_a - T_g)} \qquad \textbf{(2)}$$

where t = time (hours);
n = specific volume of the moist air used for drying (m^3/kg);
c_a = specific heat of dry air (J/kg/°C);
$(T_a - T_g)$ = dry bulb temperature drop through the grain mass;
h_{fg} = heat of vaporisation at saturation (J/kg);
DM = dry matter weight (kg);
M_o = initial grain moisture level (%);
M_e = equilibrium (final) grain moisture level (%); and
Q = airflow rate (m^3/hour).

Table 4 offers designers some general guidance on minimum airflow rates for wheat and maize (based on U.S. experience) in order to achieve drying rates fast enough to avoid moulding in temperate climates.

Note that slightly increasing the temperature of the air by adding heat will increase the rate of drying. However, the recommended airflow rates should not be reduced to account for this, since the increased drying air temperature also increases the temperature of the moist grain above the drying front, and thereby increases the rate of mould development. The airflow rates in Table 4 are therefore recommended for both ambient air drying, and low temperature air drying.

Table 2. Tabulated values of equilibrium wet-bulb temperature for grain at varying moisture content.

Dry bulb grain temp	5°C	10°C	15°C	20°C	25°C	30°C	35°C	40°C
(a) Wheat								
8%				3.7	6.5	9.6	12.3	15.3
10%			2.5	7.2	11.0	15.2	19.5	24.0
12%		1.0	6.0	10.2	14.7	19.0	24.0	28.5
14%		2.7	7.4	12.0	16.5	21.0	26.0	31.0
16%		3.8	8.5	13.0	18.0	22.5	27.3	
20%		4.9	9.8	14.6	19.3	24.0	29.0	
(b) Maize								
8%		2.2	6.0	10.0	13.9	18.0	22.4	26.8
10%	−1.0	3.5	8.0	12.2	16.4	21.0	25.8	30.7
12%	0.8	5.3	9.8	14.6	19.2	23.9	29.0	33.2
14%	1.9	6.7	11.6	16.2	21.1	26.0	31.1	
16%	2.8	7.9	12.8	17.7	22.5	27.4		
20%	4.0	9.1	14.2	18.8	23.8	28.8		

Table 3. Storage life of maize.

Maize temp (°C)	Storage life in days under aeration for varying maize moisture				
	15.5%	18%	20%	24%	30%
−1.1	2276	648	321	127	61
1.7	1517	432	214	85	40
4.4	1012	288	142	56	27
7.2	674	192	95	37	18
10.0	450	128	63	25	12
12.8	299	85	42	16	8
15.6	197	56	28	11	5
18.3	148	42	21	8	4
21.1	109	31	16	6	3
23.9	81	23	12	5	2
26.7	60	17	9	4	2

Table 4. Minimum airflow rates for in-store drying in USA.

Grain	Grain moisture (% wet basis)	Minimum airflow rate (m^3/m^3/min)	Minimum airflow rate (L/sec/t)
Wheat	20	2.4	30
	18	1.6	20
	16	0.8	10
Shelled maize and grain sorghum	25	40	50
	20	2.4	30
	18	1.6	20
	16	0.8	10

Source: USDA (1965).

The figures in Table 4 are consistent with those recommended for in-store drying of rice in near-tropical conditions (such as in Southeast Asia) where it is recommended that minimum airflow rates of 1.5 m^3/m^3/min are adopted. In-store drying in such regions should not be attempted unless the initial grain moisture is not more than 18% and the grain bed depth is less than 4 m.

Direction of Airflow

Consideration of direction of airflow direction is more usually associated with aeration system design than with drying systems. In-store drying systems almost always involve upward movement of air through the grain. Aeration systems, on the other hand, can use either upward or downward airflow.

There are advantages and disadvantages in both alternatives and there seems to be no universal consensus as to which option is better in any given circumstance. The advantages and disadvantages of each are summarised below.

Upward airflow aeration

Advantages

- The compression of the air as it is blown into the bottom of a storage, results in a small rise in air temperature and thereby a reduction in the relative humidity of the air. A temperature rise of 3–4°C can remove the danger of increasing grain moisture content in high ambient relative humidity conditions. This can be particularly important in subtropical climates where the lowest temperatures are recorded at night when relative humidity can be close to 100%.
- In situations where warm grain may be added to a bin after aeration has begun, the use of upward aeration avoids the situation where air passes first through the warm grain, and thence downwards to warm the previously cooled grain underneath.
- In hot conditions, air may be warmed under a storage roof. Upward aeration blows this warm air out of the storage, rather than pulling it down through the grain mass.
- The last cooled layer of grain in the grain mass is the top surface layer, where grain temperature and moisture levels are easily checked.
- Upward airflow results in more uniform air distribution, particularly in flat stores.

Disadvantages

- In cool conditions, the top surface of a grain mass will cool naturally, as will the roof of the storage. Upward airflow through warmer grain may result in condensation of moisture in the cooler upper layer, or on the underside of the storage roof. [This can be minimised by installing a small fan in the storage roof.]
- Increase in grain moisture levels around the aeration duct can occur if the average relative humidity of the aeration air is above the equilibrium relative humidity of the grain.

Downward airflow aeration

Advantages

- In cool conditions, including those applying to subtropical conditions, the risk of moisture condensation under the storage roof and in the upper levels of grain is minimised.
- In the event that high relative humidity air is used for aeration, any moisture increase in the grain is spread over the entire surface area, rather than concentrated around the air inlet duct. [Not relevant where an elevated plenum floor is used.]
- Greater cooling can be achieved because there is no heating effect from the fan. This can be important in tall silos where high static pressures are required.

Disadvantages

- There is no air temperature increase and reduction in relative humidity caused by the fan. This can be important in subtropical climates for the reasons described above.
- The slowest area to cool is at the bottom of the grain bulk where monitoring of grain temperature is difficult.
- It is inappropriate where warm grain may be loaded on top of grain that has already been cooled by earlier aeration.
- Grain dust can be drawn down through the grain bulk and cause choking of the aeration ducts.
- In silos with suspended steel floors: under freezing conditions in temperate climates, air may be warmed and moistened as it is drawn down through the grain bulk. This can result in severe condensation when the air comes into contact with the silo base and cause ice build up in the grain, preventing emptying of the silo.

It can be seen from the above that there are no clear arguments in favour of one system or the other. However, in Australia, upward aeration is more common than downward aeration, and most users in the USA are firmly in favour of upward aeration for the reasons given above.

Air Distribution Ducting

The method of distribution of aeration or drying air into a storage is important from the point of view of obtaining an acceptable uniformity of airflow in the grain mass.

There are three main types of distribution systems:

- elevated perforated storage floor;
- above floor air ducts; and
- in-floor air ducts.

Elevated perforated storage floor

The most efficient and uniform air distribution into a grain mass is achieved with an elevated perforated floor in the base of the storage, which effectively provides a 100% contact area between the grain mass and the incoming air (Fig. 1). This type of floor is effective only in flat floored storages, and is more costly than the alternatives. It is, however, very commonly used in the central mid-west of the USA where in-store drying is prevalent; some silo suppliers in the region manufacture pre-formed floor panels which lock together with light gauge support legs to form a relatively low-cost elevated perforated storage floor, suitable for cleaning out with a sweep auger.

Above-floor air ducts

More commonly, air is ducted into the grain mass (or out of it, in the case of downward aeration) by means of air-ducts that are either built into the storage floor, or are placed on top of it. Above-floor ducts are less costly, but make emptying of the storage more difficult, particularly with end-loaders or sweep conveyors. Nevertheless, above-floor ducts are a practical engineering solution, particularly when retrofitting ducting to an existing storage floor, and they can be particularly useful in self-emptying bin bottoms where their protrusion above the floor surface does not inhibit the discharge of grain.

Above-floor ducts are usually made from corrugated perforated steel sheet which is rolled into circular or (more commonly) semi-circular shape and fitted to the floor of the storage. In flat storages where the grain height is low (less than 10 m), it is common to install the ducts in a manner that makes them easily removable to allow emptying of the storage with end-loaders and other portable equipment—for instance, round ducts may be secured with hoops or straps and fixed to the floor with bolts screwed into recessed sockets cast into the floor so as to avoid protrusions which interfere with cleaning when the ducts are removed (Fig. 2).

It is not possible to corrugate and roll plate thicker than 1.6 mm, hence in deeper bins, where grain pressures are high, it is usually necessary to reinforce the ducts with steel framing (Fig. 3). In the case of sloping (e.g. conical) bin bottoms, it is necessary to securely anchor the ducts to the bin floor to prevent them being dragged down the floor with the grain (Fig. 4). Structural analysis and design of these ducts is an art rather than a science, since the load imposed by the grain on a duct is somewhat indeterminable and, furthermore, the load capacity of a reinforced corrugated steel duct is not easy to estimate accurately. Interestingly, in the writer's experience, few duct failures have occurred in bins of up to 2500 t capacity, whereas in larger capacity silos (5000 to 70 000 t) built in the 1980s, even heavily reinforced ducts have frequently failed as a result of unexpectedly high grain pressures.

An alternative to the use of corrugated rolled steel ducts, is the use of ducts formed with stainless steel 'wedge-wire', as used for the manufacture of rotary screens. Ducts formed from this material are extremely strong, and hygienic in that they largely prevent dust and brokens entering the duct through the apertures. They are, however, very much more expensive than corrugated perforated plate (Fig. 5).

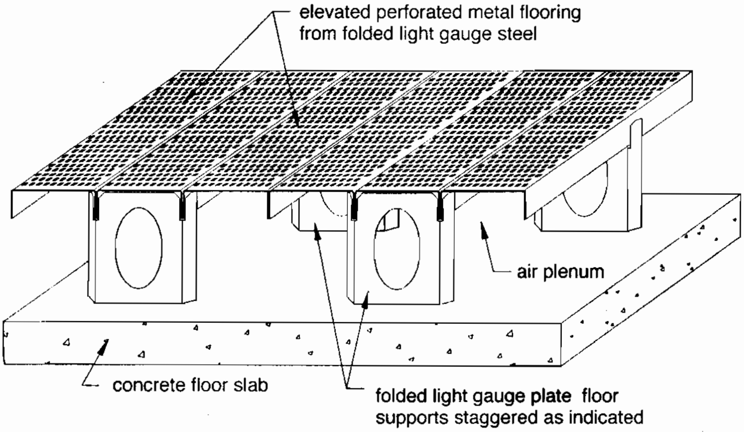


Figure 1. Method of construction of elevated plenum floor of a type commonly used in the USA.

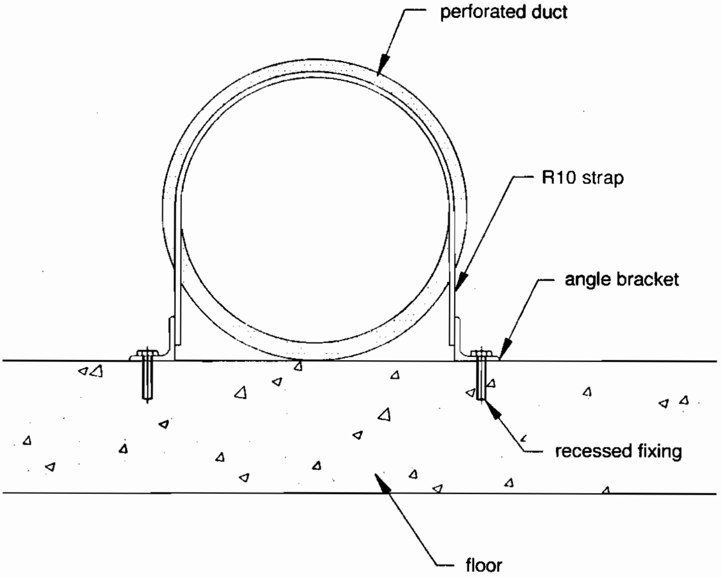
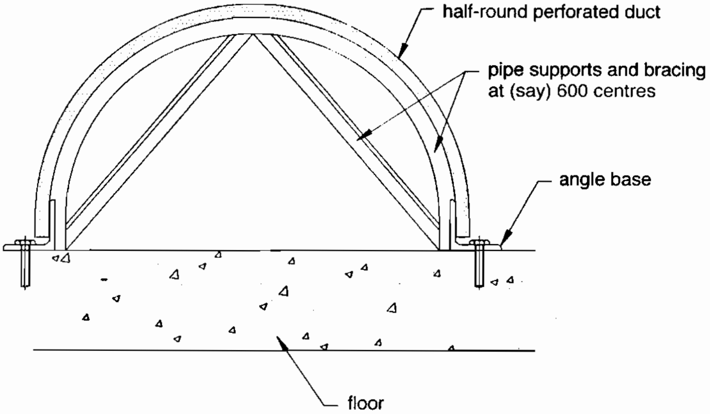


Figure 2. Typical circular aeration duct often used in horizontal storages.

Figure 3. Reinforced half-round ducting often used in silo bases.



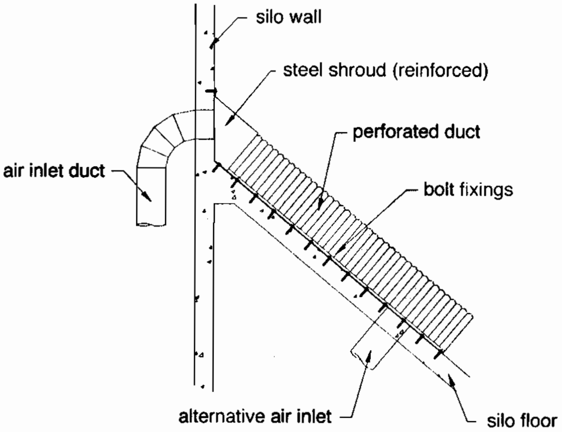


Figure 4. Reinforced half-round ducting as used in conical silo bases.

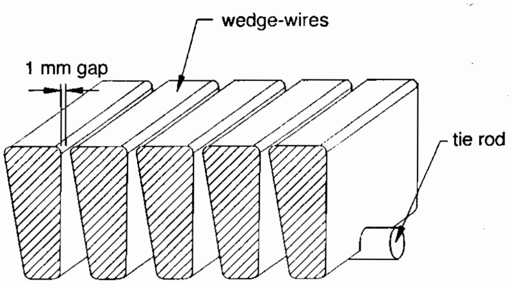


Figure 5. Typical section through wedge-wire screen.

Alternative above-floor ducts can also be formed from 'solid' plate without perforations, in such a way that allow air to escape around the bottom edges of the duct (Fig. 6). These are not commonly used in the writer's experience, but should work satisfactorily if they are made strong enough to resist the grain pressures imposed on them (Fig. 6).

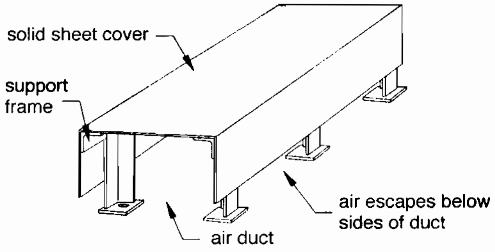


Figure 6. Non-perforated aeration duct, from which air escapes from below side walls.

In-floor air ducts

In-floor ducts are generally more expensive than above floor ducts, because the duct has to be formed (usually in concrete), and covered by a perforated steel plate placed flush with the floor surface to allow unrestricted movement of equipment for cleaning the grain off the floor surface. The perforated plate must thus be flat, and therefore substantial reinforcement must be provided, for example, in the form of an open lattice grillage made from welded steel flats (Fig. 7).

Alternatively, it should be possible to use the folded perforated steel plate sections manufactured for elevated silo floors to form covers for in-floor ducts, although the writer has not seen this done.

Where portable equipment (such as end-loaders) are used to remove grain from the storage, the wheel loads imposed on the duct covers are often more severe than the grain loads, and thus govern the design of the cover supports.

Duct Configuration

Horizontal storages

In 'horizontal' (rectangular) storages, ducts may be aligned across the storage or along the length of the storage. Both have certain disadvantages as follows:

- *Cross-floor ducts.* In a storage where the grain is peaked in the centre by use of a longitudinal conveyor, cross-floor ducts pass under varying depths of grain. As a result, the airflow rate from the outer ends of each duct will be higher than from the middle unless the ducting is modified in some way to minimise this, for instance by enlarging the duct below the centre of the storage. This has the combined effect of reducing the velocity head, and thus increasing the static pressure. It also increases the cross-sectional and surface areas of the duct, thereby reducing losses in that region (Fig. 8).
- *Longitudinal ducts.* The floor of a large horizontal storage is often only partially covered—e.g. when the storage is partly filled. In such circumstances, longitudinal ducting is exposed in the unfilled areas, and large quantities of air will escape, bypassing the grain mass.

Cross-floor ducting is usually the preferred option for horizontal storages because it allows easier control of airflow into the grain.

Ducts should be spaced as follows:

- For in-store drying, the duct spacing should be not more than half the depth of the grain (Fig. 9). (Grain depth must be uniform for in-store drying.)
- For aeration, the duct spacing should be such that the longest air-path from a duct to the grain surface is no more than 50% more than the shortest path from the same duct to the grain surface (Fig. 10).

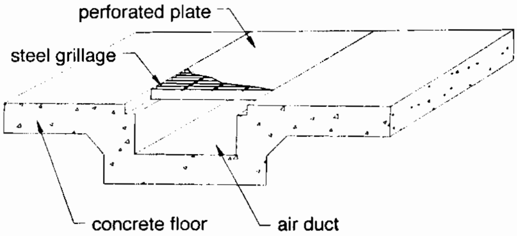


Figure 7. Typical arrangement of in-floor ducting.

Flat-bottom silos

There are several options for air distribution systems in flat-bottom silos which are less expensive than an elevated floor. The options include on-floor ducts and in-floor ducts.

Single radial duct. A single radial duct with an external fan can be used for aeration in small silos. However,

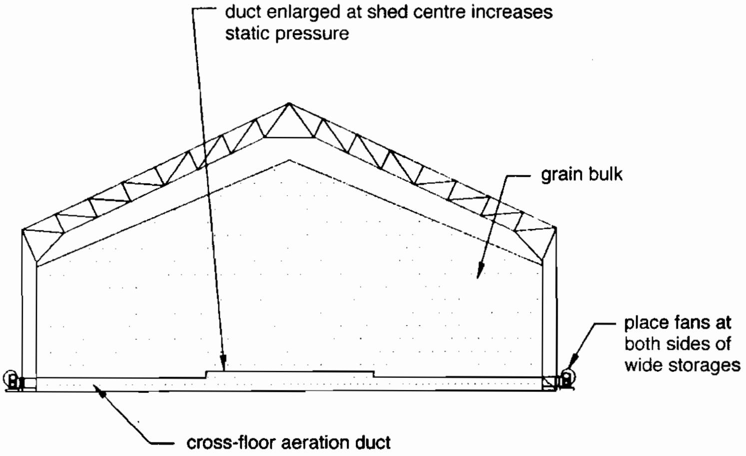


Figure 8. Arrangement of cross-floor aeration ducts and lateral duct enlargement in a large shed.

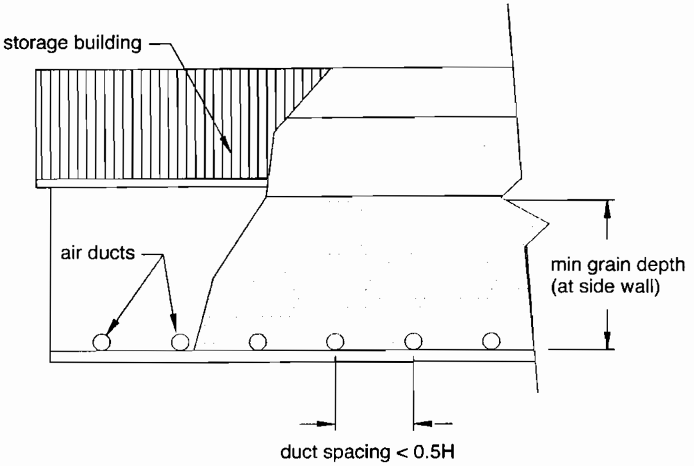


Figure 9. Duct spacing for in-store drying.

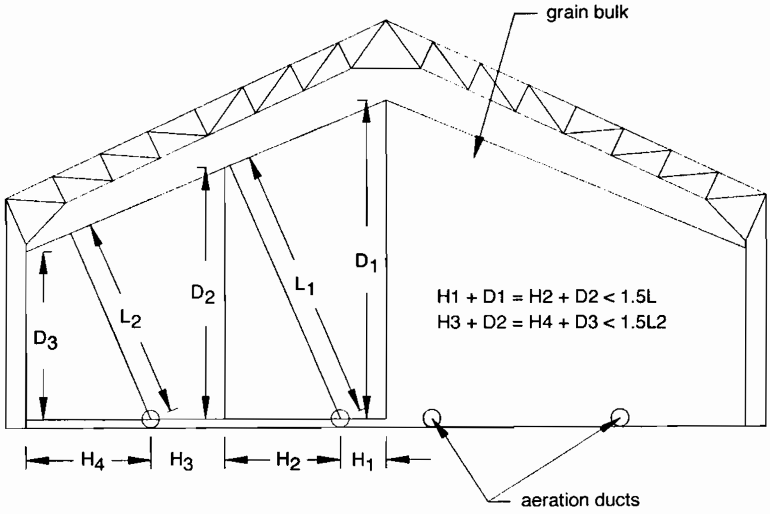


Figure 10. Recommended spacing of longitudinal ducts.

for large silos the duct size becomes excessive, and the air distribution pattern is not adequate. Single radial ducts are unlikely to be acceptable for in-store drying in silos. Multiple radial ducts are seldom (if ever) used because each duct requires a separate fan.

Parallel ducts. Parallel floor ducts are commonly used for both aeration and drying, differing only in their size and spacing. Duct spacing requirements define the number and layout of the ducts. However, the designer has to select the manifolding arrangement for the fan or fans, unless each duct is to be fitted with a separate fan. A 'tree' formation of manifold and ducts is often adopted where multiple ducts are fed from a single fan since this minimises the effective length of the path for the ducted air (Fig. 11).

V-ducts. V-formation ducts are commonly used to distribute air from a single fan into the base of flat bottom silos (Fig. 12). For in-store drying, this arrangement is suitable for only relatively small diameter bins, since in larger bins the space between the ducts becomes excessive. V-formation ducts are almost always recessed into the floor of the silo.

Perimeter ducts. Perimeter ducts have been successfully used for grain aeration in some relatively large (3000 t) flat-bottom silos designed by the author (Fig. 13). The aim was to provide good air distribution while leaving the silo floor free of protuberances. Quarter-round corrugated perforated steel plate was used to form the ducts, and each section of duct was hinged against the silo wall to permit easy access for cleaning brokens and dust.

Circumferential ducts. In 'squat' silos (i.e. silos with small wall-height to diameter ratio), the grain depth varies significantly from the outer perimeter to the centre of the silo. The length of airflow path (and hence the static pressure needed to force the air through the grain mass) thus varies significantly from the silo wall to its centre. Parallel ducts placed in the floor (even an elevated bin floor), are likely to result in a concentration of airflow towards the outer perimeter of the grain mass (where the airflow resistance is least) and substantially less airflow in the centre of the silo. The author has recently designed a system of circumferential in-floor ducts for grain aeration in such silos, each fitted with its own fan (or fans), and each duct and fan 'set' individually sized to suit the mass of grain above it. Thus, the fan serving the centre of the bin has a relatively low airflow rate but high static pressure, while the fan (or fans) serving the perimeter of the bin have a high airflow rate (because of the larger volume of grain around the perimeter) and a low static pressure (because of the lower grain depth). The system is so far untried, but is expected to be put into use on a project in China in the near future (Fig. 14).

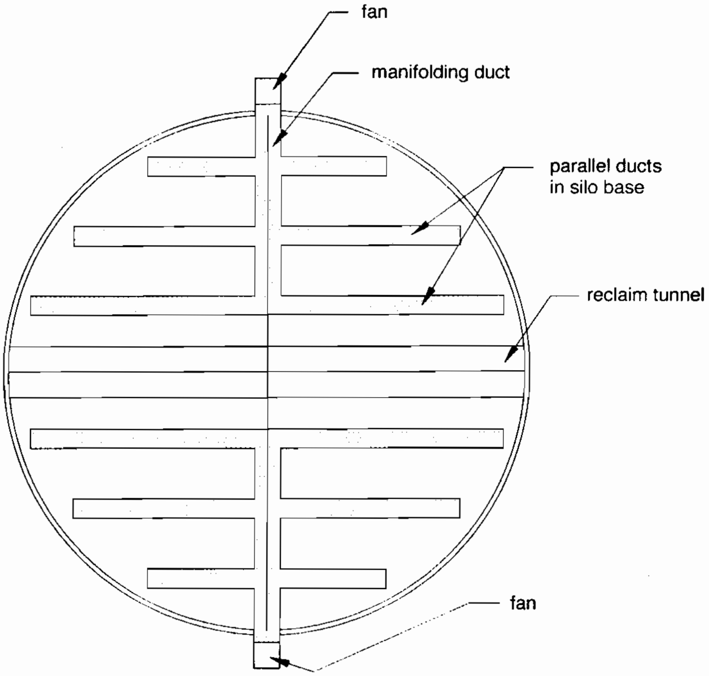


Figure 11. Typical parallel duct arrangement in a flat floor silo base.

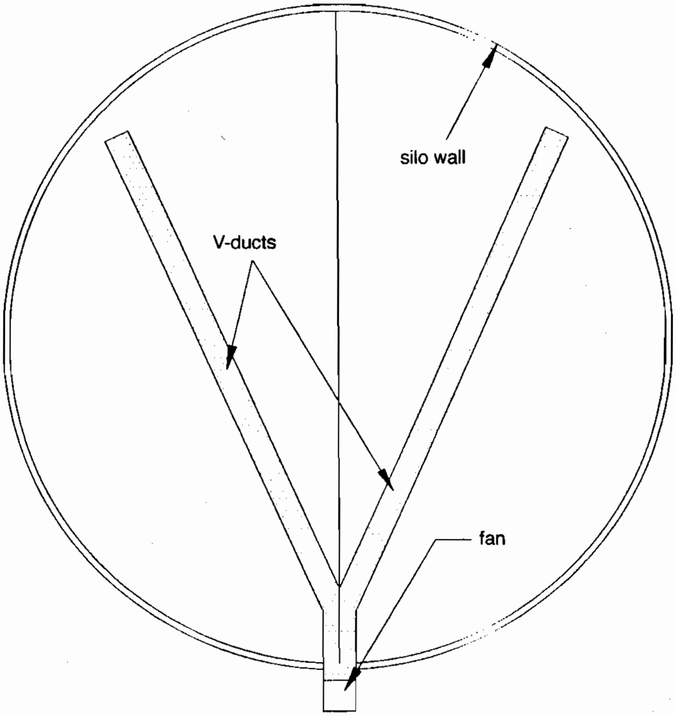


Figure 12. Typical V-duct arrangement in a flat-bottom silo.

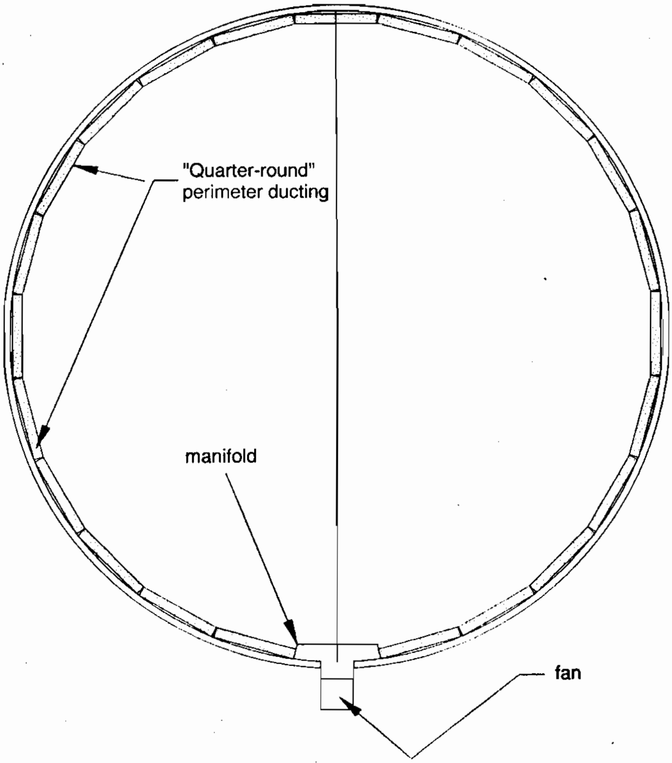


Figure 13. Arrangement of perimeter ducting in relatively large flat-bottom silos.

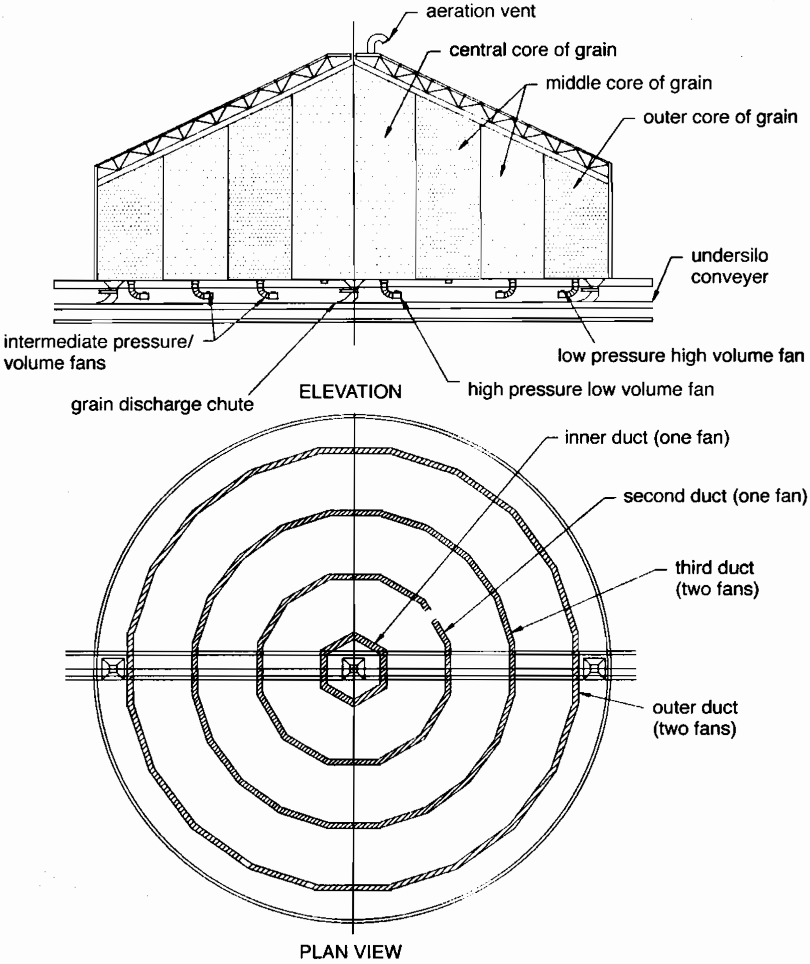


Figure 14. Aeration fan and duct arrangement for a 40 m diameter, 10 000 t silo.

Hopper bottom (self-emptying) silos

Hopper bottom silos are not often used for in-store drying of grain, since they are usually associated with high throughput requirements, which are generally inconsistent with the requirements for in-store drying. Aeration equipment is, however, often fitted to hopper-bottom silos to allow the silos to be used for 'holding' the grain for short periods without deterioration before shipping. Aeration is also often fitted to hopper bottom bins for cooling of grain after drying.

Aeration ducting in hopper-bottom silos is usually either perimeter-type or radial-type or a combination of both. Above-floor ducts are used in hopper bottom silos since there is no special advantage (but large extra costs) in building them in-floor.

Vertical ducts

Vertical ducts attached to the silo walls have occasionally been used for aeration of bins in such manner that air is blown (or sucked) horizontally across the grain in the silo, out from one duct and into the other.

Apart from requiring long ducts (full wall height) which are difficult to install, the biggest problem with them is the same as with longitudinal ducts in horizontal storages—they must be covered with grain if they are to work, and it is not possible to aerate a partially filled silo with them. There are few, if any, circumstances where they can be recommended.

Airflow Resistance in Ducts

Air movement in ducts

Air passing through ducts will lose energy from frictional effects associated with the duct shape, surface, turbulence, etc. This loss of energy results in a gradual loss in 'total pressure' (or head) as the air moves through the duct.

Total pressure is the sum of the static pressure and the velocity pressure. Static pressure is the 'normal' pressure that the air applies to the walls of the duct that it passes through; velocity pressure is the component of pressure that results solely from the movement of the air, and is equal to $V^2/2g$, where V is the velocity of the air, and g is the acceleration due to gravity. As air passes through a duct system, its velocity will change where the duct size changes; thus, where the duct size increases, the velocity pressure will decrease and the static pressure will increase, and vice versa. Along the duct system, however, the total pressure (the sum of the velocity and static pressures) will gradually diminish.

Airflow resistance in ducts depends on the size, shape, and smoothness of the duct and the velocity of air passing through it and the temperature of the air. Friction losses in straight ducts are normally determined from charts. Elbows, bends, T-junctions, etc. can add significantly to friction losses—for instance, a single right-angle 'mitre' bend in a square duct is equivalent to adding a straight duct with a length of about 75 times the depth of the duct. (Note: giving the bend a radius equivalent to the depth of the duct reduces the friction loss to an equivalent length of duct 11 times the depth.)

In most grain aeration and drying situations, duct lengths are short and few bends are required. In most circumstances, provided the air-velocity is kept low enough (see below), friction losses in ducts are small compared with the losses in the grain.

Air movement through duct perforations

The pressure drop through a perforated duct covered with grain can be estimated from Equation (3) (Brooker et al 1992):

$$\Delta P = 1.07\left(\frac{Qa}{\varepsilon O_f}\right)^2 \tag{3}$$

where: ε = void space in grain (%)

and O_f = percentage opening in duct surface (%).

where: $O_f > 10\%$, the pressure drop through the duct can be ignored.

Selection of air-duct sizes

Much work has been done recently in refining the methods of determining the optimum size of ducts for distributing air into a grain mass, and software is now available for carrying out these calculations (Wilson, S.G. 1991. Duct: a PC Program for designing seed store ducts. Personal communication). However, in the absence of such tools, there are two well recognised 'rules of thumb' which can be used to estimate the size of ducting that will minimise head losses.

- The cross-sectional area of the duct should be large enough such that the velocity of the air in the duct is not more than 10 m/second.
- The surface area of the duct should be large enough such that the escape velocity of the air from the duct into the grain is not more than 0.15 m/second (assuming a duct perforated area of approximately 10%).

Commonly used perforations suitable for grain aeration are 2.5 mm diameter holes at 6.25 mm (triangulated) centres, giving an open area of around 15%.

Airflow Resistance in Grain

There are various methods of determining the resistance of airflow through a grain mass, from which the fan characteristics and power requirements can be determined. Holman (1966) presented a simple graphical method in the form of curves for different types of grain, relating bed depth to static pressure, from which fan power could be determined.

Shedd's formula (Equation 4) is another method which can be used to calculate the airflow resistance per unit metre of grain depth:

$$\Delta P' = \frac{aQ_a^2}{\ell n(1 + bQ_a)} \tag{4}$$

where $\Delta P'$ = pressure drop per unit depth of grain

Q_a = airflow rate per unit area of floor

a and b are Shedd's constants which vary for each type of grain. Constants for some common grains are given in Table 5.

Shedd's formula gives results that are satisfactory for clean grain in small storage, but it does not reliably account for dirty grain or for deep masses of grain. It is suggested that the calculated pressure drops be increased by at least 50% to allow for factors that could restrict the airflow. Various studies have been conducted under a range of grain conditions from which Shedd curve multipliers can be determined based on variations in fines content, moisture content, filling method, and airflow direction (Brooker et al. 1992). It appears from some of these results that:

- a 3–5% fines content can increase airflow resistance by 50% above that for clean maize;
- the pressure drop per metre of maize reduces by about 50 Pa/metre per m^3/sec/m^2 of air flow (Q_a), for each 1% increase in moisture content; (the pressure drop for wheat changes by 200 Pa/metre per Q_a per 1% increase in moisture content);
- the use of mechanical grain spreaders in the inlets of silos can reduce airflow resistance significantly below Shedd's values; and
- the resistance to airflow through grain in a horizontal direction is significantly lower than in the vertical direction.

Table 5. Shedd's constants for airflow resistance.

Grain	a	b
Wheat	2.70×10^4	8.77
Shelled maize	2.07×10^4	30.40
Paddy	2.57×10^4	13.20
Sorghum	2.12×10^4	8.06
Barley	2.14×10^4	13.20
Oats	2.41×10^4	13.90
Rapeseed	3.99×10^4	4.20
Soybeans	1.02×10^4	16.00
Sunflower (oilseed)	2.49×10^4	23.70

Source: (ASAE Standards 1988)

Selection of Fans

Having determined the required airflow rate and the pressure drop in the system, it is a relatively easy matter to select the appropriate fan to meet the performance criteria.

Selection is best made from performance curves supplied by manufacturers. However, there are a few basic guidelines that designers should be aware of:

- Axial fans are most suited where static pressures are predicted to be less than 1 kPa. Above 1 kPa, centrifugal fans are likely to be more efficient. Thus, axial fans are usually used for aerating shallow depths of grain, whereas centrifugal fans are more commonly used on vertical silos.
- Axial fans are not generally suited to grain drying
- Axial fans are noisier than centrifugal fans because they usually operate at around 3000 rpm (compared with 1500 rpm for centrifugal fans). Sound attenuators may need to be fitted in noise-sensitive localities.
- Centrifugal fans should normally be of the backward-curved-blade non-overloading type. Use of this type of fan avoids overloading of the motor in situations when the airflow resistance is lower than normal and airflow rate higher than predicted—for example, when the storage is only partially filled. Fans with forward curved and straight blades will draw more air (and current) under such conditions, causing motor overloading.

Where a storage is designed so that it can be sealed for fumigation, the designer should specify fans that are readily sealable, and which have no exposed copper components which can be chemically attacked by phosphine gas. In the case of centrifugal fans, this may require minor modifications to the fan casing, for instance to allow bolting of a 'blanking' plate over the air inlet, and a gland or stuffing-box seal should be fitted where the impeller shaft enters the fan casing. Axial fans may need to be removed during fumigation with phosphine unless the motor and wiring can be sealed sufficiently to prevent entry of phosphine.

Conclusion

The paper describes the basic principles for the design of aeration and in-store drying systems. Space precludes a complete coverage of the subject, and designers should refer to some of the standard texts in the reference list for more detailed information, particularly relating to particular circumstances. The design parameters offered in this paper have been used by the author in a number of installations, and they have given good service in practice, which indicates that the parameters are at worst conservative and at best reasonably sound.

References

ASAE (American Society of Agricultural Engineers) 1988. Standards 1988. ASAE Data: ASAE D 272.1. St Joseph, MI., ASAE.

Brooker, D.B., Bakker-Arkema, F.W., and Hall, C.W. 1992. Drying and storage of grains and oilseeds. New York, Van Nostrand Reinhold.

Foster, G.H. and Tuite, J. 1982. Aeration and stored grain management. In: Christiansen, C., ed., Storage of cereal grains and their products. St Paul, MN., American Association of Cereal Chemists.

Holman, L.E. 1966. Aeration of grain in commercial storages. Marketing Research Report No 178. United States Department of Agriculture.

Hunter, A.J. 1986. Design of air distribution systems and fan selection for grain aeration. In: Champ, B.R. and Highley E., ed., Preserving grain quality by aeration and in-store drying: proceedings of an international seminar, Kuala Lumpur, Malaysia, October 1985. ACIAR Proceedings, No 15, 108–113.

USDA (United States Department of Agriculture) 1965. Drying shelled corn and small grain. USDA Farmers Bulletin 2214.

Further Reading

Bowrey, R.G. and Driscoll, R.H. 1985. A procedure to estimate the supplemental heating needs for in-store drying of paddy. In: Champ, B.R. and Highley, E., ed., Preserving grain quality by aeration and in-store drying: proceedings of an international seminar, Kuala Lumpur, Malaysia, October 1985. ACIAR Proceedings, No 15, 114–117.

Driscoll, R.H. 1985. The application of psychrometrics to grain aeration. In: Champ, B.R. and Highley E., ed., Preserving grain quality by aeration and in-store drying: proceedings of an international seminar, Kuala Lumpur, Malaysia, October 1985. ACIAR Proceedings, No 15, 67–80.

Hunter, A.J. 1983. Pressure difference across an aerated seed bulk for some common duct and store cross-sections. Journal of Agricultural Engineering Research, 28, 437–450.

Hunter, A.J. 1986. Thermodynamic criteria for optimum cooling performance of aeration systems for stored seed. Journal of Agricultural Engineering Research, 33, 83–89.

Navarro, S. and Calderon, M. 1982. Aeration of grain in subtropical climates. Rome, FAO Agricultural Services Bulletin, No 52.

Sutherland, J.W., Banks, P.J. and Griffiths, H.J. 1971. Equilibrium heat and moisture transfer in air flow through grain. Journal of Agricultural Engineering Research, 16, 368–386.

Wilson, S.G. 1994. A formulation that allows for variable seed depth in calculating flow along seed-store ducts. Journal of Agricultural Engineering Research, 58, 191–199.

Control Systems for Aeration and Drying of Grain

G. Srzednicki*

Abstract

Automatic control systems are becoming increasingly popular in grain drying processes. They include measurement, steering, monitoring and recording functions. The advantages include improvement in the product quality, minimisation of energy use, optimisation of labour inputs, and increased effectiveness. A good understanding and analysis of the drying process is essential for the design of a control system. The control systems for in-bin aeration and drying systems aim to regulate the fan operations. They will also control heater operations whenever heat is added to the drying air. In continuous-flow dryers, the parameters controlled are the drying air temperature and the speed of augers. The most common control systems used for grain drying are discussed. With increased interest in mechanical drying of grain under tropical conditions, the possibilities for introduction of automatic controllers are currently being investigated. This is occurring as a spin-off of the adaptive research in in-store drying that has been conducted over the last ten years by several ACIAR projects in Southeast Asia. It can be expected that the increasing adoption of mechanical drying systems in the countries of the region will be followed by the introduction of control systems to optimise the use of the equipment.

AUTOMATIC control plays an increasingly important role in the modern production processes and logistics. Even a well-trained operator cannot optimise a process purposefully and unequivocally. This is because production processes often involve non-linear relationships and dependencies. Rapid progress in the theory and practical applications of control systems has contributed to an improvement of productivity and performance optimisation. Also, reduction of fatigue of operators performing monotonous and repetitive tasks has resulted in a decrease in human errors. Operations involving temperature, humidity, pressure, speed, and viscosity will normally be controlled by microprocessor-based systems. Mathematical models are the basis for computer simulations that enable engineers to define the statistical limits of values for parameters that are usually subject to random effects. The great advantage of this approach is the move from an empirical to a model approach, where changes in values of parameters can be tested quickly instead of time-consuming building and testing of prototypes.

The control systems originated in the eighteenth century in the form of a speed controller for a steam engine designed by James Watt. Modern control theory emerged between World Wars I and II, through the work of Minorsky on ship steering controls that could be derived from differential equations describing the system. Later, Nyquist developed procedures to determine the stability of closed-loop systems based on the response of open-loop systems to the response of steady-state sinusoidal inputs (Ogata 1990). A very rapid development of control systems took place on the arrival on the market of affordable digital computers. This led to the widespread use of control systems in diverse areas including manufacturing, biological and biomedical applications, and transport and entertainment.

A sound understanding of the process that is to be controlled is essential for the design of a control system. The initial analysis examines the requirements of production and the capacity of the equipment used, the proposed control strategies, and the schedule of operations. It also includes an initial analysis of the potential benefits of the system.

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Mechanical drying, as an industrial operation, has seen applications of control systems for many years, especially for large-scale operations. However, with the decrease in cost of microprocessors, control systems have become increasingly accepted to capture the same advantages that they have brought to other areas of industrial production.

Grain Dryer Controls

Drying of grain to reduce the water activity of the product is the safest method of preserving grain from further deterioration during storage. The main types of dryers are in-bin dryers, using ambient air with or without supplemental heat, and continuous-flow dryers using heated air. There are also combinations of both systems, developed within the concept of two-stage drying. In a two-stage drying system grain is dried using a high-temperature fast dryer down to a moisture content of about 18% wet basis (w.b.), and then down to a safe storage moisture content (generally 14% w.b.) in an in-bin dryer using near ambient air. The latter is called an in-store dryer since grain will be stored after drying in the same bin or store (Srzednicki and Driscoll 1994). During extended storage, grain will usually also be aerated in order to further reduce the risk of deterioration.

The two main types of grain dryers require specific control systems related to their mode of operation. However, the principal objectives of the control systems are the same:

- uniform moisture distribution in the mass of grain without over- or under-drying;
- prevention of grain deterioration;
- optimum grain quality;
- maximum capacity; and
- low energy consumption.

Controllers, relevant components of the dryer, and the operator interact to achieve these objectives. The level of the interaction is used to classify different types of controls as follows (Pym and Adamczak 1986).

Manual systems

Information about the process is collected by the operator on dials or chart recorders and analysed according to established procedures or experience. The decision is made by the operator and translated into action through manually operated switches or levers.

Supervised systems

These could also be called semi-automatic systems. The operator receives information about the ongoing process on displays with adjustable setpoints that are providing a partial feedback control. However, some decisions have to be made by the operator according to established procedures and translated into action by adjusting setpoints or switches.

Automatic systems

Here, the function of the operator is largely taken over by a microprocessor that is programmed to interact between the information supplied by the sensors and the appropriate action to be taken by relays or actuators. The system will automatically handle most of the alarm conditions and also provide automatic reporting. There is still need for an operator to reset the system in case of a power failure or emergencies, but their involvement will be minimal as compared with the two previous systems.

Automatic control systems use algorithms based on mathematical models representing physical and chemical characteristics of the process, and information obtained through simulation or experiments. Mathematical simulations describe the process with sufficient accuracy to predict the result without the need for use of empirical methods. The introduction of automatic controls results in optimisation of performance of dynamic systems, in increased productivity, and in a reduction in drudgery and the risk of human error.

Control theory uses specific terminology that is defined in a number of textbooks (e.g. Shinskey 1988; Ogata 1990). The following terms are used throughout this paper:

- A *controlled variable* is a quantity or condition that is measured and controlled.
- A *manipulated variable* is the quantity or condition that will be changed in order to achieve the desired value of the controlled variable.
- A *closed-loop system* or *feedback control* is a system that reduces error in order to produce required output. The latter is generally referring to the product created by the process.
- An *open-loop system* is one in which there is no relation between control action and output.

Control Systems for Continuous-flow Dryers

Continuous-flow high-temperature dryers are used for drying large quantities of grain, generally in several passes, from field moisture down to at least 18% w.b. moisture content. This is a continuous operation involving grain of different initial moisture contents and therefore requiring appropriate adjustments of the residence time. The main types of continuous-flow dryers used in the grain industry are:

- crossflow;
- concurrent-flow;
- counterflow; and
- mixed-flow.

A comprehensive review of control systems for continuous-flow dryers can be found in papers by Bakker-Arkema et al. (1990) and Moreira and Bakker-Arkema (1992). The following cover the key points.

The residence time of grain in the dryer is the factor that determines the final moisture content and consequently the quality of the grain. Over-drying and under-drying are undesirable and lead to reduced profits of the plant. The operator or the control system has to adjust the speed of the unloading auger for a given temperature and initial moisture content of the grain. Control systems have been developed in order to minimise over-drying and under-drying of grain as compared with the manual intervention of the operator. An evolutionary process led to development of five generations of controls.

Classical feedback control

In earlier days, the operator checked the inlet and outlet moisture content on an hourly basis and adjust the speed of the auger manually. The first automatic controllers were temperature-triggered feedback controllers, measuring the temperature of the grain or of the exhaust air at different locations in the drying column. However, because of the non-linearity of the drying process, and lack of a consistent relationship between the moisture content and the temperature of the exhaust air, such systems were unreliable, especially if the moisture content changes exceeded 3% w.b. For this reason, the temperature-activated systems have gradually been replaced by moisture-activated ones.

The classical feedback controls are based on proportional-integral (PI) or proportional-integral-derivative (PID) closed-loop controls using algorithms that minimise the error between the output and the controlled variable. These controllers perform well if the relationship between the controlled and the manipulated variable is linear and if the time response is short (Whaley 1995). As already mentioned, nowadays, the controlled variable in this case is the grain moisture content. However, the classical feedback system is unstable if the moisture range is wide. This is due again to non-linearity of the drying process and the grain flow. An attempt has been made by Whitfield (1988a,b) to overcome this problem by modifying the control algorithm so as to increase the bandwidth of moisture range. This implies an initial tuning of parameters by the operator as well as recalibration, especially if there are differences in the bulk density of the grain. Another problem, common to all feedback controllers, is a slow response of the controls in case of long residence time in the dryer. In recent times, attempts have been made to increase the robustness of the controls by using linearising transformations in the control software (Courtois et al. 1995)

Optimal feedback control

This type of control uses an algorithm based on a process model approximating the drying model. The technique used attempts to minimise the governing equation by quadratic programming. In spite of the great accuracy of this type of control, the difficulty in defining the governing equation and a high computational requirement make this type of control unlikely to be adopted on a commercial scale.

Feedforward control

The principle of this type of control is based on a continuous or intermittent measurement of the main load variable, i.e. the initial grain moisture in a continuous-flow dryer. The residence time is calculated by the model based algorithm and the response time is very short. Differential equations have been developed for the transient analysis of concurrent-flow, crossflow, and mixed-flow dryers. Empirical models have then been derived from the differential equations in order to simulate the operation of each of these three types of dryer. Whitfield (1986) used a steady-state simulation to predict unsteady states caused by varying inlet moisture contents for controlling concurrent and counter-flow grain dryers. Moreira and Bakker-Arkema (1990a) developed a partial differential equation model that describes the unsteady-state operation of a two-stage concurrent-flow dryer for maize. This model was used to design an automatic control system for such a dryer. Platt et al. (1991, 1992) combined a feedforward and feedback control in order to incorporate the use of optional features for cross-flow dryers, such as inverters (aiming at reducing gradients in grain temperature and moisture across the dryer) and air recirculation. Bruce and McFarlane (1993) developed a feedback-plus-feedforward algorithm that eliminates the influence of variations in drying air temperature in mixed-flow dryers.

Adaptive control

The previously described feedback and feedforward controllers are characterised by fixed parameters used in the control law. Since a dryer operating under normal commercial conditions faces the problem of fluctuations in inlet grain moisture and temperature of the drying air, this type of control system often results in inaccurate control, leading to increased variability of the final moisture content in grain. The adaptive control system enables the controller to tune itself in spite of such fluctuations. A number of researchers worked on the process model for adaptive control. A moisture-activated feedforward controller for a crossflow dryer has been developed by Forbes et al. (1984). Nybrant (1988) developed an adaptive feedback controller for crossflow dryers, based on a linear model using exhaust air temperature. Eltigani and Bakker-Arkema (1987) developed an adaptive model based on feedforward control for crossflow dryers. It is a two-term linear model with model parameters estimated by the sequential least square method. An adaptive feedforward/feedback control for crossflow dryers has been developed by Moreira and Bakker-Arkema (1990b). Two linear models have been proposed by the authors, namely the generalised minimum variance controller and the pole placement controller. The pole placement controller was found to be faster, required fewer parameters to be estimated, and was easier to implement. It controlled the final moisture content of grain within ±0.1°C of the set-point for a moisture content differential of ±2.3% w.b. in the incoming grain.

Fuzzy logic (expert) controllers

The complexity of the control objectives, especially when the quality aspects of grain are concerned, often make them difficult to achieve using conventional controls based on a set of governing equations. This is often due to insufficient understanding of such phenomena as breakage susceptibility. Therefore, research has been carried out in recent years on fuzzy logic control and neural network strategies control that combine mathematical models of the drying process and the experience of the operator. The result is a set of rules, kept in a knowledge base, that convert linguistic control strategies into automatic commands (Zhang and Litchfield 1993, 1994). The rules are represented as membership functions called fuzzy membership matrices. The difficulty in implementing this type of control is that there is a large number of rules associated with fuzzy membership matrices. In order to implement the fuzzy logic control, the membership functions have to be fine-tuned using a wide range of process conditions, which often proves very time consuming. Although very promising at an experimental stage, fuzzy control usually requires a considerable amount of historical process data in order to be included in industrial applications.

Control performance assessment

Douglas et al. (1992) describe a method for quantification of control performance of moisture controllers for continuous-flow dryers. The authors introduce two indicators of performance called performance measures PM1 and PM2. They are defined as follows:

$$PM1 = S^{NT}_{out}/S_{out} \quad (1)$$

where S^{NT} = outlet standard deviation of the moisture under 'no touch' control, and S_{out} = outlet standard deviation of the moisture with control.

$$PM2 = OS_{allowable}/OS_{actual} \quad (2)$$

where $OS_{allowable}$ = percentage amount of acceptable off-specification product, and Os_{actual} = percentage amount of actual off-specification product.

The performance measures reflect the product moisture variation and the deviation of the mean from the target. The higher the value of the two indicators, the better is the performance of the dryer. Both performance measures can be used to compare performance of various types of continuous-flow dryers.

Control Systems for In-bin Dryers

The term 'in-bin dryers' describes a drying system that uses a fan and an air distribution system that will force drying air through the bulk of grain. The grain is contained in a bin that can be a metal or concrete silo or a horizontal warehouse. There is a range of types and sizes, varying in capacity from about 30 to several thousand tonnes. There are also various types of air distribution systems, such as perforated floors, in floor or on-floor horizontal perforated ductings, and vertical perforated ductings.

In-bin dryers can be one or other of two types. In the *high temperature type*, hot air is blown through a shallow depth of grain in order to achieve rapid drying. In the other type, air of *near ambient temperature,* or only slightly heated (usually by a maximum of 5°C above ambient) is passed through the grain mass. The relative humidity of the drying air corresponds to the equilibrium moisture content of grain that can be stored safely without significant deterioration. Grain can be dried in deep layers in the same bin, silo, or warehouse in which it will be stored. This technique is also called *in-store drying*.

During extended storage, grain that has already been dried, will need to be aerated in order to:

- reduce the grain temperature and prevent it from deterioration;
- equalise the temperature throughout the bulk of grain;
- control insects by preventing formation of hot spots; and
- prevent formation of off-odours.

The control system for in-bin drying or aeration is of the open loop type, which means the output is generally not measured or fed back to be compared with the input. The control acts on the fan and heater in high-temperature dryers and in-store dryers equipped with heaters, or on the fan alone in in-store dryers using only ambient air and in grain aeration systems. The measured variable is the temperature or relative humidity of ambient air, whereas the controlled variable is the temperature or the relative humidity of the drying air. The grain temperature is an indication of the progress of drying. In grain aeration, grain temperature may become the measured variable, triggering the fan action.

There are various performance criteria associated with the use of control systems in in-bin drying (Bakker-Arkema et al. 1990; Ryniecki et al. 1993b). Among the most commonly used are:

- energy consumption;
- over-drying;
- spoilage estimated by different methods (e.g. spoilage index, dry matter loss, etc.); and
- drying time.

Over twenty strategies have been proposed to meet these criteria (Moreira and Bakker-Arkema 1992). They involve a range of parameters such as time, temperature, or relative humidity of the drying air, target moisture content in the top layer of the grain bulk, or estimated dry matter losses. Grain drying mathematical models estimating the average moisture content of the grain bulk or grain quality criteria have been used to write control algorithms. Ancillary equipment aimed at improving the uniformity of drying (grain stirrers) and reduce the energy consumption (recirculation) has been included in the control systems with varying degrees of success (Srzednicki and Driscoll 1994). Studies aimed at optimising values of control parameters are usually based on repeated computer simulations involving a large amount of historical weather data. Stochastic models of heat transfer in a thin-layer of grain and of ambient air temperature variation have been developed in order to further optimise the value of control parameters (Ryniecki and Jayas 1992). Most of the control strategies are based on experience, but some involve mathematical optimisation techniques (e.g. Ryniecki 1991; Ryniecki and Nellist 1991a,b; Ryniecki et al. 1993a,b). Ryniecki et al. (1993a, b) compared two locations with different climatic conditions, one maritime (England), the other dry continental (Canada). A large number of computer simulations using 20 years of weather data on a hourly basis has been run using different control strategies, based on relative humidity of the drying air with fixed or variable power heater or without heater, for near-ambient air temperature drying of wheat. The above-mentioned performance criteria have been used to assess the effectiveness of the process. The authors found that a fan and heater combination with variable power heater was the optimum system for the humid maritime conditions of England, whereas a fan-only system proved to be the optimum for the dry continental conditions of Canada. Furthermore, it was found that, for the fan-only system, variable airflow significantly reduced over-drying, energy consumption, and subsequently the drying cost as compared with fixed airflow. However, a variable speed drive needed to vary the airflow rate implies additional investment in the drying plant. As a result of this work, it appears that the choice of the strategy depends very much on the climatic conditions of the site and requires a careful study of the weather conditions before the selection of a control strategy.

In high-temperature in-bin dryers the control is focusing on the temperature of the drying air and is the simplest of control systems for in-bin drying. As for the near-ambient temperature drying, the following strategies have been commercially adopted:

- continuous aeration with additional heat (max. $\Delta T = 6°C$);
- relative humidity control with upper limit;
- relative humidity control with lower and upper limit; and
- self-adjusting equilibrium moisture content.

Grain aeration being a technique to maintain the quality of grain in storage consists in blowing cool air through the grain bulk. In temperate countries this process can involve cold ambient air during winter months, cool air during the night, or artificially cooled air if ambient air temperature is high. The control strategies consist in aerating either at regular intervals, using a timer, an air temperature based time proportioning controller (Pym and Adamczak 1986), or a grain temperature based system, activated by increasing temperatures in the grain. The difficulty with the time proportioning controller is that it disregards the relative humidity of ambient air and introduces the risk of grain rewetting.

Applications of Control Systems under Humid Tropical Conditions

Southeast Asia is one of major grain-producing areas in the humid tropics. Rice and maize are by far the main cereal crops grown in the area. Two or more crops per year are becoming a permanent feature in most of the countries. This implies that some of the annual crop will be harvested during the wet season. The region is currently characterised by very rapid economic growth resulting in higher purchasing power and increased demand for quality grain. In order to satisfy the domestic demand and the export requirements, the grain industry is improving the productivity, resulting in increasing adoption of modern technology in grain drying. Large grain complexes and mills are nowadays using high-temperature dryers, and control systems are often supplied as an option by the manufacturers.

The two-stage drying technique with in-store drying as a second stage is also being adopted by the grain industry (Srzednicki and Driscoll 1995). The technical feasibility of in-store drying under humid tropical conditions has been established through collaborative work over the past 12 years between the Australian team from the University of New South Wales and research teams in the Philippines, Malaysia, Thailand and, more recently, Vietnam (Driscoll 1987; Rukunudin et al. 1988; Driscoll and Adamczak 1988; Srzednicki and Driscoll 1992). Already, during the early stages of the research, some attention was given to control systems for in-store dryers (Driscoll et al. 1989). As previously mentioned in comparing the strategies used for humid maritime and dry continental climate, in-store drying in the humid tropics requires a fan and heater for the wet season. Meanwhile, during the dry season, drying of grain can be performed satisfactorily using a fan only. The following four strategies have been devised and tested:

a) time clock control (including continuous aeration);
b) drying air temperature control;
c) relative humidity control; and
d) modulated burner control.

Given the fact that mechanical drying is still a new technique, slowly gaining ground against sun drying, especially during the dry season, it is difficult to justify additional investment in automatic control systems. An experienced operator will often be capable of switching on the fan at certain times or off when relative humidity is outside a suitable range for drying. A thermostat will also provide a crude control of the drying air. However, optimisation studies comparing drying cost for three of the above four strategies (a, c, and d) in different locations throughout the region (Malaysia, Philippines and Thailand) in dry, wet, and average years, for paddy and for maize, have shown that relative humidity control was the least expensive strategy followed by continuous aeration (Srzednicki and Driscoll 1993). The trend to generate supplemental heat by use of a rice hull furnace is reducing considerably the cost of heat energy in Vietnam (Phan Hieu Hien and Nguyen Le Hung 1995). Rice hull furnaces for in-store dryers are also under development in Thailand and the Philippines.

As far as aeration is concerned, a grain cooling system aiming at maintaining grain temperature at 19–20°C has been implemented at seventeen grain complexes of BERNAS, the recently corporatised rice handling authority in Malaysia (Teoh and Hassan 1995). The control system is based on the grain temperature and cooling is triggered by the maximum temperature grain is allowed to reach.

Hardware for Control Systems

The most commonly used process control methods today incorporate digital controllers. Among them is a considerable number of PID type feedback single loop controllers. Larger control systems will use programmable logic controllers (PLC). PLCs handle well a linear process with large time constants. However, model based controls will often require a large computational power and will require the use of process computers. The prices of PLCs and microcomputers have fallen considerably in recent years, making them more affordable for potential users. Sensors are an essential component of the system. There is a wide range of qualities and prices. Some of the sophisticated in-line moisture meters for continuous-flow dryers may be worth an equivalent of a medium capacity dryer. It is obvious that their chance of adoption is limited to very large capacity units, generally owned by large grain authorities.

As far the control system for in-store drying is concerned, given that it is based on the temperature or relative humidity sensors, plug-in data acquisition cards offer a cost-effective alternative to PLCs. Plug-in data acquisition boards plug directly into the expansion bus of a PC. Multi-function data acquisition boards include analog/digital converters, digital input/output ports as well as counter/timer circuitry. A multi-function card (Fig. 1) can be interfaced with a signal conditioning board for analog data input (from sensors) and a relay board that triggers different actions required by the process (e.g. fan, heater, dampers).

Conclusions

Control systems for grain dryers have shown rapid development in the last fifteen years. For high-temperature dryers, the control parameters are exit air temperature or the moisture content of the inlet and of the exit grain on one hand, and the speed of the discharge auger on the other. The grain moisture based controls are more accurate, but the cost of the system is higher, primarily due to the cost of the sensor. Among the commercially adopted systems are the classical feedback control and the adaptive feedback/feedforward control. The feedback control is generally slow if the residence time is long. The adaptive feedback/feedforward controller provides fast response and reduces the fluctuations of the moisture content in the exit grain irrespective of fluctuations in the moisture of the inlet grain.

As for the control system of in-bin drying, the controller acts on the fan and the heater, if the latter is required. The climatic conditions of the location determine which strategy is to be adopted. A single strategy may only partially satisfy the performance criteria (low energy consumption, prevention of overdrying, low spoilage, short drying time). Optimisation techniques are being used in order to reconcile the performance criteria.

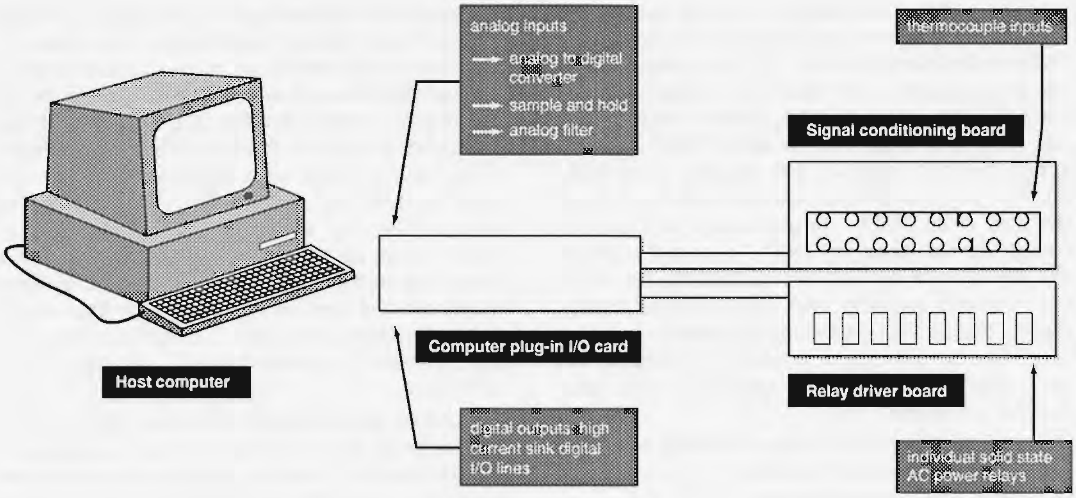

Figure 1. Data acquisition board with secondary boards (adapted from IDC 1995).

Control systems are also being introduced for in-store drying in the humid tropical climate of Southeast Asia. Relative humidity control and continuous aeration prove to be the most successful techniques for a range of climatic conditions in Southeast Asia. However, the rate of adoption of controllers is slow, except for large capacity dryers. This situation is related to relatively high cost of control equipment as compared with low margins for high quality grain. Plug-in card based systems may become an attractive option, promoting adoption of automatic controllers and resulting in improvement of grain quality and reduction of the cost of grain processing.

References

Bakker-Arkema, F.W., Kelley, R.L., and Moreira, R.G. 1990. In-bin and continuous-flow dryer controls. Paper 90-6565. An ASAE meeting presentation, Chicago Illinois, USA, 18–21 December 1990. St. Joseph, Michigan, USA, American Society of Agricultural Engineers.

Bruce, D.M. and McFarlane, N.J.B. 1993. Control of mixed-flow grain dryers: an improved feedback-plus-feedforward algorithm. Journal of Agricultural Engineering Research, 56, 225–238.

Courtois, F., Nouafo, J.L., and Trystram, G. 1995. Control strategies for corn mixed-flow dryers. Drying Technology, 13, 5–7, 1153–1165.

Douglas, P.L., Sullivan, G.R., and Whaley, M.G. 1992. Control performance measures for grain drying processes. Transactions of the American Society of Agricultural Engineers, 35, 4, 1235–1241.

Driscoll, R.H. 1987. Drying strategies for the humid tropics. In: Champ, B.R., Highley, E., and Remenyi, J.V., ed., Technological change in postharvest handling and transportation of grains in the humid tropics. Proceedings of an international seminar held at Bangkok, Thailand, 10–12 September 1986. Canberra, ACIAR Proceedings No 19, 58–68.

Driscoll, R.H. and Adamczak, T. 1988. Drying systems for the humid tropics. In: Champ, B.R. and Highley, E., ed., Bulk handling and storage of grain in the humid tropics. Proceedings of an international workshop held at Kuala Lumpur, Malaysia, 6–9 October 1987. Canberra, ACIAR Proceedings No 22, 58–68.

Driscoll R.H., Adamczak, T., and Samsudin, A. 1989. Control options for in-store drying. In: de Mesa, B.M., ed., Grain postharvest systems. Proceedings of the Tenth ASEAN Technical Seminar on Grain Postharvest Technology, Bangkok, Thailand, 19–21 August 1987. Bangkok, Thailand, ASEAN Crops Postharvest Programme, 44–51.

Eltigani, A.Y. and Bakker-Arkema, F.W. 1987. Automatic control of commercial crossflow grain dryers. Drying Technology, 5, 610–619.

Forbes, J.F., Jacobson, B.A., Rhodes, E., and Sullivan, G.R. 1984. Model based control strategies for commercial grain drying systems. Canadian Journal of Chemical Engineering, 62, 773–779.

Moreira, R.G. and Bakker-Arkema, F.W. 1990a. Unsteady-state simulation of a multistage concurrent-flow maize dryer. Drying Technology, 8, 1, 61–75.

— 1990b. A feedforward/feedback adaptive controller for commercial cross-flow grain driers. Journal of Agricultural Engineering Research, 45, 107–116.

— 1992. Grain dryer controls: a review. Cereal Chemistry, 69(4), 390–396.

Nybrant, T.G. 1988. Modelling and adaptive control of continuous grain driers. Journal of Agricultural Engineering Research, 40, 165–173.

Ogata, K. 1990. Modern control engineering. Englewood Cliffs, New Jersey, USA, Prentice Hall, 963p.

Phan Hieu Hien and Nguyen Le Hung 1995. Drying research and application in the Mekong Delta of Vietnam. Adoption of in-store drying technology in Southeast

Asia. Paper presented at the 17th ASEAN Technical Seminar on Grain Postharvest Technology, Lumut, Malaysia, 25–27 July 1995.

Platt, D., Rumsey, T.R., and Palazoglou, A. 1991. Dynamics and control of cross-flow grain dryers. 1. Model development and testing. Drying Technology, 9(1), 27–60.

— 1992. Dynamics and control of cross-flow grain dryers. 2. A feedforward-feedback control strategy. Drying Technology, 10(2), 333–363.

Pym, G.R. and Adamczak, T. 1986. Control systems for the aeration and drying of grain. In: Champ, B.R. and Highley, E., ed., Preserving grain quality by aeration and in-store drying. Proceedings of an international seminar held at Kuala Lumpur, Malaysia, 9–11 October 1985. Canberra, ACIAR Proceedings No 15, 118–128.

Rukunudin I.H., Samsudin, A., Norin, S. and Kassim, B. 1988. Bulk in-bin storage of paddy under Malaysian weather conditions. In: Champ, B.R. and Highley, E., ed., Bulk handling and storage of grain in the humid tropics. Proceedings of an international workshop held at Kuala Lumpur, Malaysia, 6–9 October 1987. Canberra, ACIAR Proceedings No 22, 205–211.

Ryniecki, A. 1991. Control systems for near-ambient grain drying. In: Chelkowski, J., ed., Cereal grain—mycotoxins, fungi and quality in drying and storage. Amsterdam and New York, Elsevier Science Publishers B.V., 499–511.

Ryniecki, A. and Jayas, D.S. 1992. Stochastic modelling of grain temperature in near-ambient drying. Drying Technology, 10, 1, 123–137.

Ryniecki A., Jayas, D.S., and Muir, W.E. 1993a. A generalized control-strategy for near-ambient drying of wheat under Canadian-prairie climate. Transactions of the American Society of Agricultural Engineers, 36(4), 1175–1183.

Ryniecki A., Muir, W.E., and Jayas, D.S. 1993b. Optimisation of control systems for near-ambient drying of wheat under maritime and continental climates. Postharvest Biology and Technology, 2, 217–230.

Ryniecki, A. and Nellist, M.E. 1991a. Optimization of control systems for near-ambient grain drying: Part 1, The optimization procedure. Journal of Agricultural Engineering Research, 48, 1–17.

— 1991b. Optimization of control systems for near-ambient grain drying: Part 2, The optimizing simulations. Journal of Agricultural Engineering Research, 48, 19–35.

Shinskey, F.G. 1988. Process control systems. Application, design, and tuning, 3rd ed. Singapore, McGraw-Hill International Editions, 526p.

Srzednicki, G.S. and Driscoll, R.H. 1992. In-store drying trial in Malaysia. In: Naewbanij, J.O., ed., Proceedings of the 13th ASEAN Seminar on Grain Postharvest Technology, Bandar Seri Begawan, Brunei Darussalam, 4–7 September 1990. Bangkok, ASEAN Grain Postharvest Programme, 197–210.

— 1993. Economic aspects of in-store drying in Southeast Asia. In: Naewbanij, J.O., Manilay, A.A., and Frio, A.S., ed., Increasing handling processing and marketing efficiency in the grain postharvest system. Proceedings of the 16th ASEAN Seminar on Grain Postharvest Technology, Phuket, Thailand, 24–26 August 1993. Bangkok, ASEAN Grain Postharvest Programme, 252–264.

— 1994. Advances in research on in-store drying. In: Highley, E., Wright, E.J., Banks, H.J., and Champ, B.R., ed., Stored product protection. Proceedings of the 6th International Working Conference on Stored-product Protection, Canberra, Australia, 17–23 April 1994. Wallingford, Oxon, U.K., CAB International, 351–358.

— 1995. Adoption of in-store drying technology in Southeast Asia. Paper presented at the 17th ASEAN Technical Seminar on Grain Postharvest Technology, Lumut, Malaysia, 25–27 July 1995.

Teoh I.C. and Hassan, B.B. 1995. Paddy cooling in BERNAS grain complexes. Paper presented at the 17th ASEAN Technical Seminar on Grain Postharvest Technology, Lumut, Malaysia, 25–27 July 1995.

Whaley, M.G. 1995. Using model-based controls in cereal drying. Cereal Foods World, 40(1), 19–22.

Whitfield, R.D. 1986. An unsteady-state simulation to study the control of concurrent and counter-flow grain driers. Journal of Agricultural Engineering Research, 33, 171–178.

—1988a. Control of a mixed-flow drier. Part 1: Design of the control algorithm. Journal of Agricultural Engineering Research, 41, 4, 275–287.

— 1988b. Control of a mixed-flow drier. Part 2: Test of the control algorithm. Journal of Agricultural Engineering Research, 41, 4, 289–299.

Zhang, Q. and Litchfield, J.B. 1993. Fuzzy logic control for a continuous crossflow grain dryer. Journal of Food Process Engineering, 16, 59–77.

— 1994. Knowledge representation in a grain drier fuzzy logic controller. Journal of Agricultural Engineering Research, 57, 269–278.

Evaluation of Available Technology

Socioeconomic Factors as Determinants of Drying Technology Requirements

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Abstract

The unalterable realities of climate, technology, and economics of the grain industry dictate that only fairly large scale users can profit from drying and storage technology. To design for them has been interpreted as in conflict with the development and ethical objectives of publicly funded research; that is, that it should benefit small producers and consumers. It appears unlikely that the state would be willing or able to subsidise sufficient small units, on a sustainable basis, to dry a significant proportion of the crop. Low adoption rates for unsubsidised small units, problems inherent in cooperatives, and contraction of parastatal grain handling indicate that neither designing technology for the small producer nor attempts to redesign social organisation to fit feasible technology (via cooperatives), has benefited producers or consumers. If the success of technology is to be evaluated by whether it is adopted, saves grain, and benefits consumers, then drying and storage technology should be designed in consultation with the medium-scale commercial users, to be profitable at the scale of those who actually handle the crop after harvest.

THIS paper has two sections: method and findings. The first sketches a method of rapid socioeconomic research on product chains that I developed to carry out appraisal and feasibility studies of applied science projects. In the section on findings, I argue that over-emphasis on the equity goals in bodies that fund cooperative international applied science and in policies of some developing countries toward their grain industries, had unintended consequences that delayed the development and adoption of grain-saving technology.

Method of Rapid Appraisal of Product Chains

I began doing the 'socioeconomic' part of appraisal and feasibility studies of proposed applied science projects in the late 1980s. The terms of reference did not detail what was my task or how to do it, and the literature was silent. The limit for any field study was and remains two weeks. About half of that would be spent in meetings and looking at the physical and human resources of the proposed developing country cooperating scientific institution. In the one week that was left for fieldwork with potential users of the technology, I would have to work fast and systematically to acquire information on which to make recommendations.

After some reflection, I decided that although funding for projects is justified on the ground of *national needs*, that is not the same as *user demand.* Drying machines (or other technologies) are investment goods: potential users would demand them (i.e. be prepared to outlay scarce capital) only if they expected to make a profit. Moreover, this would be true of any kind of user: even cooperatives and parastatals that are not obliged to make a profit are more likely to invest in operations that offer profit and cut losses, than in known loss-makers.

I decided that my most useful contribution would be to examine whether the proposed technology would be profitable enough for the proposed users or other potential users to want to invest in it. To do that, I wanted to contact some of the proposed users, inspect their operations and ask whether they had in fact the problem that the project said they had and that the proposed technology offered to solve. That the nation (or the industry, or the total

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of producers and consumers) suffers some notional loss between potential and real grain, does not mean that there is any operator who suffers some of that as a money loss and who would therefore contemplate investment to save it. If the problem was real, how did the people in the industry currently deal with it?

As the proposed technology offered to save the 'quality' of the product, I thought it vital to check in what quality the product reached that operator, and whether they would profit from quality maintenance. That would depend on whether the market could discriminate and would pay a premium (= impose a penalty discount) for what the scientists call 'quality'. It would be vital to investigate how the operators in the system grade and price, for what features, and the size of the margins.

These technical and economic matters could not be handled by economic tools that took into account only supply and demand: grain remains a political crop and a political commodity. Governments regulate inputs, outputs, stocks, and transactions of grain, because they seek support of the large number of producers and consumers. Nationalist and populist concerns about the appearance of national self-sufficiency in the staple grain that symbolises their daily bread, affects the legitimacy of a regime. Governments intervene in markets for land, water, machinery, fuel, fertilizer, pesticides, labour, and credit. Government may set floor and ceiling prices for the staple grain, maintain counter-seasonal and buffer stocks and control its export and import. Given that grain is a political crop, it is necessary to ascertain state policies towards the industry and the financial capacity of the state to sustain the cost of implementing them.

Some reflection on the literature, and rough familiarity with the rice industry in the Philippines, led me to conclude that the conventional graphs of producers' and consumers' benefits offered no guidance on the worth of proposed technology. The graphs operate at the macro-economic level, they lump together as 'producers' all the operators along a product chain in which only one could use the technology. Yet from the point of view of that technology user, all the others are 'consumers' of his product, though the actual producer may receive little benefit. Moreover, the graphs assume what is to be tested: that technology is profitable for the user and is adopted. That approach could be no guide to the micro-economic question of whether there is any user whose anticipated profit will induce his demand for the technology.

No producer is likely to invest in new technology unless his 'consumers' (i.e. those who buy his product, not final consumers), can detect and are able and willing to pay a sufficient premium price for quality that innovation preserves or produces. In developing countries there is little vertical integration, so that a long chain of operators may intervene between final consumer and the operator who would have to use the innovation for it to be effective. For instance, those final consumers who can afford it may pay more for rice with a smaller quantity of yellow and broken grains. Timely and well-conducted mechanical drying of paddy should reduce the percentage of yellowed and broken rice, features penalised in the market. But the farmer or buying station in a position to dry paddy soon enough after harvest, sells not rice but paddy. He would use mechanical drying only if the trader or miller who buys that paddy could detect that higher milling quality and be made to pay for it. This made it vital to investigate how the industry grades and prices grain from farm to the retailer. Thinking on these lines raises such questions as the extent to which poor milled quality is a result of poor drying as against poor milling and how much both are a result of small demand for high milled quality of standard varieties.

I therefore developed a 'product chain' approach. It is designed to study most closely the proposed user of the technology, but in the context of the whole industry and its regulation by market and state. A product chain approach investigates two matters:

i) internally at each link, i.e. for each kind of operator through whose hands the product passes, the value-adding operations and technical and business strategies; and

ii) externally at each link, how relations are conducted between this operator and a) the previous operator from whom he buys and b) the next, to whom he sells (grading, pricing, payment, credit, information, power).

The product chain approach examines: at each node and in movements between them the physical operations through which the product passes, the condition in which it is received and passed on, speed of turnover, and whether operator produces to custom order or on speculation; seasonal variations in supply, demand, costs, and credit; variations in scale of operators at each node and any differences in their systems; the size and ratio between each operator's fixed and working capital, availability and cost of major credit and effect on operations of a hypothetical investment in the proposed technology; and the effect at each node and transaction of any government regulations and legal/illegal exactions by officials and strongmen.

The product chain approach can be set out in a diagram as in Figures 1 and 2. An earlier paper (Fegan 1995) set out its first application, in a project to develop technology to dry fish in Indonesia.

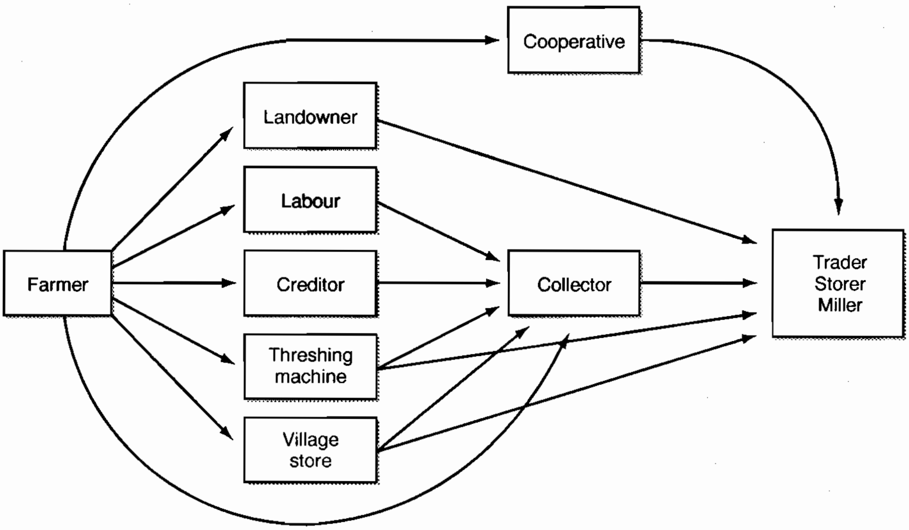

Figure 1. Segment of a producer chain for rice.

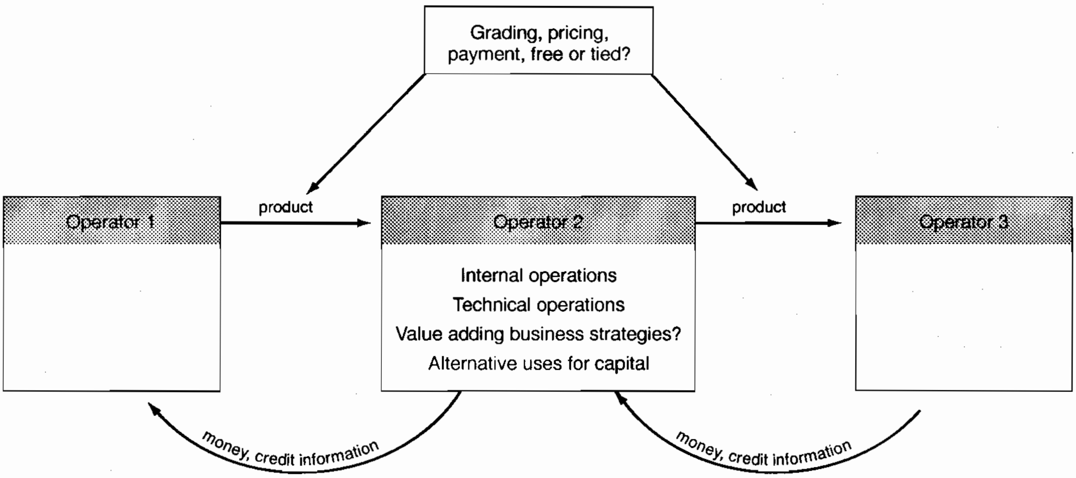

Figure 2. Investigating an operator in a product chain.

The systematic product chain approach is adaptable and in the haste and chaos of fieldwork provides built-in cross-checking. Research can begin at any node and proceed in any sequence. It is important to check the kinds and scales of operators at each node, to check for entrepreneurs who combine several functions and bypass some kinds of operator, and to check for seasonal and regional variations. Among key data are whether operators' relations with supplier and customer are anonymous and totally independent or are tied by relations of partnership, consignment or long-term credit, that constrain either to send or receive and may affect price. It is important to explore how grading, measuring, pricing, and payment are conducted, especially at a distance, and especially with a perishable product that the trans-porter might pilfer, neglect or switch. In practice, I make a constantly revised sketch of the product chain, and note queries for other kinds of operator.

By the time a small sample of operators at each link has been asked about transactions with its suppliers and customers, each transaction will have been looked at from each side, and there will be three versions of the strategies and relations of each kind of operator.

It is difficult to accomplish these tasks in the short time of a week or so in an unfamiliar country, but it can be done provided that the researcher can take control of the itinerary. Host country institutions commonly treat a feasibility study by anyone working for a potential donor as something between tourism and a diplomatic mission. The appropriate schedule for the host's perception conflicts with that necessary to accomplish the mission's objective to rapidly acquire information on which to base recommendations. It is vital to propose in writing well before arrival what kinds of sites, operations, people, and in what regions, one wants to interview. On arrival it is essential to scrutinise, re-negotiate and pare the itinerary to minimise visits to government offices and research stations at which one will receive hospitality and be shown progress in unrelated fields. The time regained can be used to maximise time with professional operators in the product chain.

It is important to take some pains with translations. It would be rare good fortune to come across a translator fluent in all the technical dialects of engineering, agriculture, economics, and sociology in all of the national language, English, and the local or class dialects of potential users. Patterns of courtesy to officials and foreigners commonly inhibit responses, especially disagreement. I pre-brief the translator of the day on what the questioning aims to explore, so they will understand why the questions are asked and can act as colleague rather than translation machine, to explore the ramifications of the answer. I ask for full running translation of answers, and keep full notes.

In practice, commercial operators have proven invariably patient and courteous in sharing part of their enormous store of knowledge about the industry in which they operate. In several projects, wholesale traders have provided a flood of valuable information about their rapidly changing industry, and perceptive questions and observations about the proposed technology.

The kind of information this method provides is rarely available in any publication. Information on product chains is rare and where any is available it is usually long out of date. The information is often new to host-country scientists, perhaps because their education then research projects for government departments, universities, and foreign funders are detached from direct contact with the people in the industry. Moreover, some national applied science institutes have become more or less dependent on foreign government or NGO donor grants. Foreign funding has historically set equity (i.e. social reform) before adoptability (i.e. profit to user) goals. Funder preferences combined with their own religious and socialist moral reform ideologies and bureaucratic linkages, lead the institutes to prefer linkage to the parastatal and cooperative operators and to shun the capitalist operators. At the extreme, researchers in some national institutes are embarrassed at and seem afraid of direct contact with commercial operators, especially where those are not of the majority ethnic group. Institutional ignorance of how the commercial industry really operates, combines with ideological aversion to anything that might help capitalist operators. Together, these attitudes lock some institutions into designing for scales or institutional arrangements that cannot work.

Effects of Funder and National Policies on Design and Adoption

Engineers work best when they design to fit the needs of a clearly defined real user. However, for a long time the equity-before-profit policies of foreign funders and national research institutes directed engineers to design machines to fit some improbable users: individual small farmers, farmers cooperatives, or parastatal grain handlers. Those policies excluded designing for the commercial traders and millers who handle the bulk of the grain in most ASEAN countries.

The layout of project proposal forms and donor ranking criteria encourage proposal writers to give high priority to the equity goal of benefiting the rural poor. The charters of some national research organisations, e.g. the Philippines National Postharvest Institute for Research and Extension (NAPHIRE), appear to do the same. Together, these lead applicants to propose to design machines that can redistribute excessive income and power from capitalist middlemen (often foreign Asian, i.e. ethnic Chinese), to indigenous poor farmers and the state.

Some unchangeable laws of physics and economics make it impossible to design a machine that could be technically and economically efficient at a scale suitable to be owned by and be used once per year to dry the 3-5 t/ha crop of an individual Javanese micro farmer with 0.25 ha, or even that of a Filipino or Thai farmer with 2 ha. One solution that offers to raise grain throughput to an economic scale but retain farmer ownership, is to join farmers together for their common benefit in a cooperative. However, farmer cooperatives have a dismal history of collapsing with bad debts and bad feelings after the usual three year project cycle during which external funds and personnel hold them together.

The other large-scale, non-capitalist, non-Chinese organisational form is the parastatal grain handling bureau (e.g. BULOG–National Logistics Agency, Indonesia; NFA–National Food Authority, Philippines; LPN–National Paddy and Rice Authority, Malaysia). Government has traditionally set contrary and self-destructive goals for parastatal grain organisations: buy dear in harvest season to keep up prices for the poor farmers, sell cheap in the scarcity season to keep prices down for the poor consumers. Required by policy to run at a loss, parastatals in the 1990s are in decline as budget deficits, IMF Structural Adjustment Program conditions, and GATT/WTO rules begin to bite.

However, to make cooperatives viable and parastatals efficient would require moral and social reform. Engineers proved not notably better at moral and social reform than politicians, administrators, religious leaders, and NGOs who specialise in that. Moreover, if the machines that were supposed to help non-capitalists compete had proved profitable, it seems likely that capitalists would have adopted them and remained stern competitors for the non-capitalist operators. More than a decade of publicly funded research on grain drying was led by the priority given to equity, into designing dryers too small to be efficient or into attempts to design utopian organisations to fit machines large enough to be efficient.

The recent successes of Thailand's King Mongkut's Institute of Technology Thonburi (KMITT) team in gaining adoption of both first- and second-stage drying machines appears to have come about because they put adoptability (i.e. profitability) before equity and were allowed to design for real not morally ideal customers. The prototype machines were designed in close consultation with a commercial grain trader who envisaged using them in his operations and built by a commercial manufacturer of agricultural machinery. The machines have been scaled up, manufactured, and in their first year, exported from Thailand. This success does not indicate that engineers have made important conceptual breakthroughs. Rather, funders and some national institutes (KMITT but not NAPHIRE) have recently allowed engineers to design for the scale at which machines become mechanically and economically efficient, if efficiently managed. That happens to coincide with the scale of medium to large commercial operators, with whom KMITT has good relations. Installing subsidised or free drying machines in cooperatives about to self-destruct or parastatals about to lose their procurement funds, offers no fair test of whether the units would be economic under efficient management.

Adoption of Machines and Market Intervention

In some countries, government pursues political goals through an ensemble of state controls and subsidies towards the grain industry, at significant direct budget cost. Some of the policies cause disincentive to private investment in grain-saving technology and thereby cause large costs to farmers, consumers, and the nation. Foreign funders have not taken a policy decision to have economists analyse the cost of policy and who bears those costs. Had they done so, they could point out to governments the extent to which some of their problems are policy caused and require a changed policy, not new technology, to solve them.

For instance, Malaysia maintains a paddy price higher than the world market price of rice, to favour the indigenous Malay farmers. In the 1980s, the government required the parastatal National Paddy and Rice Authority (Lembaga Padi dan Beras Negara, LPN) grain agency to pay for wet paddy at the same price per kilo as dry paddy and to act as buyer of last resort. Wherever the discount for moisture is not sufficient to cover the weight loss in drying and the cost of drying, farmers (and other sellers) have no incentive to dry. Indeed, they may have an incentive to soak their grain in order to sell water at the price of paddy. As the discount for moisture content was below drying cost, commercial traders withdrew from purchasing wet paddy. All wet paddy was therefore delivered to LPN, which had to invest in very large mechanical drying capacity. Meantime, there were long truck queues waiting to deliver wet paddy to the relatively few LPN depots. The depots accumulated wet stockpiles awaiting drying, and at the same time as private storage was idled, LPN had to invest in covered storage for dried grain. Significant quantities of the grain spoiled. Some that was dried had a low price on milling, because delay in drying caused the grain to turn yellow. Prosperous Malays rejected the low quality local rice, buying cheap but better quality smuggled Thai rice. In that case, many problems of grain drying were policy caused. Realistic price margins for moisture would have induced farmers, traders, etc. to use existing and new facilities to dry and store.

Funding proposals in the postharvest area come from engineers and food technologists and are directed at improving the production process. Where the problem turns out to be policy caused, project personnel have not been able or willing to call in an economist to define the total cost of state policies and who bears them. With ACIAR, for example, aside from the problem of special expertise, one consideration may be that since the Centre is responsible to a government agency, it has grown an unwritten policy that scientists working on its projects should not comment on the policies of host governments.

The Thai rice industry demonstrates that mechanical drying and the two-stage drying concept are technically feasible for rice in the humid tropics. It demonstrates that each stage of mechanical drying is economically feasible under Thai conditions. However, as Thai conditions are not all present in other ASEAN countries, adoption there may lag. Thai conditions include a surplus-producing country where both rice and maize face a buyers' market with good margins for high milled quality (= strong penalties for low quality), where state intervention in markets is light. The relatively free Thai markets for rice and for maize allow sufficient margins between wet and dry paddy and between grades of milled quality rice to give incentives for early drying and allow sufficient margins between seasons to give an incentive to good storage. The capitalist trader-millers who have adopted the technology are located in a central place where throughput allows economies of scale and they have a high-incentive commercial management system. Finally, Thailand's KMITT does not shun co-operation with the commercial traders and millers. Where one or more of those conditions are not present, technological feasibility does not necessarily mean economic feasibility and adoption of mechanical drying may lag until policy changes allow suitable conditions.

The pursuit of 'quality' costs money that operators would be unwilling to invest unless the market will pay for that quality. In the product chain from farmer to consumer, each actor will invest in maintaining quality only if he expects his (not national) benefits will sufficiently exceed costs. That depends on whether the next actor in the product chain can discriminate for quality and will pay a margin for high quality (= penalise or reject for low). The demand for technology to save quality is a derived demand: it is high where markets for the end-product have good margins for quality.

Changes in the Thai maize industry that did not occur in the Philippines industry reflect the differences between surplus and deficit producer markets, between industries with high and low margins for quality and between countries where scientists did and did not collaborate with the commercial industry. However, in line with what a product chain analysis would predict, two preconditions had to be met for the reform of the Thai yellow corn industry: development of a method that allowed large maize buyers to discriminate aflatoxin levels, and readiness of livestock raisers and feedmills to reject or penalise according to degree of contamination.

It is not possible to detect aflatoxin contamination of maize with the naked eye. However, contamination of this major ingredient of livestock feed caused serious losses to large livestock corporations. Thai university scientists collaborated with corporations to develop fast, cheap, and simple test kits that allowed buying stations to reject or impose penalties in grade and price according to aflatoxin content. This allowed feedmillers to segregate maize procurements by aflatoxin content, in order to direct it to species according to their tolerance. The prospect of a load being rejected at a distant feedmill after expensive transport, caused upcountry wholesalers to install their own blacklight testing.

Development of the test induced the product chain to invest in early drying. Farmers and traders discarded visibly mouldy cobs and made every effort to dry early, to prevent mould formation and so minimise the risk of rejection, and to attract the feedmill price premium.

The demand side: grading and pricing for quality

The size of margins for milled quality of standard varieties depends on whether a country exports or imports grain and whether a large enough proportion of its population can afford to be fussy about milled quality. Feasibility studies showed that margins for milled quality of rice are bigger in Thailand than the Philippines.

Thailand has been a long-term surplus producer, facing discriminating export customers. While the bulk of the population had low income they were a market for lower grades. In recent years, sustained rapid economic growth has enabled an increasing proportion of Thai domestic rice consumers to afford to pay good margins for rice with a low percentage of broken and yellow grains.

By contrast, the Philippines rice industry faces a sellers' market that tolerates low quality. The Philippines usually hovers around rice balance, with deficits more common than surplus. The parastatal NFA has a monopoly of external trade but may import too late (e.g. Tiglao 1995). The economy has had a long period of slump from around 1980, with a high proportion of the populace too poor to pay good margins for low percentages of broken and yellow kernels. There are recent signs of increasing margins for better grades of milled rice but the large proportion of the population who must shop by price perpetuates high demand for low milled quality.

Similar buyers' versus sellers' markets characterise the Thai and Philippines markets for yellow corn as a stockfeed ingredient. I noted earlier that in Thailand channels for collaboration between university-based scientists and corporations enabled development of cheap, rapid tests for aflatoxin. In the context of the Thai buyers' market for maize, this helped reform the Thai industry and induce early mechanical drying.

The Philippines yellow corn industry is in chronic deficit; it faces a sellers' market in which hand-to-mouth supplies oblige feedmillers to accept whatever is available. In 1992 feedmills either used aflatoxin-binding agents or mixed local maize with stockpiled

U.S. or occasionally Thai good quality (and cheaper) maize to control aflatoxin levels for sensitive species and growth stages. The two of the 'big six' feedmillers contacted had no in-house tests for aflatoxin. They said the cost and delays of government testing, in the context of chronic shortage, left no option all along the product chain but to amalgamate grain down to FAQ quality. Inspection of traders stocks and interviews with farmers and traders in production regions in Mindanao confirmed that grading took into account only moisture content and inclusions, and that there was no attempt to segregate by quality.

It also became apparent that the policies of the cooperating research institutions differed: Thai researchers progressed by designing technology to fit the existing postharvest commercial traders, whereas Philippines researchers shunned commercial traders, diverting their energies to efforts to change the structure of the postharvest industry to fit the technology and to pursue social equity.

Economies of scale and potential users

Both computer simulation and experience with by now a large number of designs, reconfirm the usual economies of scale properties of heat machines: the larger the unit, the cheaper the cost per tonne. This sets up a conflict between project goals to produce equipment likely to be adopted and therefore save national losses, and a major social welfare goal of publicly-funded research to help the great number of small poor farmers. KMITT and NAPHIRE gave different priorities to national welfare versus welfare of small farmers.

Since unalterable facts of physics and economics make designing a dryer for the individual small farmer quixotic, design for first-stage mechanical paddy drying focused on a mobile unit suitable for a cooperative (or custom hire) and larger stationary units suitable for a trader-miller. The larger unit has the lower cost per tonne, especially if location on a highway or central place allows it to maximise days of use per year by tapping a wide area, where ecological variations offer a longer harvest season.

A mobile machine was trialled in 1994 that can dry about 0.5 tonnes of paddy per hour, which would amount to the output of 1 hectare at an optimistic yield of say 5 t/ha, in one 10 hour working day. Daily throughput may be less in practice because of loading, unloading, and tempering time. That is around the minimum scale at which the cost per tonne of fast drying is acceptable, but is about the maximum size that remains towable on wet-season village roads.

Although a number of mobile units were ordered in 1995 in the Philippines, all early orders appear to be from cooperatives. They are financed by subsidised government loans, justified as part of GATT/WTO adjustment but approved during the campaign period for the May 1995 Congressional and local elections. It will be difficult to evaluate in the Philippines whether the mobile dryers are technically and economically successful. Aside from the political subsidy, 1995 has had unusually high world rice prices, while floods around harvest in part of the Central Luzon rice bowl may have required an unusual level of salvage drying of water-damaged paddy that might have been unsaleable in a year of normal prices. Given the problems inherent in farmers' cooperatives in the Philippines, it can be predicted that they will under-utilise the dryers because of procurement and organisational problems and that the cooperatives will default on these as on previous soft loans.

To achieve the national savings in grain objectives of the project, it would be necessary for there to be capacity to dry a significant proportion of the wet season crop soon enough after harvest to avoid deterioration. This can be achieved only if enough units will be available and used to their potential. Given that most of the farms in any village have the same rainfall and/or irrigation, their planting and therefore harvest dates are bunched into about four weeks. If a village cooperative worked one mobile dryer 7 days a week for 10 hours a day it could dry in a month at most the harvest from 30 ha, around 20% of the cropped area of an average village. Thus, timing constraints mean a cooperative dryer may be both unable to serve all members (bottleneck) and to reach sufficient throughput to achieve a low cost per tonne. Mobile units would be able to break local drying bottlenecks and to lower fixed costs, only if they could be custom hired outside the home cooperative to areas with different harvest timing. But cooperatives lack entrepreneurial incentive to do that and may have contrary rules.

Whether the drying bottleneck can be broken by small mobile dryers will depend on whether small entrepreneurs can make money by following the harvest, as do owners of light, IRRI-designed, axial flow threshing machines. That could happen if enough entrepreneurs foresee profit and buy the machines from the makers. It is more likely that entrepreneurs will find ways to lease dryers from the cooperatives, or buy them from defunct cooperatives at a discount. However, in the Philippines the small margins for milled quality of standard varieties and poor quality of much milling equipment and skills, make it unlikely that (if they could discriminate the difference) millers would pay a premium for mechanically as distinct from sun-dried grain.

Despite NAPHIRE campaigns to eliminate highway sun drying, there is in 1995 more non-highway sun-drying capacity available to Philippines farmers than ever before. In connection with elections in May 1992 and May 1995, governors and Congressmen approved government grants for 'multi-purpose drying platforms' in almost every rice-monocrop village and for concreting a couple of hundred metres per village of 'farm to market roads'. Farmers whose cooperative has a mobile dryer will choose between sun drying on their own account (absorbing the cost of haulage to and from the drying platform or road), custom on-farm mobile mechanical drying with the cooperative machine, custom mobile mechanical drying by an entrepreneur, or selling wet grain at a discount to a trader with sun or mechanical drying capacity. Competition between these options means that cooperative and entrepreneur operators of mobile dryers cannot charge more than the alternatives, which in wet harvest weather means the spread between the wet and dry price offered by traders with sun-drying floors. Some commercial traders may invest in a stationary dryer which, being larger, has a lower operating cost per tonne. If cooperatives charge less than commercial rates in order to benefit members or get throughput, drying losses may help send them broke unless they can achieve an unprecedented level of efficiency in these low-incentive organisations. In this context, the ready availability of sun-drying floors means it is important that extension continues to promote to farmers and traders, best practice for first-stage and complete sun-drying.

Fixed site first-stage dryers have few size constraints and provided throughput is sufficient, cost per tonne falls with size. A 0.8 to 1 t/hour fluidised-bed dryer built by a commercial firm to a KMITT/ACIAR project design for a capitalist merchant in Thailand is said to have been used daily throughout the wet season. The merchant expressed interest in a larger unit and is said to have been satisfied with the performance of a 5 t/hour unit at a capital cost of $US16,000, while a 10 t/hour unit has been built. Within a year of contact between the project's Thai KMITT project team, the manufacturer and capitalist traders, models of 1, 5, and 10 t/hr were developed and the manufacturer is said to have sold some 10 fluidised-bed units, two of them to Indonesia's BULOG. The speed of response indicates that the technology has become profitable without capital or running subsidy at this scale, in the context of a capitalist trader as user and Thailand's market and price structure.

Second-stage drying

In-store, slow second-stage air-drying is subject to economies of scale and is not economically feasible for a user smaller than a medium trader and miller, a multi-village cooperative, or a depot of a parastatal grain agency. Brief research in January 1995 indicated that both the large numbers of multi-purpose village cooperatives set up or revived in the Philippines around 1992–93 and the municipal federations of those, were in financial collapse from the usual self-destruct mechanisms built into cooperatives. They were unlikely to be capable of handling a significant proportion of grain. Governments have scaled down the level of subsidy to parastatal grain handling organisations in the Philippines, Malaysia, and Indonesia and with that the proportion of the crop that they handle. A recent article (Schwartz 1995) indicates that Vietnam is trying to recentralise postharvest handling and trade of rice. The prospect is that, for the foreseeable future, capitalist traders and millers will handle the bulk of the grain except in China and Vietnam and will do so in increasingly open markets.

Conclusions

1. Rice, the staple grain in Asia, is a political crop with many small producers and consumers. Concerns about welfare, votes and unrest among numerous rural majority producers account for policies to intervene in prices for farm inputs. Anti-Chinese populist sentiments, concerns about food security, consumer unrest and pressure on wages and inflation account for state policies to intervene in supply, storage, and price of grain outputs. State intervention that narrows the seasonal price margins, discourages investment in good storage.
2. Parastatal grain handling agencies that attempt to maintain a floor price for paddy procurement and a ceiling price for rice release necessarily make large operating losses by buying and selling against the market. Government capacity to subsidise farm inputs and losses in trading is set by and contributes to the size of its cumulative debt and its current budget deficits. Throughout the region, the state's willingness and capacity to intervene in markets has decreased in the last decade, so that parastatal grain handling organisations handle a diminishing proportion of the crop. Research should be redirected to design for and cooperate with the capitalist sector that handles the bulk of the crop.
3. Maize is a political crop because it has many small producers but (except in the Philippines where white corn is a regional staple), is less political than rice because yellow corn has few direct consumers. This accounts for state concern with inputs subsidy and a floor price but absence of a ceiling price and minor parastatal agency involvement in storage or maintaining buffer stocks.
4. Both rice and maize industries in countries that regularly export face discriminating buyers' markets that discount for poor quality. Margins for quality in such industries induce grading, segregation by grade, and investment in equipment and good management to maintain quality.
5. Grain industries in countries at or below self-sufficiency face a sellers' market where end-users must accept whatever quality is available locally, margins for quality are low, poor quality

grain is seldom dumped, grain of different qualities is not segregated but mixed down to acceptable market grade, and discriminating users must seek high quality from imports or in wet season pay a premium for high quality grain stored from the last dry season harvest. For maize, there is minimal attention to grading except in respect of dryness and inclusions. For rice, the biggest margins are for variety.

6. For rice, margins for different milled grades of the standard varieties reflect the level and distribution of income. In the poorer countries, proportions of discoloured and broken grains that would be unsaleable in prosperous countries have a ready sale to the poor majority. Demand for high milled quality grain increases with rising national income and a rise in the proportion of consumers for whom rice purchases take a low proportion of their weekly income so that they can afford to be fussy.
7. For maize, shortage of internal production and the possibility of higher quality imports at the same or lower price, gives feed millers little option but to accept low quality, variable aflatoxin-contaminated local grain, mix it with binding agents for aflatoxin-sensitive livestock species and growth stages and/or stockpile imported grain for those. Hand-to-mouth supplies discourage investment in maintaining quality of unsegregated short-term stocks.
8. For maize, surplus of internal production and no imports allow feed-millers to test and reject for aflatoxin contamination, pay margins for quality, stockpile top grades, and invest in quality maintenance in storage.
9. Discriminating for aflatoxin levels cannot be done with unaided senses. If large-scale livestock raisers, feedmillers, grain storers, and traders have available in-house, rapid, cheap testing and appropriate staff then they can test, reject, grade, price, and segregate by aflatoxin level. Price premiums/penalties fed back from livestock-raising end-users induce backward linkages via feedmillers, storers, traders, and farmers to adopt drying and storing practices that produce low aflatoxin.
10. Where policy instruments set penalties for moisture content just at or below the weight loss in drying plus cost of drying, sellers and resellers have no incentive to dry, or may even have an incentive to wet their grain before sale. Where government seeks farmers' votes or political passivity, and/or to eliminate capitalist (especially ethnic minority) middlemen, and requires parastatal grain handling agencies to set low penalties and act as buyer of last resort, then
    - i) farmers have no incentive to perform on-farm drying;
    - ii) farmer co-operatives that invest in drying capacity lose money, default on dryer loans, and collapse *even if the dryers and management were efficient*;
    - iii) private traders have no incentive to dry and withdraw from procuring wet grain and from investing in drying;
    - iv) the parastatal depots are flooded with high moisture grain, setting up transport queues, which results in deterioration in quality on farm, in truck queues and after procurement while stockpiles await dryers;
    - v) the parastatal agency is obliged to invest scarce development funds in unnecessarily large drying capacity, and to take large annual losses in drying costs, losses of quantity and quality, storage costs, and in trading;
    - vi) because of policy-induced drying delays, milled output from such a system has a high proportion of brokens, discoloured and off-odour grain and is discounted in end markets;
    - vii) if incomes of a significant proportion of the population are high enough, their demand for high quality grain induces imports; and
    - viii) the parastatal system has high built-in levels of loss in quantity and quality that can cover and invite corruption.
11. Other regulatory interventions to pursue equity had perverse unintended consequences. In the Philippines, government set out to benefit the poor rice and maize farmers in areas far from market, and poor consumers, by fixing freight price per tonne for rice and maize below that for other commodities. The unintended consequences included that commercial shippers treat grain as a cargo of last resort and let it lie (and deteriorate) at ports so long as higher freight cargo is available. Moreover, shipping companies shunned investment in bulk-loading ships, and port authorities avoided investment in bulk-loading and unloading gear. As a result it is cheaper and quicker to ship maize to Manila from Bangkok or Houston than from ports in Mindanao.

References

Fegan, B. 1995. A rapid socioeconomic assessment of the salted dried fish industry in Indonesia and its implications for demand for and design of, improved drying technology. In: Champ, B.R. and Highley, E., ed., Fish drying in Indonesia. Proceedings of an international workshop held at Jakarta, Indonesia on 9–10 February 1994. Canberra, ACIAR Proceedings No 59, 31–43.

Schwartz, A. 1995. Problems in the paddy. Far Eastern Economic Review, 21 September 1995.

Tiglao, R. 1995. Myopia in Manila. Far Eastern Economic Review, 28 September 1995.

Effect of Drying on Grain Quality

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Abstract

Among others, drying can affect the quality of rice or other cereal grains (with a hard vitreous endosperm) in two prevalent and distinctive ways:

1. Through moisture readsorption — Rice, as well as other cereal grains, is hygroscopic. The low-moisture (dried) grain readsorbs moisture from any source to which it is exposed. Moisture adsorbed through the grain surface causes the starch cells to expand and produce compressive stresses. Since the grain is a 'free body', compressive stresses are countered by equal but opposite tensile stresses at the grain centre. When the compressive stresses at the surface exceed the tensile strength of the grain at its centre, a fissure develops. Fissured grains usually break during milling. Sources for grain moisture readsorption are discussed.
2. Through rapid drying (to near storage moisture) — Rapid drying produces a steep moisture gradient in the grain. As this gradient declines after drying, the grain surface receives moisture from the interior and expands, while the grain interior loses moisture and contracts. As this combination of stresses (compressive at the surface and tensile at the centre) develops with time, the grain fails in tension by pulling itself apart at its centre. The rheological aspects (stress, strain, and time) that cause the grain failure are discussed.

RICE, as all other cereal grains, ripens and begins to dry in the field. Ripening of the grains is gradual and progressive and each individual grain cycles daily in moisture content. Lower moisture contents are reached on successive drying days. During the early ripening process, the grain loses moisture only. Later, the grain dries during the day and then may readsorb some moisture at night before continuing the drying process on the following day. When a rice grain dries to below 14 or 15% moisture content (m.c.) during the day and then readsorbs moisture at night, the grain will/may fissure, because of the moisture readsorption.

Development of Fissures in the Rice Grain

From moisture readsorption

The moisture adsorption–fissure concept is not unknown, but is a rather new perception in the rice industry. The commonly prevailing concept has been that the rice grain 'sun-cracks' or 'sun-checks' as it dries in the field. Sun-cracking of the rice grain was first proposed by Copeland (1924). The sun-crack was defined as a fine cross-wise cracking of the grain caused by rapid drying in the sun. Early crop rice was more subject to sun-cracking than was late crop rice. The term 'sun-crack' appeared to be a reasonable explanation for what was happening and was readily accepted throughout the world by the rice industry.

As rice production became mechanised, heated forced-air dryers were developed to dry the large volumes of high moisture harvested paddy. Any cross-wise cracking of the grain that was subsequently observed after drying was conveniently referred to as 'sun-cracking' of the grain. Hence, the term carried over into mechanised heated forced-air drying and is still widely used throughout the world.

In those days, research momentum was being channelled toward paddy drying and other initiatives received little support and attention. This is unfortunate because the moisture adsorption–fissure phenomenon was discovered in Japan by Kondo and Okamura (1930). When translated into English, the title of their work is 'Fissuring of the Rice Grain from Moisture Adsorption.' Their treatise is 19 pages long and probably is the most enlightening, detailed, and comprehensive article that has ever been written on the rice moisture adsorption–fissure concepts. How-

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ever, their work was not mainstream research and received little attention in the scientific world for the following reasons: 1) their work was not widely published and hence was not accessible to many scientists; 2) the mainstream of rice research was on drying; 3) it was published in the German language; and 4) few postharvest rice researchers could read German, and therefore were unable to read the article. Even today there remains a need to translate their work into a more commonly prevailing language and then republish in one or more technical journals that have a worldwide distribution. Kondo and Okamura summarised their work with eight conclusions. These cannot be repeated here, but can be found in Kunze (1991). Their final conclusion states:

> It is without any doubt that moisture adsorption by the dried grain is the definite cause of fissured grains. It follows then that it is very important that dried grains be quickly stored in air-tight conditions to prevent moisture adsorption.

Thus, the milling quality loss that had been attributed to paddy drying was put into its proper perspective, but the information did not permeate the paddy drying community in other parts of the world.

The research of Kondo and Okamura (1930) did not go completely unnoticed, because a few postharvest rice scientists did cite their work. Perhaps the most prominent of these is Stahel (1935), who worked in Surinam. Stahel was unaware of Kondo and Okamura's work while he was doing his own, but then found theirs before he published his results. Stahel's conclusions followed those that had been drawn by Kondo and Okamura. According to Stahel, the fine cross-wise cracks that resulted when paddy was remoistened from being left out of doors overnight were responsible for most of the breakage in milling. Before 1930, it was believed that these cracks were due to drying in the sun. But this was not correct. Stahel was unable to produce sun-cracks by drying thin layers of paddy in the sun to less than 10% (m.c.) He dried paddy to various moisture contents in the sun and then remoistened the grains to determine at what level the grains would crack from the readsorption of moisture. He found that the initiation of cracks from moisture readsorption varied with variety, but generally occurred when grains had dried to 14 or 15% m.c.

Stahel (1935) was also familiar with other previously published rice literature. He took exception to the use of the 'sun-crack' term and pointed out that this was a misnomer because the cracks were not due to rapid drying in the sun, but rather to a rise in moisture content.

In the ensuing years, the mainstream of postharvest rice research continued in the area of drying. Stahel's (1935) findings along with those of Kondo and Okamura (1930), were gradually buried in volumes of technical rice drying literature. The early concept of sun-cracking never lost its acceptance and then prevailed for three additional decades before being seriously challenged.

As the rice scientists developed and published their research on drying, other scientists were working on the drying of wheat. The literature indicates that there was little if any communication between the two groups, even though it would appear that the two cereal grains could have much in common. Few rice researchers cited wheat researchers and few wheat researchers cited work of rice researchers in their journal articles.

Sharp (1927) did studies on the density of wheat as influenced by freezing, stage of development, and moisture content. He found that when the air-dried kernel was remoistened it lost some of its density. He proposed that removal of the regained moisture caused 'air spaces' to develop in the grain. Some time later, Swanson (1943) studied the effects of moisture on the physical and other properties of wheat. In particular, he was interested in the rewetting of wheat during harvest. Weights taken of test volumes during harvest showed that non-weathered samples at the millers were, on average, 1.81 kg heavier than weathered samples. He concluded that the swelling from rewetting disturbed the internal compact condition of the grain. He reasoned that after the water was again removed, vacuoles were left in the grain and these decreased its specific gravity and hence its test weights.

The research of Sharp (1927) and that of Swanson (1943) provided the challenge for other researchers to find the 'air spaces' or 'vacuoles' which these researchers envisioned to develop in the redried wheat. Milner et al. (1950, 1952) used X-ray techniques to determine internal insect infestation in wheat. This work was followed by Milner and Shellenberger (1953) who studied the physical properties of weathered wheat in relation to fissures detected radiographically. Their observation was that fissures appear because of stresses produced when moisture swollen grains *are dried*. The weathering (wetting by rain or snow) of unharvested wheat in the field, followed by atmospheric drying, involved an irreversible decrease in density of the grain. Their discovery of the internal fissures at right-angles to the longitudinal axis of the grain afforded visual proof of the internal spaces in weathered wheat as postulated by both Sharp and Swanson. Their data indicated that cracking occurred when a certain degree or rate of shrinkage of the hydrated endosperm was exceeded. (These scientists at this time—1953—were still attributing the development of fissures to rates of drying. Researchers from the same laboratory put the situation into its proper perspective only 6 years later.

Grosh and Milner (1959) studied the penetration of water into the wheat kernel and the internal cracking which ensued. Their comments are quoted below:

> Cracks radial and transverse to the crease occurred in the hard vitreous endosperm *in advance of water movement* through the kernels... Direct evidence that cracks form in wheat *as a result of wetting* the endosperm alone (tempering) has not been offered previously.

Thus, the moisture adsorption–fissure concept was recognised and clearly defined in the rice industry by 1935 and in the wheat industry by 1959. The two groups were not communicating with each other and neither were they communicating with the researchers of other cereal grains that had a hard vitreous endosperm.

After 1935, drying and storage continued to be the primary focus of rice researchers for the decades ahead. Yet if the 'truth' is not properly defined and understood, it will continue to surface and tell those who seek it that they have not yet achieved their goal. Subsequent moisture adsorption work was peripheral and incidental. Kik (1951), working in Arkansas, studied the nutritive qualities of rice. He observed that cracks were present in kernels before they were milled and that these kernels were responsible for much breakage during milling. He reported that these cracks resulted from the remoistening of dry rough rice and *not from drying too rapidly in the sun.* He cited the works of both Kondo and Okamura (1930) as well as that of Stahel (1935). Kik's observation was peripheral to his work and failed to impress those scientists for whom the information should have been meaningful.

As postharvest rice research continued, few researchers were informed about the research of their colleagues on other continents. Langfield (1957), who published in Australia, reported that 'it is well known that much of the grain breakage during harvesting or milling results from fine crosswise cracks that have developed in the grain *during the ripening process*. This cracking or checking, which is commonly referred to as sunchecking, results from *rapid fluctuations in atmospheric humidity during the ripening process*.'

Desikachar and Subrahmanyan (1961) in India, also made significant observations on the formation of cracks in rice during wetting and their effect on the cooking characteristics of the grain. Some of their comments follow:

> Milled or parboiled rice develops transverse lines of cracks when soaked in water. It took a longer time for the cracks to develop in parboiled rice than in raw rice... Rice is very susceptible to this type of cracking during moistening or wetting... The development of these cracks was dependent on time and temperature of the soak water... The development of cracks on the grain immersed in water seems to be a direct effect of hydration, since the development of these lines is a gradual process and depends on the temperature of the soak water... A certain time (about 3 or 4 minutes in the case of raw rice and about 20 minutes in the case of parboiled rice) elapses before the cracking starts which suggests that hydration precedes cracking.

Rhind (1962) also made some observations which give insight into the mechanics of fissure development. He states:

> The highest tensile stresses can be expected in the driest parts, i.e. in the surface layers during drying, but in the inner part of the grain during adsorption... Grains which are badly cracked are 'destined to break' and do so with a minimum of milling.

Huysmans (1965) reported that paddy which is harvested too late will have a great number of sun-cracked grains and that there will be a high percentage of broken rice in the milled product. Sun-cracked percentages found for a given variety of medium grain during 1962–63 were below 10% up to 45 days after flowering with head rice percentages of over 50%. At 50 days after flowering, the sun-crack percentage increased to 25.5% with a head yield of only 36.8%.

The foregoing is a brief and partial review of moisture adsorption technology in rice and wheat as it can be found in the literature. Yet scientists in the world still seem to be in doubt about the effects of moisture adsorption by a low-moisture (dried) grain. The following was published in the early 1970s:

> Grain development (rice) is essentially complete within 3 to 4 weeks after flowering. Endosperm cracks or fissures in rough rice, *some researchers claim*, result from the contact of the dehydrating caryopsis to liquid moisture such as dew.

The author of this paper published his first article in 1965. At that time the 'sun-cracking from drying' concept strongly prevailed. Fissuring from moisture readsorption was unknown by scientists, engineers, and drying experts. The phenomenon was rediscovered through efforts to determine the physical and mechanical properties of rice. The grain could not be fastened into a cylindrical holder with a water-base adhesive without developing a fissure. These efforts were finally discarded and the focus of the work was directed to determine the basis for the development of the fissure or fissures. Grain-ends were ground off to have a flat surface so that the grain would stand on a damp wetted surface such as a wet napkin. Within an hour, the mounted grain developed one or more fissures. This observation caused the title of the proposed research to be changed from a study of the 'Physical and Mechanical Properties of Rice' to 'Environmental Conditions and Physical Properties Which Produce Fissures in Rice' (Kunze 1964). The

Chairman of the Dissertation Guidance Committee was Dr Carl W. Hall, a member of the National Engineering Academy in the United States. He is world renowned for his many books and in particular for his book entitled 'Drying and Storage of Agricultural Crops' (Hall 1980). More than three decades of moisture adsorption work have followed.

The initial works were published by Kunze and Hall (1965, 1967). The research was with brown rice and was published in the Transactions of the American Society of Agricultural Engineers. The work confirmed and also commenced to reintroduce into the literature the works of Kondo and Okamura (1930), Stahel (1935), Kik (1951), and Desikachar and Subrahmanyan (1961). Although all of these references are cited in Kunze's (1964) dissertation, the complete transcript of Kondo and Okamura's work was not found and obtained until August 1975. A crucial need remains for it to be translated and distributed to grain drying researchers.

Kunze subsequently pursued the moisture adsorption phenomenon with some difficulty because this concept was controversial (not compatible with accepted technology) and had a low-priority status with financial support sources. However, graduate students from developing countries were interested and wanted to work with rice. They subsequently supplied the expertise and manpower to make it a thriving and productive program.

Kunze and Choudhury (1972) watched the fissures develop as brown and milled rice grains were exposed to a moisture adsorption environment. From these observations, they developed hypothetical stress distributions for both desorption and adsorption of moisture by the grain. Their illustrations show tension at the grain surface and compression in the interior when the grain is drying. Technically, these stresses give no justification for the grain to pull itself apart during drying. A tensile failure could logically occur on the grain surface. Adsorption stress distributions showed the grain to be in compression at the surface and in tension at its centre. Whenever the internal tensile stress exceeded the internal tensile strength, there was justification for grain failure (an internal fissure to develop). These stress distributions agree with those proposed by Rhind (1962). Kunze and Choudhury (1972) further found that milled rice required only half as much exposure time to produce a fissure as did brown rice. Additional work showed that milled rice in a given environment adsorbs moisture about twice as fast as brown rice. According to Henderson (1972), brown rice dries about twice as fast as rough rice under a given drying condition.

Further research focused on grain fissuring potentials in the harvesting and drying of paddy (Kunze and Prasad 1978). They determined where low-moisture grain may be exposed to a moisture adsorbing environment. Such conditions could exist in the field before harvest, in the combine hopper, field buggy, transport truck, holding bin, and in certain dryers ahead of the drying front. McDonald (1967), working in Australia, showed that rice grains on a single panicle in the field may vary in moisture content by 10 percentage points during the drying process. The variation within a plant could be greater and within a field, greater still. Chau and Kunze (1982) and Kunze and Calderwood (1985) found that paddy samples with a field moisture of 22% may contain grains between 15 and 45% m.c. A freshly harvested paddy mass at 22% field moisture has an interstitial relative humidity of 97%. The air in a continuous-flow, nonmixing heated-air dryer enters the wall of grain and becomes humid warm air. Low-moisture grains ahead of the drying front may readsorb moisture and fissure before the drying front reaches them.

In developing countries, if cut rice plants are laid out in the field and left too long, the driest and most mature grains may soon fissure from moisture readsorption at night. The drying rice grains may already fissure on the stalk before it is cut. After the rice plants are put into a bundle but then left exposed over night, the little bundle with comparatively more grain exposure will develop more fissured grains than the big bundle with relatively less grain exposure (Kondo and Okamura 1930).

Dried rice in storage can also fissure from moisture adsorption environments in the tops of storage bins, from aeration, and from subsequent transport, shipping, and processing operations.

From rapid drying

Life would be more simple if a single cause could be attributed to every observed effect; if all fissured rice grains could be attributed to the readsorption of moisture by the grain. This is, however, not the case, because rapid or fast drying produces a fissure after drying that is visually the same as the one which results from moisture adsorption. The adsorption fissure develops while the moisture is being adsorbed by the grain. But the fissures which result from rapid drying start to develop shortly after drying and then continue to develop for 48 hours or more. Both grain failures appear to be visually the same and both are equally effective in reducing the milling quality of the grain.

I was in India at the Indian Institute of Technology (IIT) at Kharagpur in 1975. We dried high-moisture paddy in a single pass from 29.8 to 9.1% m.c. in a column 63.5 cm deep with an air temperature of 59°C (138°F). The procedure was contrary to all established rice-drying practices. The initial moisture content was too high, the drying pass was too long (12 hours), the drying bed was too deep, and the temperature was too high. After drying, the paddy was milled.

It gave a total milling yield of 76% and a head rice yield of 74%. Yet, after drying and milling, the milled rice grains soon began to fissure and within hours all of them were fissured. The milled rice grains fissured hours after drying. This observation justified further investigation. Fissuring of the rice grain after heated air drying was studied by Kunze (1979). Photographic documentation was used to show that: certain grains were not fissured at the end of drying; these grains fissured after drying; a time interval after drying was necessary before the fissures developed; and a fissure does not relieve the stress over a long section of the grain. Several fissures may develop within one grain.

The movement of moisture (in or out) in a rice grain triggers its rheological properties. Rheology is the relationship of stress, strain, and time that can be observed in a product. Strength of a material can be expressed, within limits, by stress and strain alone. The rheology of a material is expressed by stress, strain, and time; thus indicating that the stress–strain relationship is dynamic and subject to change with time. Such a relationship is evident in rice as it adsorbs and desorbs moisture.

A search of the literature then revealed that Craufurd (1963), working in Sierra Leone, West Africa, appeared to be the first to report the development of fissures in the rice grain after rapid drying. The comments below are from his manuscript:

> In fast drying of paddy, cracks do not develop until the drying has ceased. Presumably the cracks develop as the moisture gradient within the grain is relaxing... Since cracks originate at the centre of the grain, they develop while the centre of the grain is losing moisture to the drier outer layers... In drying it is not the rate at which water is lost from the grain that causes cracking, but some other factor associated with the rate at which the moisture gradient relaxes after drying.

Such information was new in the literature and once again received little attention from rice drying associates. The information was not compatible with that which seemed to be known and did not permeate the rice industries in other countries and continents. But again, it is difficult to keep the 'truth' submerged. The work of Craufurd re-emerged and was confirmed by Ban (1971) in Japan. There is no evidence that Ban was aware of Craufurd's work. Researchers in Japan recall that Ban was severely ostracised for his seemingly discordant work; but after his associates returned to their laboratories and confirmed it, they presented him an award. Ban concluded that the cracking does not happen during drying, nor immediately thereafter. Even when the rapidly dried rice was stored under airtight conditions, an increasing number of cracks appeared for the next 48 hours. Ban gave no explanation for these crack rings (fissures) but proposed that the crack ratio test for dryers in Japan be delayed for 48 hours or more after grains are dried. The observation by Ban was wholly in agreement with that of Craufurd. Milner and Shellenberger (1953), while working with wheat, incorrectly reported that fissuring during the drying process was favoured by elevated initial moisture and increased drying rate. Their data suggested that cracking occurred when a certain degree or rate of shrinkage of the hydrated endosperm was exceeded. They further reported that the mechanics of this kind of cracking had been treated thoroughly by Earle and Ceaglske (1949). The work of Earle and Ceaglske with macaroni shows that the cracking occurs after drying. Their comments were (at the end of drying):

> Where this moisture gradient is large, the macaroni may fail by tension at the inner surface upon the removal of the moisture gradient... This type of failure is one of the most puzzling to commercial operators, for the macaroni looks and feels strong as long as the drying is in progress. Soon after the fans are stopped the cracking starts.

So the observation of fissuring and cracking after drying by Earle and Ceaglske (1949) with macaroni seems to preempt those of Craufurd (1963), Ban (1971), and Kunze (1979) with rice. They all observed cracking (fissuring) not necessarily during drying but rather after drying. All used a high rate of drying which left a steep moisture gradient in the macaroni or rice at the end of drying.

Further support is given to the fissure after drying phenomenon by more recent researchers. White et al. (1982) studied the development of stress cracks in popcorn as a result of drying and rehydration. Their results agree with those of previous rice researchers who found that stress cracks in popcorn are caused by a redistribution of moisture after the grain has been removed from the dryer. The delay before the stress cracks occur is related to the moisture gradient in the kernel when drying is stopped. Cracks developed during the reconditioning process (moisture adsorption) rather than afterwards, as was found in the drying process. After the work of Ban (1971), Nishiyama et al. (1979) developed a crack generation equation to predict the percentage of fissured grains at any time after drying. Kato and Yamashita (1979) worked to minimise the fissures after drying by temporarily storing grains at 60°C. High storage temperatures helped to reduce the development of fissured grains but did not eliminate them.

Sharma and Kunze (1982) also studied post-drying fissure developments in rough rice. A few kernels fissured while drying, but most fissures developed within 48 hours after drying. Some, however, did not develop until nearly 120 hours thereafter. Nguyen and Kunze (1984) investigated the effects of post-drying treatments on fissures which developed in rice after rapid drying. They reported that a 11% relative humidity and 45°C environment engendered fewer fissures in grain than other storage environments which had less tendency to remove surface moisture.

Grains with partial fissures can often be observed in milled rice. What causes them? Do fissures in field rice develop in the same way as fissures in storage moisture rice? Fissures from moisture readsorption which develop in storage moisture rice develop essentially completely across the grain within a fraction of a second.

Dry paddy was rewetted by Craufurd (1963) in an effort to determine where cracks began on or in a rice grain. When whole grain brown rice was placed into water, all cracks which developed were whole cracks and these developed so fast that he was unable to determine their point of origin. Henderson (1954) conducted X-ray studies and showed that cracks (fissures) began at the centre of the grain and then progressed outward parallel to the minor axis.

If a physical action occurs with sufficient speed and intensity, it produces a sound. Robert Young, a graduate student in Agricultural Engineering at Texas A&M University, was the first to record on tape the audible sound made by a grain of popcorn when it fissured from moisture readsorption (Stermer and Kunze 1992). Later, Jivo Kouva, Chief of the chemical analysis laboratory of Satake Ltd in Saijo (Hiroshima), Japan demonstrated that a low-moisture rice grain produces a sharp audible snap when it fissures. Stermer and Kunze used a sound transducer to observe the snapping sound on an oscilloscope and subsequently developed an acoustical detection device to record the fissures as they developed in moisture adsorbing rice.

All of the foregoing information confirms that a low-moisture (dried) rice grain will fissure 1) from moisture readsorption, and 2) after rapid drying (to near storage moisture or below) if the dehydration is stopped with a steep moisture gradient in the grain. The rice grains fissure *during* moisture adsorption but in the second case they fissure *after* rapid drying. The second case explains why we have the universal practice of not running milling quality samples immediately after a lot of rice is dried. Instead, we wait as long as practicable before doing so. Readsorption of moisture on the surface of a grain after it has been dried rapidly can also cause rice to fissure. But the foregoing research indicates that such loss in milling quality develops even if the grains are maintained in an airtight container. Moisture migration within the grain, as the gradient reclines, is believed to cause these fissures to develop.

Aside from fissures which develop after rapid drying of paddy, we need to identify where low-moisture grains are exposed to moisture adsorption environments. Chau and Kunze (1982) studied moisture content variations among rice grains at the time of harvest. When field rice in a plot was at 22% moisture content, they found moisture differences up to 29% between grains (groups of 10) harvested from the tops of the most mature panicles and from the bottoms of the least mature ones. The longer rice at harvest moisture was left in the field, the greater was the probability that lower moisture grains would fissure on the stalk before harvest.

More recently, Sarwar and Kunze (1989) conducted research on relative humidity increases that cause stress cracks in low-moisture maize. They found that grains equilibrated to 10% m.c. before being exposed to 75% relative humidity or above, would fissure. All grains fissured when the exposure to relative humidity was 92% or above. No grains fissured when the initial grain moisture was 15% or above. Therefore, the moisture adsorption reaction of maize is essentially parallel with that of rice. However, it is perhaps more important that rice maintains its integrity since it is consumed as a whole grain.

Research that moisture adsorption, by low-moisture rice or other cereal grains with a hard vitreous endosperm, produces fissured grains is sufficiently prevalent that it is no longer only a theory. With some exceptions, the phenomenon is accepted today. The moisture can be liquid or vapour. The mainstream of grain drying research is shifting to include the moisture adsorption aspects. The information is becoming useful and is beginning to find application in the grain industries.

Research Opportunities

One of the needs of the rice industry is for producers, millers, and processors to apply the information to practices. Research to date has provided just enough information to indicate the nature of the grain. But this body of knowledge needs to be expanded by those who work with rice. How long and how fast can rice at a given moisture content be dried without inducing fissures in the grains after drying? To what moisture content can high-moisture rice be rapidly dried without inducing after-drying fissures? We think that this is 15 or 16% m.c. Are these values consistent for all varieties? What treatment or treatments can be developed that will inhibit or prevent fissures in grains after rapid drying? How long can paddy at various storage moistures (10 to 14%) be exposed to various relative humidities (80 to 100%) without developing fissures? We need to better define the moisture adsorption fissure response in rice types and forms. Can we flash-dry the hull on high-moisture paddy and efficiently shell the grain? Can we flash-dry the bran on the resulting brown rice and mill the high-moisture rice?

Can we dry high-moisture milled rice without causing surface cracks in the grain? Can we develop a system that will burn the removed hulls to flash dry the hulls on more high moisture paddy and then continue to use the heated air to flash-dry the bran on brown rice? Finally, can we use the warm and somewhat humid air to slowly dry the milled rice? Can we make the rice drying industry energy independent by using its own inherent fuel source (hulls)? The foregoing are visions today but they are goals for tomorrow. Team efforts are needed to address these possibilities. The breeders, engineers, producers, dryer operators, storage managers, and processors need to work together to bring these visions to an expeditious fruition.

Research Applications

Available information now needs to be applied in the rice industry. Jenkins (1989) used a modified harvesting technique where rice panicles were cut and swathed in the field. These panicles were then covered with chopped rice straw to provide protection from the sun during the day and from dew at night. The modified technique showed a nearly 20 point improvement in the head rice yield compared with an open window treatment. Banaszak and Siebenmorgan (1990) related fissured rice in the field to grain moisture content, weather, and application of fertiliser. Rice from highly fertilised plots generally required 2 days or more to mature and dry to a given moisture content previously observed in rice harvested from the lesser fertilised plots. When rice samples from either fertiliser level reached 17 to 18% m.c. in the field, the proportion of fissured grains subsequently increased very rapidly. Head rice decreases closely followed fissured grain increases observed in the field. Other research currently in the publication process relates to the fissure resistance of rice varieties, fissure developments related to moisture adsorption stresses in rice, transient moisture gradients in paddy mapped with finite element methods (FEM) and related to fissures after heated air drying, and numerous others.

The body of knowledge on 1) moisture readsorption by storage moisture grains, and 2) the fissuring after rapid drying aspects is being integrated into the grain drying literature and should provide the basis to improve the quality of dried grain. Drying and moisture readsorption are inherently related. Drying provides the potential for moisture readsorption that can be very detrimental to grain quality. Information on the fissuring after drying phenomenon needs to be thoroughly disseminated in the grain industries so that dryer operators, storage managers, and grain processors properly understand their processes and procedures, and thereby have the potential to improve them.

A few grains have been observed to fissure during drying. Current concepts of mechanics coupled with the hygroscopic nature of the grain do not justify the development of these fissures. An imperfection in the grain can provide the needed justification. For example, a small surface crack in the endosperm can create an appropriate avenue for fast moisture removal which could cause the crack to grow across the grain into a fissure. Also, this paper does not mean to imply that improperly operated combines, conveyors, and processing machines do not have the potential to break grain and reduce grain quality. The energy is there to produce breakage. Operators must diligently seek to keep this damage to a minimum. Equipment and machines which inherently damage grain in their operation will eliminate themselves from the commercial market.

References

Ban, T. 1971. Rice cracking in high rate drying. Japanese Agricultural Research Quarterly, 6,113–116.

Banaszak, M.M. and Siebenmorgan, T. J. 1990. Head rice yield reduction rates caused by moisture adsorption.Transactions of the American Society of Agricultural Engineers, 33, 1263–1269.

Chau, N.N. and Kunze, O. R. 1982. Moisture content variation among harvested rice grains. Transactions of the American Society of Agricultural Engineers, 25, 1037–1040.

Copeland, E.B. 1924. Rice. London, MacMillan and Co., Ltd.

Craufurd, R.Q. 1963. Sorption and desorption in raw and parboiled paddy. Journal of the Science of Food and Agriculture, 14, 744–750.

Desikachar, J.S.R. and Subrahmanyan. 1961. The formation of cracks in rice during wetting and its effects on the cooking characteristics of the cereal. Cereal Chemistry, 38, 356–364.

Earle, P.L. and Ceaglske, N.H. 1949. Factors causing the checking of macaroni. Cereal Chemistry, 26, 267–286.

Grosh, G.M. and Milner, M. 1959. Water penetration and internal cracking in tempered wheat grains. Cereal Chemistry, 36, 260–273.

Hall, C.W. 1980. Drying and storage of agricultural crops. Westport, Connecticut, USA, AVI Publishing Company, 381p.

Henderson, S.M. 1954. The causes and characteristics of rice checking. The Rice Journal, 57(5),16, 18.

Henderson, S.M. 1972. Combine hulling of rice, potential and evaluation. American Society of Agricultural Engineers Paper No. 72-333, St. Joseph, Missouri, ASAE.

Huysmans, A.A.C. 1965. Milling quality of paddy as influenced by timing of the harvest. International Rice Commission Newsletter, 14(3), 4–12.

Jenkins, B.M. 1989. A modified swath harvesting technique for rice: Part I. Influence on moisture, quality and harvester performance. Transactions of the American Society of Agricultural Engineers, 32, 1399–1408.

Kato, K. and Yamashita, R. 1979. Study on method of prevention of rice crack-effect on storage under constant warm temperature after drying. Presented at the 1979 Spring Meeting of the Society of Agricultural Machinery, Japan.

Kik, M.C. 1951. Nutritive studies on rice. University of Arkansas, College of Agriculture, Agricultural Experiment Station Bulletin 508.

Kondo, M. and Okamura, T. 1930. Der durch die feuchtigkeits zunahme verursachte querris (Doware) des reiskorns, Ber des Ohara Institut für Landwirtschaftl. Forschungen, 4, 429–446.

Kunze, O.R. 1964. Environmental conditions and physical properties which produce fissures in rice. Ph.D. thesis, Michigan State University, East Lansing.

— 1979. Fissuring of the rice grain after heated air drying.Transactions of the American Society of Agricultural Engineers, 22, 1197–1201, 1207.

— 1991. Moisture adsorption in cereal grain technology—A review with emphasis on rice. Transactions of the American Society of Agricultural Engineers, 7, 717–723.

Kunze, O.R. and Calderwood, D.L. 1985. Rough rice drying, Chapter 6. In: Juliano, B.O., ed., Rice Chemistry and Technology, St. Paul, Minnesota, American Association of Cereal Chemists, Inc.

Kunze, O.R. and Choudhury, M.S.U. 1972. Moisture adsorption related to tensile strength of rice. Cereal Chemistry, 49, 684–696.

Kunze, O.R. and Hall, C.W. 1965. Relative humidity changes that cause brown rice to crack. Transactions of the American Society of Agricultural Engineers, 8, 396–399, 405.

— 1967. Moisture adsorption characteristics of brown rice. Transactions of the American Society of Agricultural Engineers, 10, 448–450, 453.

Kunze, O.R., Peralta, E.K., and Turner, F.T. 1988. Fissured rice related to grain moisture, weather and fertilization rates. American Society of Agricultural Engineers, Paper No. 88–6510. St. Joseph, Missouri, ASAE.

Kunze, O.R. and Prasad, S. 1978. Grain fissuring potentials in harvesting and drying of rice. Transactions of the American Society of Agricultural Engineers, 21, 361–366.

Langfield, E.C.B. 1957. Time of harvest in relation to grain breakage on milling in rice. Journal of the Australian Institute of Agricultural Science, 23, 340–341.

McDonald, D.J. 1967. 'Sun cracking' in rice. some factors influencing its development and the effects of cracking on milling quality of the grains. Unpublished MS thesis, University of Sydney, Australia.

Milner, M., Lee, M.R., and R. Katz. 1950. Application of x-ray technique to the detection of internal insect infestation of grain. Journal of Economic Entomology, 43, 933–935.

Milner, M. and Shellenberger, J.A. 1953. Physical properties of weathered wheat in relation to internal fissuring detected radiographically. Cereal Chemistry, 30, 202–212.

Milner, M., Shellenberger, J.A., Lee, M.R., and Katz, R. 1952. Internal fissuring of wheat due to weathering. Nature (London), 170(4326), 533.

Nguyen, C.N. and Kunze, O.R. 1984. Fissures related to post-drying treatments in rough rice. Cereal Chemistry, 61, 63–68.

Nishiyama, Y., Satoh, M. and Shimizu, H. 1979. Crack generation of rough rice after drying. Journal Faculty of Agriculture Iwate University, 14, 277–287.

Rhind, R. 1962. The breakage of rice in milling: a review. Tropical Agriculture, 39, 19–28.

Sarwar, G. and Kunze, O.R. 1989. Relative humidity increases that cause stress cracks in corn. Transactions of the American Society of Agricultural Engineers, 32, 1737–1743.

Sharma, A.D. and Kunze, O.R. 1982. Post-drying fissure developments in rough rice. Transactions of the American Society of Agricultural Engineers, 25, 465–468, 474.

Sharp, P.F. 1927. Wheat and flour studies. IX. Density of wheat as influenced by freezing, stage of development and moisture content. Cereal Chemistry, 4, 14–46.

Stahel, G. 1935. Breaking of rice in milling in relation to the condition of the paddy. Tropical Agriculture, 12, 255–261.

Stermer, R.A. and Kunze, O.R. 1990. Acoustical detection of fissures developing in storage-moisture rice. Abstracted in Proceedings of the 23rd Rice Technical Working Group, 26–28 February, Biloxi, MS., 88.

Swanson, C.O. 1943. Effects of moisture on the physical and other properties of wheat. II. Wetting during harvest. Cereal Chemistry, 20, 43–61.

White, G.M., Ross, I.J., and Poneleit, C.G. 1982. Stress crack development in popcorn as influenced by drying and rehydration processes. Transactions of the American Society of Agricultural Engineers, 25, 768–772.

Small-scale Grain Dryers

Justin A. Tumambing*

Abstract

The grain production sector in Southeast Asia is generally fragmented, small-scale, labour intensive, and uses traditional-level technology. Not surprisingly, the majority of the drying technology adopted is of the small-scale type.

This paper reviews and evaluates small-scale dryers that have been adapted or at least promoted in drying grains in Southeast Asia. These dryers vary in terms of method of heating the grain (forced convection, natural convection, conduction), method of holding the grain (batch, recirculating-batch, continuous-flow), control systems (manual, semi-automatic, automatic), stage of drying process (pre-drying or first-stage drying, second-stage drying, single-stage drying), and drying capacity (1–6 t per 8 hour operating day).

This paper also describes the level of adoption of each small-scale drying technology and the underlying reasons for particular adoption levels. Recommendations are made about the requirements and features of a small-scale dryer needed to warrant adoption of the particular drying technology.

OVER the past three decades, great gains have been achieved in the humid tropical countries of Southeast Asia in terms of increasing grain production, particularly rice and maize. These gains were primarily due to the widespread adoption of grain production technology (high-yielding and early-maturing varieties, superior cropping practices, higher levels of inputs) coupled with the expansion of irrigated cropping. However, associated with this increase in grain production is the harvest of one of the plantings during the wet season, leading to wet grain handling problems.

The traditional way of solving wet grain handling problems is sun drying. However, the sunshine is unreliable during the wet season, such that mechanical dryers are resorted to. Because of fragmented landholdings, small-scale and labour intensive operations, and existence of traditional-level technology, the mechanical dryers being used in the region are mainly small scale.

The commercial small-scale grain dryers most common in the region are of the forced-convection type where heated air is forced through a layer of grain. The air is the convective medium that supplies heat for evaporating moisture from the grain kernels and then carries the water vapour out of the grain mass. Other types of small-scale dryers existing in limited numbers are the rotary conduction dryers, where the grain is heated through conduction with a very hot rotating drum or cylinder, and the natural convection dryers, where hot air by its natural tendency to rise passes through a relatively thin layer of grain.

Small-scale drying systems vary according to:

- the method of holding the grain (batch, recirculating batch, continuous-flow);
- the fuel used for heating and drying the air (kerosene, diesel oil, or biomass such as rice hulls and maize cobs);
- the geometric configuration of the grain holding device (flat bed, vertical column, rotating drum);
- the type of blower or fan forcing the heated air through the grain mass (centrifugal, axial flow, or propeller type);
- drying air temperature and time of exposure of the grain to the drying air stream;
- provision for mechanical loading and unloading of the grain (bucket elevators, belt conveyors, screw conveyors); and
- system of controlling and monitoring drying air temperature and grain moisture, and fire safety controls.

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Flat-bed Dryers

Flat-bed dryers are among the first type of small-scale dryers that existed in the humid tropics. This was started by the 2 t flat-bed dryer design developed by the University of the Philippines at Los Baños (UPLB) in the Philippines during the early 1960s. The dryer (Fig. 1) has three main parts: a rectangular box (drying bin) to hold the grain above the plenum; a fan and engine to force the drying air through the grain; and a kerosene burner to heat the drying air. The drying bin has a floor area of 1.86 × 3.72 m. The grain depth is kept at about 45 cm to limit the resistance to airflow to less than 250 Pa (1 inch water gauge) static pressure. Air at a rate of 12.7 $m^3/min/m^2$ of drying floor area is forced by a propeller fan into the plenum chamber below a perforated metal floor. The drying air temperature is kept below 43°C to minimise fissuring and maintain seed viability. About 8 hours are required to dry wet paddy from 24% wet basis down to a safe storage level of 14% wet basis.

The original intention of designing the UPLB 2 t flat-bed dryer was to develop a low-cost paddy dryer for the farmer, without considering the drying requirements of the end-user. It turns out that, after several hundred units have been manufactured and sold throughout the Philippines, this dryer has proven to be too large for an individual farmer with less than 2 ha of land and too small for a farmer cooperative, rice trader, or miller. Other problems that arise in using this dryer are the high cost of operation, the need to mix the grain during the drying operation to prevent overdrying of the bottom grain layer, and unprofitability to invest in by a single farmer.

In spite of the many problems encountered in the use of the UPLB 2 t flat-bed dryer, it formed the basis of other dryer designs in Southeast Asia. The Thailand Department of Agriculture has its bigger version of a flat-bed dryer. Malaysia developed its 30 t capacity version which is basically a large flat-bed dryer with an inclined bed.

IRRI has its own version of a 2 t flat bed dryer called a vertical batch-in-bin dryer. The main difference of this dryer from that of UPLB is in the configuration of the drying bin. The drying bin (Fig. 2) is composed of two vertical columns constructed out of inclined wooden slots which also serve as unloading ports. The drying air is forced sidewards between the two columns. This dryer is claimed to operate more efficiently than the original flat-bed dryer, by using an airflow rate twice as much thereby removing about 2% moisture per hour. This was made possible by using a more expensive but efficient vane-axial fan. However, manual grain mixing during operation is very difficult, and a large moisture gradient after drying could therefore be a problem. A manufacturer in Isabela, Philippines (ACT Machineries) is producing a similar vertical batch-in-bin dryer suitable for maize. This dryer is available in capacities of 1.25, 2.5, and 3.5 t and uses an indirect-fired inclined grate furnace as heat source.

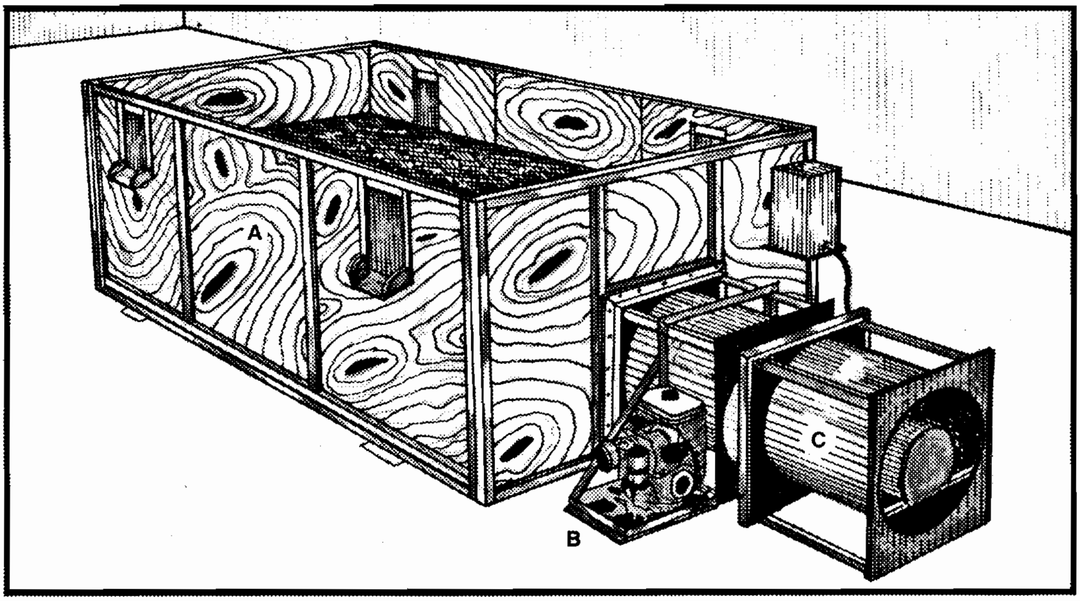


Figure 1. The University of the Philippines at Los Baños (UPLB) 2 t flat-bed dryer: A, box to hold the grain above a plenum; B, fan and engine to force the drying air through the grain; C, kerosene burner to heat the drying air.

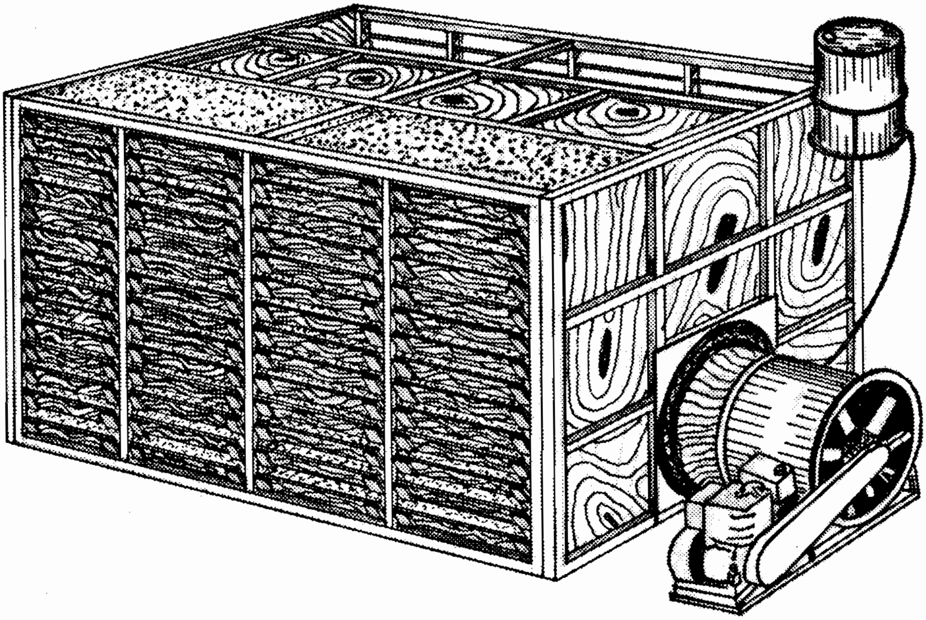


Figure 2. The International Rice Research Institute (IRRI) 2 t vertical bin dryer.

Several local dryer manufacturers in the Philippines developed and marketed their own versions of the flat-bed dryer. The Mariñas Manufacturing Co. in Pila, Laguna, Philippines has its tilting-bed and twin-bed versions using an indirect-fired inclined step-grate furnace as a heat source. Kuizon Enterprises of Bato, Leyte, Philippines has a reversible-airflow flat-bed dryer using a cheaper but efficient direct-fired horizontal grate furnace (Fig. 3). The reversible-airflow feature of the Kuizon dryer has eliminated the need for grain mixing. The Kuizon dryer, although a flat-bed dryer, is still making its way in the market particularly in the Visayas and Mindanao areas in the Philippines because it is available in various capacities (1, 2, 2.5, 5, 20, and 30 t), has lower drying costs due to the use of smokeless, no-ash rice-hull furnace and has a lower labour requirement than sun drying due to its reversible-airflow feature and multiple unloading ports. Other local dryer manufacturers have their own design of a rice-hull furnace but have basically the same drying bin configuration.

In Vietnam, the University of Agriculture and Forestry (UAF) developed five models of flat bed dryers (2, 3, 4, 6, and 8 t/batch) using indigenous materials. Phan Hieu Hien (1993) reported that the 4 and 6 t capacity flat-bed dryers were successfully promoted in the rice-growing Mekong Delta provinces in southern Vietnam, with about 200 units used during the 1991 wet-season harvest. To date, there are now about 600 units manufactured and used in the area. The dryer (Fig. 4) is composed of a drying bin usually made of concrete or brick, a locally fabricated axial fan driven by a diesel engine borrowed from other machines (pumps, boat, etc.), and a rice-hull furnace patterned on an IRRI design. Based on the information gathered during the promotion of these dryers, the following points are worth noting:

- the dryers were used mostly by small farmers and not by rice millers;
- the dryers are owned mostly by contractors and farmer groups; and
- dryer manufacturers play the role of extension workers by providing on-the-spot demonstrations and practical training in dryer operation to prospective buyers.

Recirculating Batch Dryers

A recirculating batch dryer is a hybrid of batch and continuous-flow dryers. A batch of paddy is continually moving and is recirculated within the dryer during the entire drying process. This type of dryer uses a wide temperature range of 40–80°C depending on the initial moisture content of the grain. Some of this type employ airflow rates equal to that of continuous-flow dryers. Faster drying rate is encountered than in the normal batch dryers particularly during the initial stage of drying when a higher drying air temperature is used.

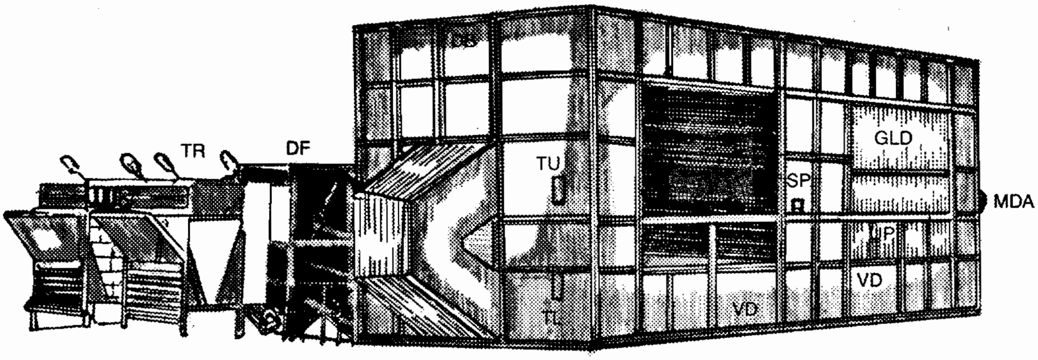


Figure 3. Schematic of the Kuizon reversible airflow batch dryer. DB, drying bin, reversible airflow; RF, rice-hull furnace (twin), smokeless flame; TR, temperature regulator; DF, drying fan, low-speed, centrifugal; ARV, air reversing valve; TU & TL, thermometers (upper and lower); GLD, grain loading doors (on both sides of DB); VD, vent doors (on both sides of DB); MDA, mechanical door actuator, opens and closes GLDs simultaneously; UP, unloading ports (on both sides of DB).

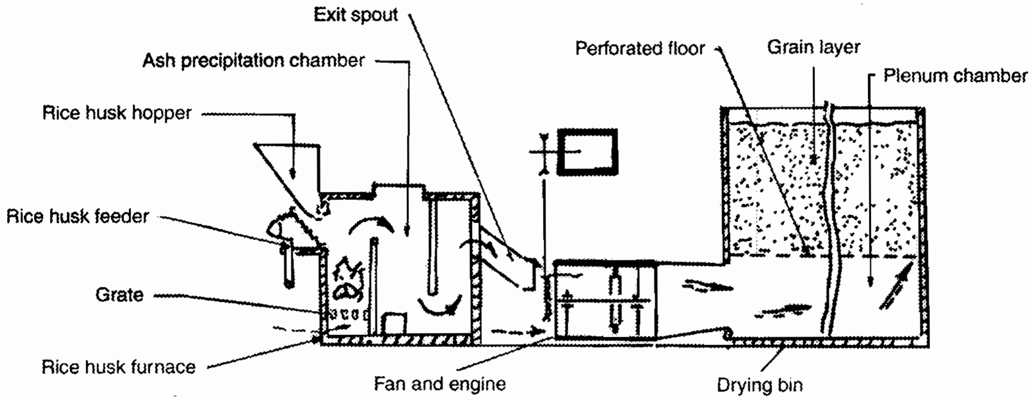


Figure 4. Schematic of the flat-bed dryer developed by the University of Agriculture and Forestry, Ho-Chi-Minh City, Vietnam.

Figure 5 is a schematic drawing of the recirculating batch dryer commonly found in the humid tropics. This type was first introduced by the Japanese under the brand name Satake or Kaneko, with holding capacities of 2–3 t. It has a large holding or tempering bin on top with a small drying section at the bottom. The drying section consists of two columns with a grain thickness of 15 cm. Paddy is loaded from gunny sacks or plastic bags into the elevator hopper at the bottom and lifted to the top. When the drying section and the tempering bin are full, the drying process begins. Recirculation is accomplished by a screw conveyor across the bottom to collect the grain, and a bucket elevator to lift the grain back to the top. The drying air temperature used ranges from 40 to 50°C and it takes about 12 hours to dry the grain from 24 to 14% moisture content (m.c.). This dryer is easy-to-operate and self-contained since it is equipped with electronic controls for regulating the drying air temperature and grain moisture content. However, the controls are sensitive to dusts and require regular and strict maintenance. Besides, the screw conveyor which is subjected to the abrasive action of paddy wears out easily and requires frequent repair or replacement.

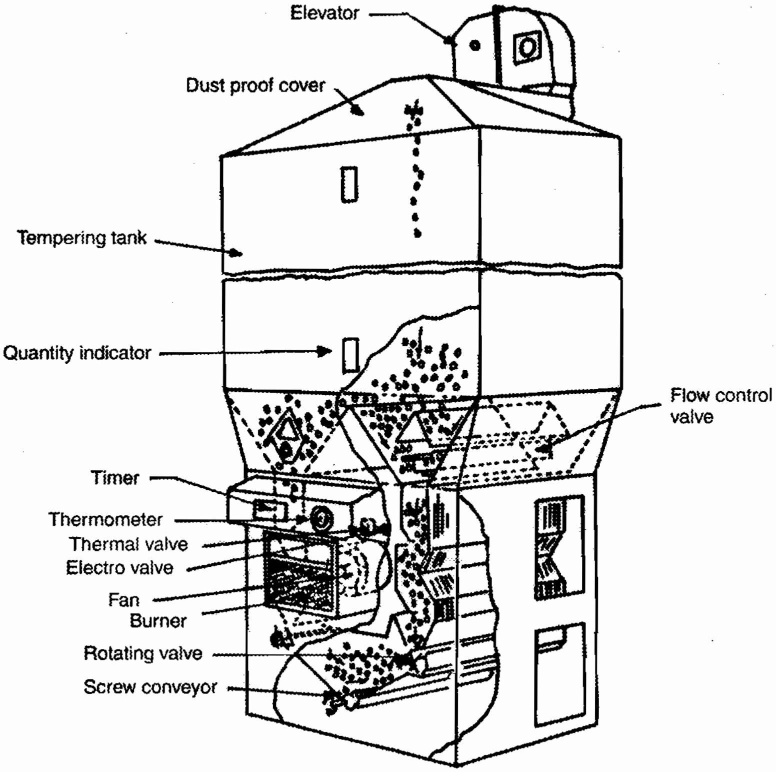


Figure 5. Schematic of the Japanese recirculating batch dryer.

Nowadays, the larger-capacity recirculating batch dryers flooding the market in Southeast Asia come from Taiwan. They are basically the same as the Japanese models, except that due to mass production and use of cheaper materials, the cost per unit dryer is somewhat lower. These dryers are available in capacities ranging from 2.5 to 10 t per unit. They are sold usually in a battery of at least four units, together with ancillary equipment such as a pre-cleaner, receiving and holding bins, and grain handling equipment. Many of the big Chinese rice millers in the Philippines have this type of dryer because of its capability to meet the very fast turnover of stocks (3–5 days) and the easy terms of payment.

Warehouse-Type Dryer

The International Rice Research Institute (IRRI) developed a warehouse-type dryer using non-conventional energy sources. The heat source for drying comes from a centre-tube-type furnace fuelled with agricultural waste such as rice hulls, coconut husks, and saw dust. Two vortex wind machines located on the roof provide the suction pressure to circulate drying air inside the warehouse. The dryer (Fig. 6) has a holding capacity of up to 8 t/batch, suitable for cooperative or village-level operation, or for a group of farmers or rice mill operators. It can be used for drying and storing different commodities in separate lots. Experimental drying runs conducted at IRRI in Los Baños, Laguna, Philippines showed that 6 t of paddy can be dried from 20 to 14% m.c. in 6 hours using a drying air temperature of 39–42°C and air suction rate of 9.83 m^3 /minute/m^3 of paddy (Halos et al. 1983). In terms of milling quality of dried paddy, milling recovery was found to be 67.5% and head rice recovery 83.5%.

This drying technology works effectively only in areas where there are consistently high wind velocities to produce the required air suction rate. Besides, the present design of the vortex wind machine needs improvement to be efficient and economical for its intended uses. Vo-Ngoc et al. (1989) conducted wind-tunnel testing of the IRRI vortex wind machine and recommended some modifications to eliminate the reverse flow of air and hence improve the efficiency.

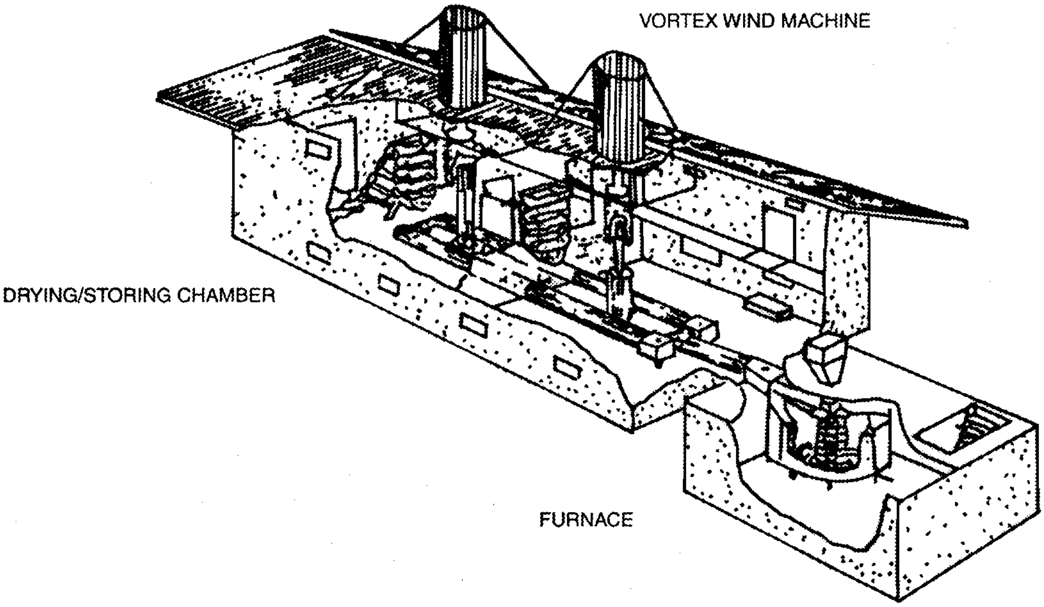


Figure 6. Schematic view of warehouse-type dryer developed by the International Rice Research Institute (IRRI).

More than a decade since its development, this warehouse-type dryer remains uncommercialised. This is primarily due to the following technical and geographic factors.

- Most of the grain-growing areas in the Philippines do not have consistently high wind velocities to achieve the minimum air suction rate of 9.83 $m^3/min/m^3$ of paddy.
- The dryer works effectively for skin dry paddy (18–20%) and not for the very wet paddy (>24%) common during the wet season. This dryer cannot be used for fast pre-drying of wet grains, which is a requirement during the wet season peak harvest.
- The dryer is acceptable only as an intermediate technology.

Natural Convection Dryer

Manilay (1984) described a natural convection dryer (modified Brooks dryer) developed by the Silliman University College of Agriculture (SUCA) suitable for small-scale maize farmers of Central Visayas in the Philippines. The dryer (Fig. 7) is made up of indigenous materials and uses firewood, coconut husks, or maize cobs as fuel for the oil drum surface and heat exchanger. Air above the drum surface is heated and is induced upward by a removable plywood hood placed above a 2.4 × 0.25 m tray with perforated sheet-metal flooring. Under normal operating conditions, about 750 kg of shelled maize at 15 cm grain depth could be dried from an initial moisture content of 24% to a final moisture content of 14% in 8 hours.

This dryer has found its place in the province of Negros Oriental, Central Visayas, Philippines where over fifty (50) units are now being used by individual farmers and farmer associations. The successful adoption of this dryer in the area can be attributed to the following factors:

- low investment and operating costs;
- simplicity of design;
- ease of operation;
- indigenous materials used for construction;
- higher farm-gate price of dried maize; and
- relatively lower initial moisture content (21–14%) of maize for drying and small volume of harvest.

In Indonesia, a study was conducted by Soemangat et al. (1989) on local versions of this type of pit dryer for maize. They modified the pit dryer and constructed four versions which vary in terms of indigenous materials of construction. Results of the study showed that about 1 t of shelled maize at 20 cm grain thickness can be dried from 30 to 17% in 8 hours. For maize in cobs, 1 t at 35 cm thickness can be dried from 32 to 17% in 16 hours. The drying margin is calculated to be twice as much as the maximum drying cost, making the dryer potentially profitable.

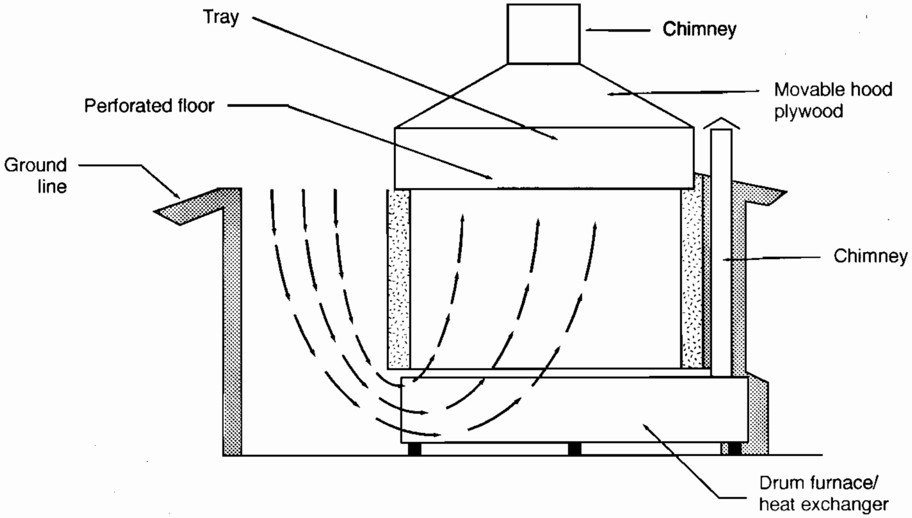


Figure 7. Schematic drawing of the Silliman University College of Agriculture (SUCA) pit-type maize dryer.

Jindal et al. (1987) of the Asian Institute of Technology (AIT) developed an AIT version of a natural convection grain dryer. This dryer is basically an experimental one with a holding capacity of 240 kg of wet paddy. The dryer (Fig. 8) is composed of four thin vertical columns (10 cm thickness) exposed on both sides to hot air. The lower part of each column is inclined by 30 degrees to allow gravitational unloading of paddy. A windmill on top of the drying columns provides additional draft to increase the airflow rate. The drying air is heated by a pipe heat-exchanger using an inclined step grate rice-hull furnace. Drying tests showed that 240 kg of wet paddy could be dried from 24 to 14% m.c. in 46 hours at a drying air temperature of 45°C.

Pre-Dryers

As a result of the recommended two-stage drying strategy to alleviate the wet grain handling problems in the humid tropics, various designs have been developed for first-stage dryers or pre-dryers. These pre-dryers are intended to rapidly dry the high moisture harvest down to about 18%, at which the grain can be stored safely for about 3 weeks. Some of these pre-dryers have gone through wide-scale adoption while others are still in the experimental or development stage.

NAPHIRE 'flash' dryers

NAPHIRE has developed rapid pre-dryers for drying paddy from 24 to 18% in 15 minutes using a drying air temperature of 80–90°C with minimal effect on milling quality. The original design was a 300 kg capacity mobile, batch type consisting of two vertical columns (15 cm thick per column) with a reversible airflow feature to minimise the moisture gradient within the bed thickness to about 1%. During the time this dryer was conceptualised, the need for mobility existed since there were still many areas where transport facilities were lacking. Hence, the capacity of this dryer was limited to 300 kg. A modified version of the dryer (Fig. 9) had been made which operates in continuous-flow to eliminate downtime and increase the capacity. The continuous-flow version has a cooling section to cool down the grain to within 5°C of ambient air temperature. It has also provision for recycling the exhaust air from the drying and cooling sections to save energy consumption by as much as 35%. The pre-drying capacity ranges from 500–600 kg/hour depending on the initial moisture content. The heat for drying comes from either a kerosene burner or a rice-hull furnace. Air requirement is supplied by a blower with a capacity of 85 m^3/min at 190 Pa static pressure. A 7 h.p. gasoline engine provides the power needed for the blower and other drives.

Further modifications of this dryer were made to provide flexibility in operation. These include the provision for recirculating the grain back into the drying section and using two sources of heat, a rice-hull furnace as main heat source and a kerosene burner as a back up heater. With the grain recirculating feature, it is possible to completely dry the grain from 18 to 14% m.c. in two-passes using drying air temperature of 60°C. A stationary version was also developed for those users that need no field drying and that require higher drying capacity. The stationary models have capacities of 1.5–3.0 t/hour.

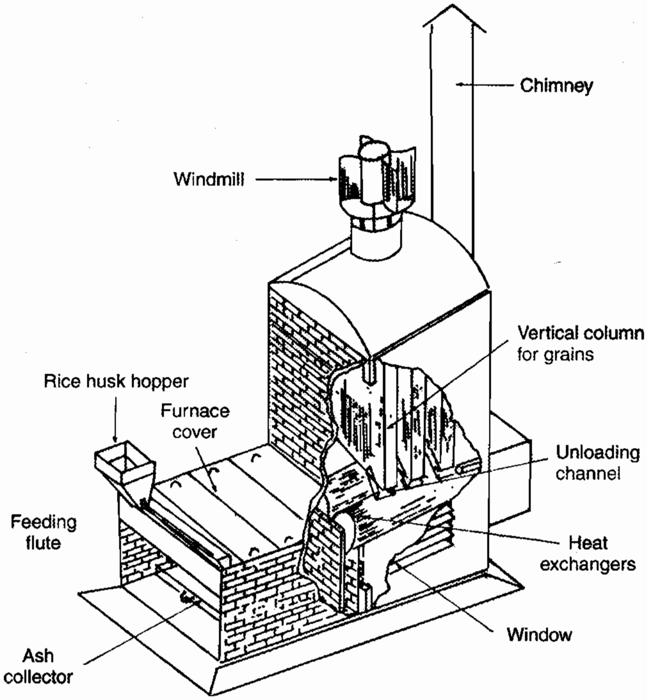
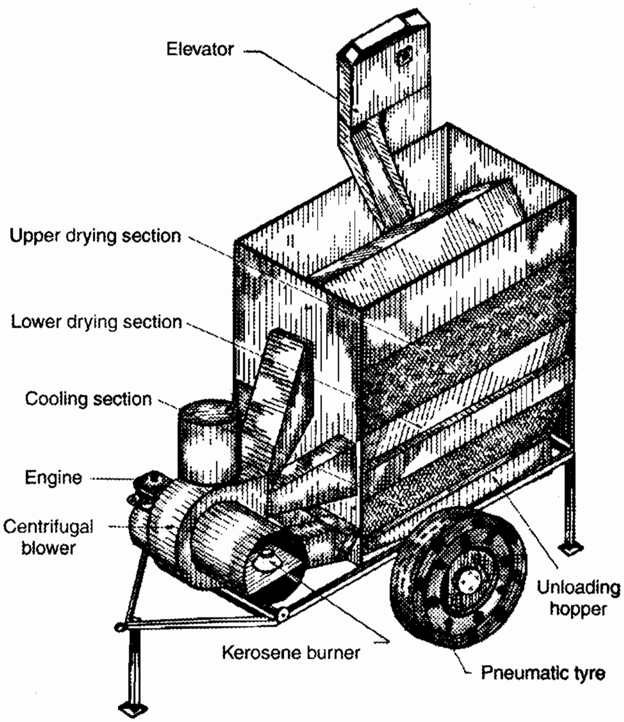


Figure 8. Schematic of the Asian Institute of Technology (AIT) natural convection dryer. (left)

Figure 9. Schematic of the mobile 'flash dryer' developed by the National Postharvest Institute for Research and Extension (NAPHIRE), Philippines. (right)



This pre-dryer has reached the commercialisation stage with the support of the extension program of NAPHIRE and the Grain Production Enhancement Program (GPEP) of the Philippine Department of Agriculture. There are now 14 accredited manufacturers nation-wide producing and selling this dryer. About 1000 units had been sold nationwide since 1992.

Rotary 'flash' dryer

The Philippine Department of Agriculture and IRRI collaborated in the development of a paddy pre-dryer for small and medium-scale rice millers, traders and farmer cooperatives in typhoon prone areas. Stickney et al. (1988) reported the prototype dryer with a capacity of 0.8–1.3 t/hour, pre-drying the wet paddy from 23–32% initial moisture content to around 16–18%. Paddy grain is heated to a high temperature of 80–95°C for about 100 sec exposure time without detrimental effect on the milling quality, except that milled rice appeared yellowish due to a parboiling effect. Combustible gases from the rice hull gasifier are completely burned to provide hot air for heating the rotary drum. The pre-dried paddy is then briefly sun dried to about 14% during favourable weather conditions.

The original prototype has gone through some modifications to make it commercially attractive. The latest version (Fig. 10) was developed by Engr. A.T. Belonio of the Central Philippine University in Iloilo, Philippines.

The modifications include the use of a rice-hull furnace instead of a gasifier, a compact cooling section, and a centralised drive from a 6 h.p. diesel engine. This dryer is exclusively manufactured by Jamandre Industries Inc. based in Iloilo. It comes in two capacities: 250–500 and 500–700 kg/hour. More than fifty units have been sold in Iloilo and neighbouring provinces.

IRRI developed a rotary pre-dryer that is mobile, simple in design, and uses indigenous construction materials. Jeon et al. (1989) described the rotary pre-dryer suitable for paddy, maize, peanuts, and coffee beans. The dryer (Fig. 11) has a throughput capacity of 200 kg/hour at a recommended rotating drum speed of 6 rpm. A small axial fan supplies the air needed for combustion. The fan and the drum are driven manually through a series of shaft and chain links. The drum temperature is kept at 150–200°C to limit the grain temperature to below 70°C.

Results of the drying tests showed that a one-pass pre-drying did not affect milling quality except for lower degree of whiteness. This dryer was not commercialised primarily because of very small capacity and labour-intensive operation.

AIT has developed a rotary dryer intended for disinfestation and rapid pre-drying of high moisture paddy. The experimental dryer (Fig. 12) consists basically of an inclined step grate-type furnace and a cylinder that rotates slowly in the flue gas chamber. A continuous helical spiral is attached to the inside wall of the cylinder. A study by Jindal and Obaldo (1987) showed a suitable heating surface temperature of 100–180°C (capable of drying paddy from 26.9 to about 16% m.c. without significant reduction in milling quality). The heating of paddy suppressed fungal growth and respiration rate effectively. The viability of the paddy seeds was drastically reduced to as low as 2% germination rate.

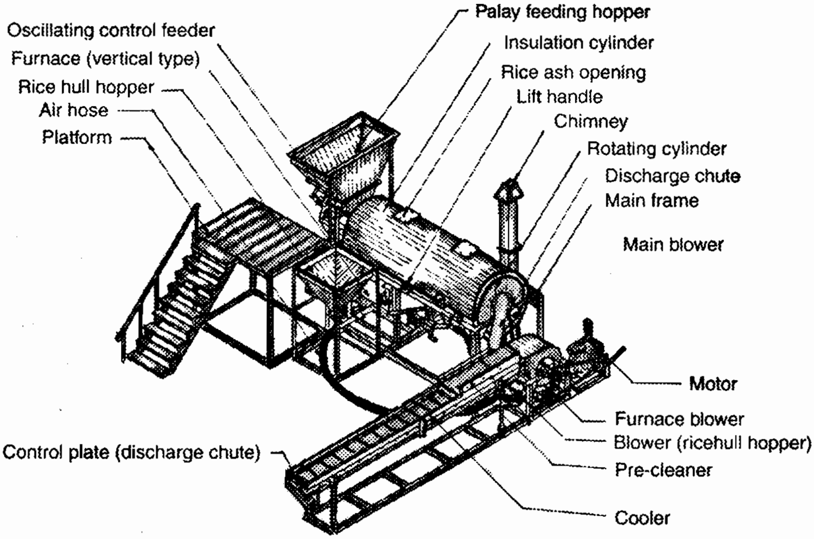


Figure 10. The rotary conduction 'flash' dryer.

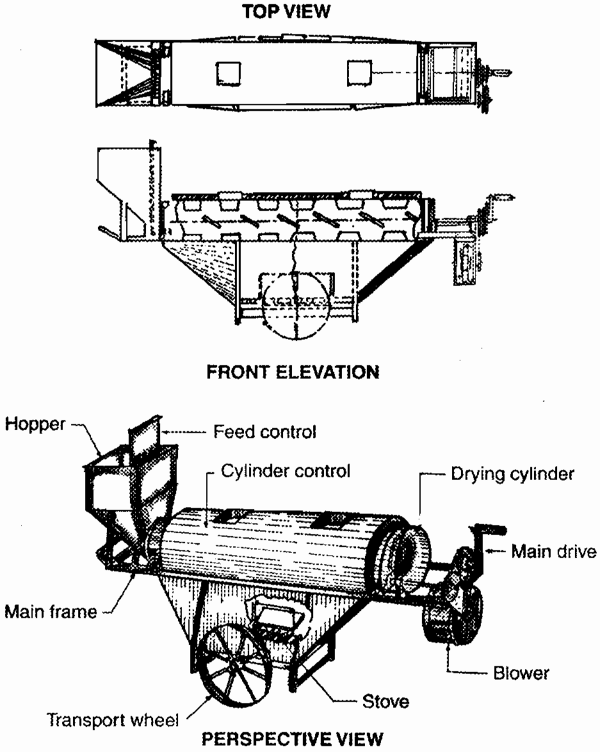


Figure 11. Plan drawing of the International Rice Research Institute (IRRI) pre-dryer. (Model with cooling fan at the discharge end.)

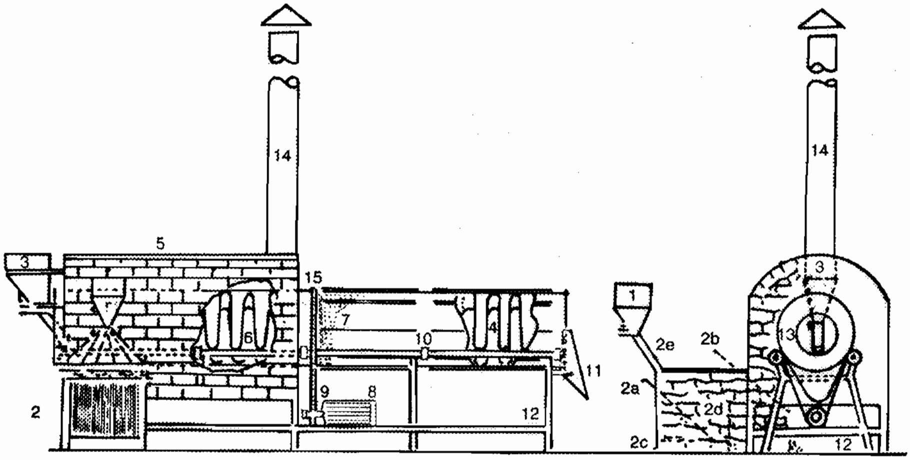


Figure 12. Schematic of the Asian Institute of Technology (AIT) rotary pre-dryer: 1, rice-husk hopper; 2, furnace; 2a, adjustable inclined grate; 2b, adjustable ash trap; 2c, ash collector; 2d, brick wall; 2e, husk flow equaliser; 3. paddy inlet hopper; 4, electromagnetic vibrator; 5, brick dryer housing; 6. rotary dryer; 7, perforated rotary cooler; 8, electric motor; 9, chain drive; 10, ball bearing; 11, paddy outlet guide; 12, angle bar frame; 13, helical baffles; 14, chimney; 15, flange joint.

Fluidised-bed dryer

A fluidised-bed dryer is one where the grain is subjected to a very high airflow (up to 150 $m^3/min/m^2$ of drying floor area) causing the grain to suspend in the air and exhibit fluid-like behaviour. A drying air temperature of up to 120°C is used to effect a high heat transfer rate. Because grains particularly rice and maize are sensitive to fissuring at high temperatures, fluidised-bed dryers are suitable only for first-stage drying where the high moisture grains are pre-dried to around 18% moisture content. Tumambing (1993) and Soponronnarit and Prachayawarakorn (1995) conducted laboratory-scale continuous fluidised-bed drying of high moisture paddy and found that paddy with moisture contents greater than 24% (wet basis) was pre-dried to about 18% using a drying air temperature of over 100°C and an air velocity of about 2 m/s without detrimental effect to milling quality. The benefits of fluidised-bed drying are fast drying rate, uniform product moisture content, and reasonable energy consumption when used for pre-drying and thermal disinfestation of the grain.

A prototype 1 t/hour continuous fluidised bed dryer was constructed and installed by King Mongkut's Institute of Technology Thonburi and Rice Engineering Supply Co. Ltd. at a paddy merchant's site in Thailand. The prototype dryer was successfully used during the 1994 harvesting season (Soponronnarit 1995).

Spouted-bed dryer

A spouted-bed dryer as the name implies is characterised by a spouting bed of particles or grains in the centre of a conical-cylindrical chamber. The spouting is brought about by blowing high-velocity air through a small section at the bottom of the bed. As in the case of a fluidised-bed dryer, spouted-bed dryers have high heat and mass transfer rates and good mixing of grains. They compare favourably with fluidised-bed dryers in terms of capital and operating costs, due to lower airflow rates.

Srzednicki and Driscoll (1993) reported a laboratory study on the drying behaviour of paddy and maize using a conical-cylindrical spouted bed dryer. It has been found that a two-compartment drying model was adequate to describe the falling rate process. Development of this type of dryer for use as a first-stage dryer for high moisture grains was limited to laboratory scale due to scaling-up problems of the design.

Conclusions and Recommendations

Small-scale dryers in the region have varying degrees of adoption. Some have reached the point of commercialisation while others remained at the experimental and development stages. From the preceding review and evaluation made of the different small-scale dryers, some recommendations can be made for a particular type of dryer, if it is to be widely adopted:

- Before proceeding with the design and development of a particular type of dryer, a systems or market study should first be done, taking into consideration the specific drying requirements of the target end-users, its affordability, social constraints, environmental impact and gender sensitiveness. The features common to commercialised dryers are affordability, ease of operation, low operating cost, high capacity, and flexible operation.
- The basic principles associated with the drying process and its design are now fully understood and almost perfected, such that simulation models are now becoming a basic tool of dryer designers. However, what seems to be needed now is not a novel dryer design but rather to take advantage of the good features of existing dryer designs and maximise the benefits that can be derived by retrofitting them into the specific requirements of the end-user.
- There should be some programs from government or private agencies geared towards the extension and commercialisation of proven, appropriate drying technologies.
- The 'copy-cat' propensity among Southeast Asians should be exploited by way of creating success stories or showcases to provide multiplier effect.
- The dryer manufacturers should have active involvement in the development of a dryer, at least in the fine tuning of the prototype. This is to provide them with the knowledge about the dryer necessary during the training of end-users on dryer operation. Besides, the manufacturer is skilled in optimising the material specification and constructing the dryer into a saleable form.
- The developed dryer should not only be technically efficient and economically viable but it should also be socially acceptable, enviromentally friendly, and gender sensitive.

References

Halos, L.S., Jeon, Y.W., and Bockhop, C.W. 1983. Design and performance of a multi-purpose dryer using non-conventional energy sources. Paper presented at the 33rd Annual Convention of the Philippines Society of Agricultural Engineers. April 1983, VISCA, Baybay, Leyte.

Jeon, Y.W., Halos, L.S., and Elepaño, A.R. 1989. Design and performance evaluation of an IRRI pre-dryer. In: de Mesa, B.M., ed., Grain Postharvest Systems. Proceedings of the 10th ASEAN Technical Seminar on Grains Postharvest Technology, Bangkok, Thailand, 19–21 August 1987, 70–82.

Jindal, V.K. and Obaldo, L.G. 1987. Rice husk-fired rotary dryer for the disinfestation and rapid drying of paddy. In: de Mesa, B.M., ed., Grain protection in postharvest systems. Proceedings of the 9th ASEAN Technical Seminar on Grains Postharvest Technology, Singapore, 26–29 August 1986, 42–54.

Jindal, V.K., Chungu, A.S., and Guarte, R.C. 1987. Design and development of a natural convection grain dryer. In: de Mesa, B.M., ed., Grain protection in postharvest systems. Proceedings of the 9th ASEAN Technical Seminar on Grains Postharvest Technology, Singapore, 26–29 August 1986, 55–67.

Manilay, A.A. 1984. The African dryer as a dryer for maize. Post Harvest Quarterly, 8(4), 5–6.

Phan Hieu Hien 1993. Using batch grain dryers for the summer–autumn crop in Southern Vietnam. In: Naewbanij, J.D. and Manilay, A.A., ed., Proceedings of the 14th ASEAN Technical Seminar on Grain Postharvest Technology, Manila, Philippines, 5–8 November 1991, 113–127.

Soemangat, Atjeng, M.S., Darmawan, S., and Hadi, K.P. 1989. Studies on the maize pit dryer at the village level. In: de Mesa, B.M., ed., Grain postharvest systems. Proceedings of the 10th ASEAN Technical Seminar on Grains Postharvest Technology, Bangkok, Thailand, 19–21 August 1987, 112–126.

Soponronnarit, S. 1995. Drying of paddy and maize in Thailand. In: Champ, B.R. and Highley, E., ed., Postharvest technology for agricultural products in Vietnam. Proceedings of an International Workshop, Hanoi, Vietnam, 8–9 December 1994. ACIAR Proceedings, No. 60, 61–65.

Soponronnarit, S. and Prachayawarakorn, S. 1995. Optimum strategy for fluidised bed paddy drying. Drying Technology, in press.

Srzednicki, G.S. and Driscoll, R.H. 1993. High moisture grain drying with spouted bed dryer. In: Naewbanij, J.D. and Manilay, A.A., ed., Proceedings of the 14th ASEAN Technical Seminar on Grain Postharvest Technology, Manila, Philippines, 5–8 November 1991, 113–127.

Stickney, R.E., Piamonte, V.N., and Belonio, A.T. 1988. DA–IRRI paddy dryer with rice hull gasifier. In: Naewbanij, J.O., ed., Proceedings of the 11th ASEAN Technical Seminar on Grains Postharvest Technology, Kuala Lumpur, Malaysia, 46–58.

Tumambing, J.A. 1993. Mathematical modelling and design of a continuous fluidised bed dryer for pre-drying of high moisture paddy in the humid tropics. Unpublished Ph. D. Thesis, University of New South Wales, Sydney, NSW, Australia.

Vo-Ngoe, D., Longval, J.R., Srivastava, N.K., Jeon, Y.W., and Aalos, L.S. 1989. Wind tunnel testing of the IRRI vortex wind machine. In: de Mesa, B.M., ed., Grain postharvest systems. Proceedings of the 10th ASEAN Technical Seminar on Grains Postharvest Technology, Bangkok, Thailand, 19–21 August 1987, 83–100.

Use of Continuous-flow Grain Dryers in Thailand

Keeradit Bovornusvakool*

Abstract

This paper describes the development and application of continuous-flow grain dryers for the maize, soybean, and paddy industries in Thailand. The most popular locally made unit is an LSU-type cross-flow dryer with perpendicular air baffles that give more homogeneous drying than one-directional air baffles. The main features of this dryer, including air volume, heat source and combustion characteristics, and pollution control, are considered. The operational, environmental, and cost advantages and disadvantages of different energy sources are considered. The performances of different types of continuous-flow dryers are compared.

ANNUAL grain production capacity of Thailand (Table 1) is more than 20 Mt, comprising mainly paddy, maize, and soybeans.

Grain Dryer Development in Thailand

Maize drying

Mechanical drying of grain was first introduced into Thailand about 30 years ago, at the large, maize-export terminals. A handful of imported dryers inadequately served several million tonnes of wet grain. All export terminals were located in Bangkok or suburban areas. Traffic congestion drove the terminals to a special, up-country grain-export zone 15 years later. Aflatoxin effects again drove the drying facilities northwards, where most of the maize is grown, so that the grain could be dried immediately after harvest.

As the dryers moved northwards, against the flow of the maize to be exported and approaching the maize-growing area, their ownership shifted from large conglomerates to small individual rural merchants. Concomitantly, dryer sizes decreased, from industrial terminal scale with sophisticated handling and cleaning systems, to smaller, single units with only one or two items of handling equipment.

Soybean drying

Soybean drying has been a success story because the temperatures and exposure times required are similar to those for maize. Soybean drying is restricted to the large-scale soybean oil industry.

Paddy drying

Mechanical drying of paddy was initially done incorrectly: without proper knowledge, people tried to dry paddy in the same way as they did maize. The outcome was a disastrous reduction in head rice yield and drying therefore was discouraged.

Table 1. Production of major grain crops in Thailand.

Year (July–June)	Maize (Mt)	Paddy (Mt)	Soybean (t)
1985–86	5.35	17.93	309,424
1986–87	4.09	16.33	356,484
1987–88	2.31	15.33	337,745
1988–89	4.50	17.55	516,811
1989–90	4.39	18.48	672,368
1990–91	3.72	14.90	530,112
1991–92	3.50	17.51	435,587
1992–93	3.50	17.30	480,148
1993–94	2.85	16.48	513,099
1994–95	4.12	18.07	527,580
1995–96	4.04	n.a.	533,994

Source: Center for Agricultural Statistics, Office of Agricultural Economics, Ministry of Agriculture and Cooperatives, Bangkok, Thailand.

In fact, the drying hardware or equipment for maize and paddy are exactly the same: the same dryer, the same fan, the same controlling system, etc. The only difference is in the software; that is, the technique of how to dry paddy properly. Many textbooks state the need to have an 8–12 hour tempering period between

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subsequent passes through the dryer. This again discouraged the use of continuous dryers for paddy as a very large scale investment would be involved for the various stages, including specially designed tempering bins and complicated material handling systems. In Malaysia, people swayed by this theory even turned to inefficient flat-bed dryers.

It was eventually verified that a single, continuous-flow, recirculating batch dryer with simple feed and discharge systems can give satisfactory head rice yields; much better, indeed, than conventional sun drying if the system is designed and operated properly. Moreover, artificial drying is—in the long run—more economic.

Parboiled rice drying

Artificial drying for parboiled rice is uncommon, because of the large initial investment needed. Because of the excessive moisture content of paddy after soaking in water, to dry parboiled needs kiln dryers and a series of continuous-flow vertical dryers, in addition to the continuous steaming equipment. Thus, artificial drying facilities for parboiled rice are limited to only the few leaders in the business who can afford them.

As the parboiled rice-drying process is continuous and can be fully automated, control of rice appearance can be achieved by varying parameters such as steaming pressure, soaking and steaming time, temperature, etc.

Milled rice drying

A new strategy has been developed to obtain better head rice yield after milling. The paddy is milled at 16–17% moisture content (m.c.) in order to reduce the amount of broken rice, after which the milled rice will be dried again in a continuous-flow dryer to the storage moisture content of 14%.

Key Features of Popular Drying Units Made Locally

The author has considerable experience with cross-flow continuous dryers with two-directional air baffles for maize, soybean, and paddy, and with several fuels such as fuel oil, diesel fuel, husks, cobs, steam heat exchangers, etc. He has also developed dryers for seed, with the goal of maximising germination. From his experience, the following are the key features with a bearing on the performance of grain dryers in Thailand.

Two-directional air baffles

The LSU-type cross-low dryer with perpendicular air baffles has proven to dry more uniformly than dryers with unidirectional air baffles.

Air volume

Air volume has a very significant role in drying. Some manufacturers have tried to discount the

Table 2. Comparison of fuel consumption in 'N-Line' dryers.

Cost components	Fuel oil or diesel oil	Steam heat exchanger	Rice husk, maize cobs, or solid waste fuels
Heating	Direct heating contributing to highest efficiency	Indirect via coil heat exchanger	Indirect heat via pipe heat exchanger. Proper design and configuration to avoid direct radiation can lead to longer dryer life
Operation	Fully automatic	Fully automatic for steam control	Manual or semi-automatic by setting upper and lower temperature limits for automatic feeder
Environmental effects	Negligible, if sulfur-rich oil is avoided and complete combustion is achieved	In case of oil-fired boiler, negligible if sulfur-rich oil is avoided and complete combustion is ensured. In case of husk-fired boiler, ashes from husk can be collected by means of wet scrubber	Ashes from husk can be collected by wet scrubber
Variable cost	Cheaper than steam-heated dryer but dearer than husk-fired dryer	In case of oil-fired boiler, dearest. In case of husk-fired, dearer than husk- fired dryer but cheaper than oil-fired dryer	Lowest
Maintenance cost	Lowest	Dearer than oil-fired dryer but cheaper than husk fired dryer	Highest

amount of air, so as to avoid high-cost fans. A low pressure head and a fan delivering a large volume of air should be used for successful drying and should also result in energy savings. The advantage of a large air volume is more obvious in larger size dryers. The recommendations of Morey et al. (1974) on air volume have been found to be sound.

Complete combustion

In case of oil burners, in most of the countries in Asia, the price of fuel oil is normally cheaper than diesel oil. Also, compared weight for weight, the calorific value of fuel oil is greater than that of diesel oil. Most of the dryer manufacturers had to use diesel oil because of their failure to ensure complete combustion, resulting in dried grain contaminated with a tar-like residue. This undesired effect is more obvious in maize drying where the germ area is white and vulnerable to contamination. Any dryer doing well in the maize business is a virtual guarantee that it is causing no contamination. In order to achieve complete combustion, besides having the proper fuel–air ratio, the design of secondary air and tertiary air is very important. Ignition port and combustion chamber design play significant roles in ensuring complete combustion. Insulation of these areas is also important. Table 2 compares fuel consumption and running costs of 'N-Line' dryers using various fuels.

Oil burner

Burners with modulating control are better than two-stage burners as continuous function as continuous adjustment is better than step-function adjustment.

Pollution control

The use of artificial dryers was initially impeded by the resulting air pollution; it was only after the initiation and success of dust filtration that they came to be generally accepted.

The main difficulty in collecting dust from dryers is the very large volume of air that needs to be handled. Trapping dust from large volumes of dust-laden air in self-revolving rotary filters, and the use of high suction but low volume fans to extract the dust from the filters have proven to be successful strategies.

Fluidised-bed Paddy Drying

Somchart Soponronnarit*

Abstract

The development of fluidised-bed paddy drying in Thailand is described in this paper, starting with an experimental batch dryer and culminating with a commercial continuous-flow dryer. A mathematical model of the fluidised-bed paddy drying system is derived.

Fluidised-bed paddy dryer is now fully commercialised in Thailand. The potential is great, especially for high moisture grain.

COMBINE harvesting of paddy is becoming popular in Thailand, especially in the central and lower northern regions of the country. Consequently, the problem of high moisture grain is now very serious. Rice mills are responsible for the problem due to strong competition for grain and therefore are looking for appropriate methods of drying. It has been suggested that high moisture paddy should be dried quickly to approximately 23% moisture content (dry basis[1]) then subjected to ambient air drying in storage (Soponronnarit et al. 1994; Driscoll and Srzednicki 1991). Following two-stage drying, cost and product quality appear to be optimised. During the first stage, fluidised-bed drying is an alternative to conventional hot-air drying. Its advantages are: (1) uniform product moisture content, and thus high drying air temperature can be employed but with less overdried grain; (2) high drying capacity due to better heat and mass transfer; and (3) a much smaller drying chamber and thus a significantly lower initial cost.

Soponronnarit and Prachayawarakorn (1994) reviewed research and development work on fluidised-bed drying of grain, and conducted both experimental and simulation studies on batch fluidised-bed paddy drying (Fig. 1). Their results showed that the maximum drying air temperature had to be limited to 115°C and final moisture content of paddy to 24–25% if product quality in terms of head rice yield and colour were to be maintained. To maximise drying capacity and minimise energy consumption, an air velocity of 4.4 m/s, bed thickness of 9.5 cm (corresponding to a specific airflow rate of 0.1 kg/s/kg dry matter of paddy), and fraction of air recycled of 80% should be employed. Specific energy consumption in terms of primary energy, which is equal to heat plus 2.6 times electricity, was reported at approximately 7.5 MJ/kg of water evaporated. An economic analysis showed that the total drying cost was approximately US$0.08/kg of water evaporated. Both figures, energy consumption and total cost, are relatively attractive, particularly for Thai conditions.

Soponronnarit et al. (1996a) described the development of a cross-flow, fluidised-bed paddy dryer with a capacity of 200 kg/hour (Fig. 2). Experimental results showed that final moisture content of paddy should not be lower than 23% if quality in terms of both whiteness and head yield were to be maintained. Drying air temperature was 115°C. Simulation results indicated that the appropriate operating parameters should be as follows: air speed, 2.3 m/s; bed thickness, 10 cm; and fraction of air recycled of 80%. With these conditions, energy consumption was close to the minimum, while drying capacity was near maximal. In this study, moisture of paddy was reduced from 30 to 24%.

Following the success of the development of the cross-flow fluidised-bed paddy dryer, Rice Engineering Supply Co. Ltd, a private company in Thailand, showed interest in collaborating in the development of a prototype with a capacity of approximately 1 t/hour (Soponronnarit et al. 1996b). The prototype is shown diagrammatically in Figure 3. It comprises a drying section, a 7.5 kW backward curved blade centrifugal fan, a diesel fuel-oil burner, and a cyclone. The bed

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[1] Unless otherwise stated, the moisture contents (m.c.) quoted in this paper are dry basis.

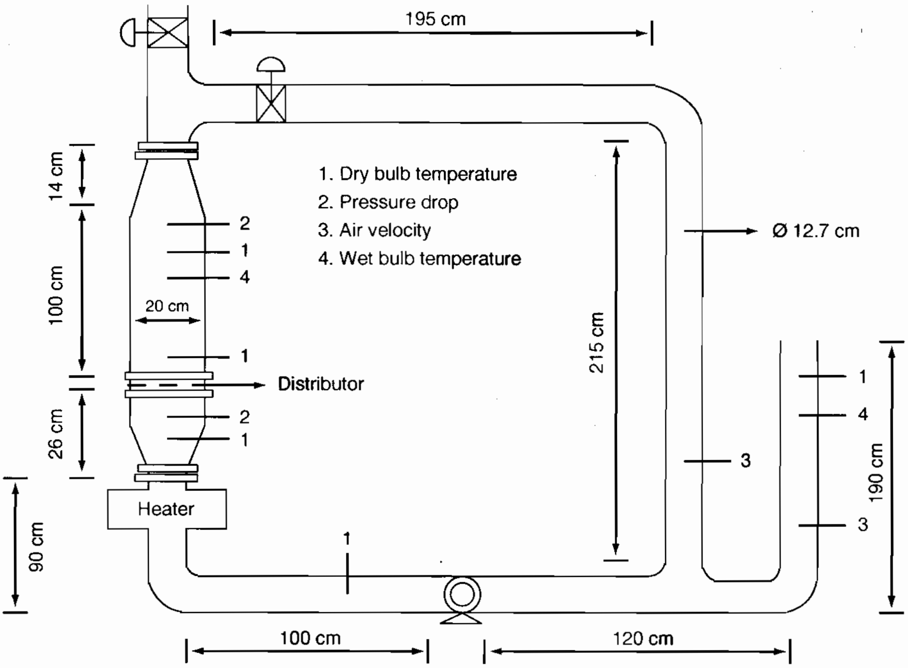

Figure 1. Diagram of experimental batch-type fluidised-bed dryer.

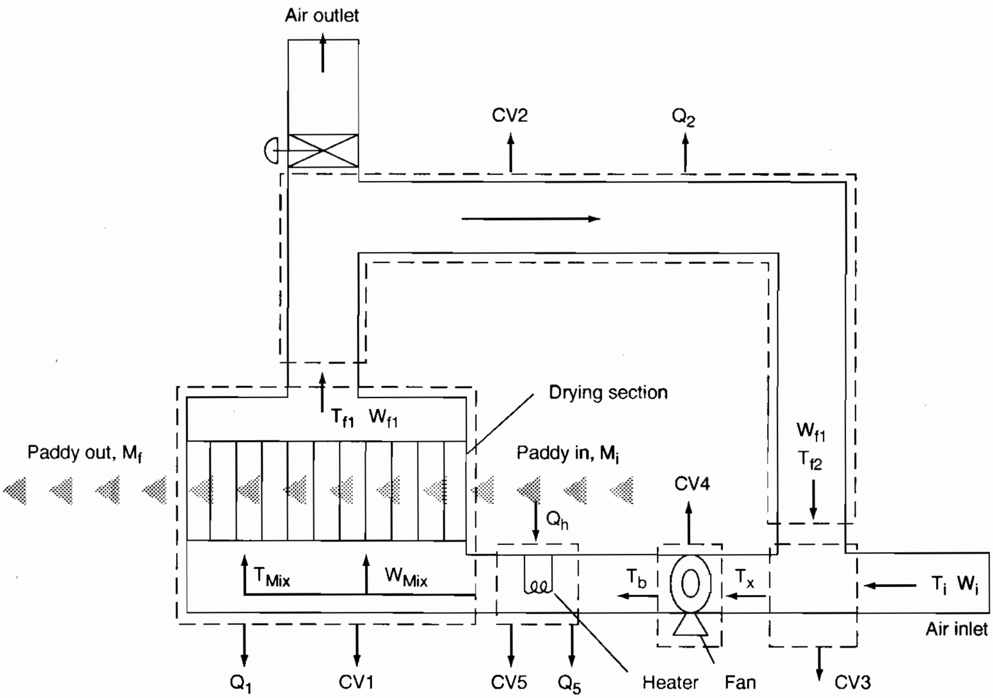

Figure 2. Control volumes of continuous cross-flow fluidised-bed drying system: ◀ grain flow; ← airflow; T, temperature; W, humidity ratio; M, grain moisture content; Q, heat; CV, control volume.

length, width, and height of the drying section are 1.7, 0.3, and 1.2 m, respectively. The depth of the paddy bed is controlled by a weir. Paddy is fed in and out by rotary feeders. In operation, hot air (temperature controlled by thermostat) is blown into the drying section through a perforated steel sheet floor. The air and grain flows are perpendicular to each other. A small portion of the air leaving the drying chamber is vented to the atmosphere, while the remainder, after cleaning in a cyclone, is recycled to the dryer following mixing with ambient air and reheating to the desired temperature. The feed rate of paddy can be varied from less than 1 t to more than 1.5 t. More detail is given in Yapha (1994). Experimental results showed that the unit operated efficiently and yielded high product quality in terms of head yield and whiteness. In reducing the moisture content from 45 to 24% using an air temperature of 100–120°C, a fraction of air recycled of 0.66, a specific airflow rate of 0.05 kg/s/kg dry matter, a superficial air velocity of 3.2 m/s, and a bed depth of 0.1 m, total primary energy consumption was 2.32 MJ/kg of water evaporated, of which 0.35 was primary energy from electricity (electrical energy multiplied by 2.6) and 1.79 was primary energy in terms of heat.

As a result of the success of the prototype, commercial fluidised-bed paddy dryers with capacities of 5 and 10 t/hour are now available. More than 20 units have been sold since the beginning of 1995.

The objective of this paper is to describe the development of fluidised-bed paddy drying, including the mathematical model used. Important results obtained from both laboratory-scale and prototype dryers will be presented.

Development of Mathematical Model

It was assumed that there was thermal equilibrium between drying air and product and that the air and grain flow were plug type. The model is similar to that presented by Soponronnarit and Prachayawarakorn (1994). Figure 2 shows control volumes (CVs) for the derivation of energy and mass equations based on fundamental physical laws.

1. Equation of mean residence time

The empirical equation of mean residence time of paddy developed by Sripawatakul (1994) was used. It is written as follows:

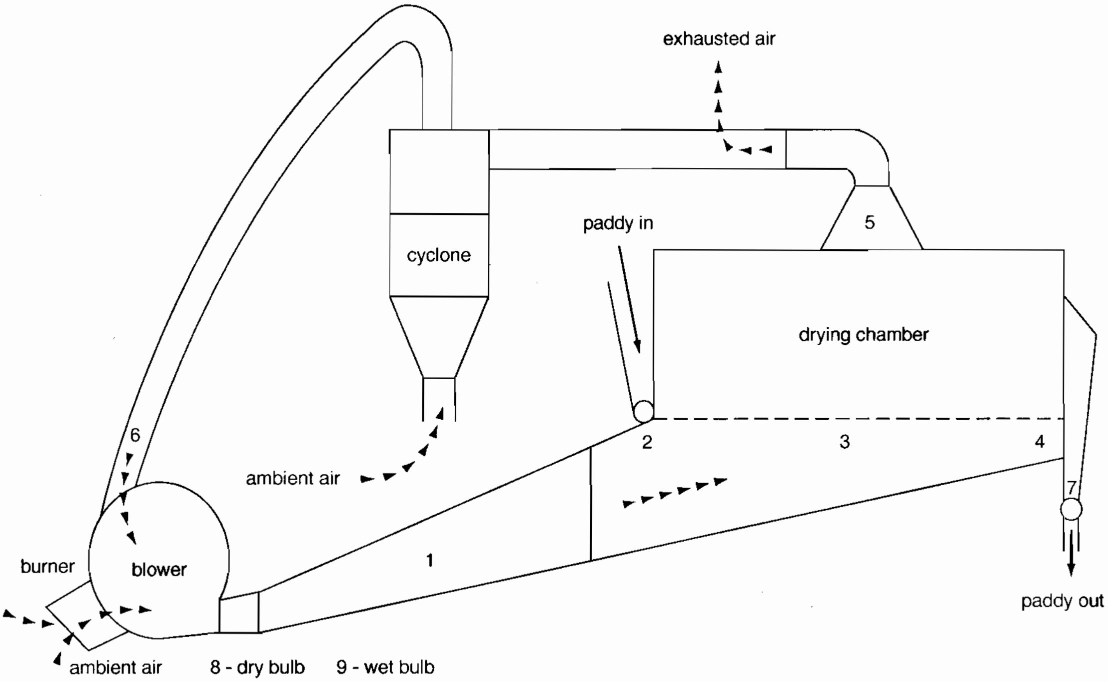

Figure 3. Diagram of fluidised-bed paddy dryer. Numbers indicate where temperature measurements were taken.

$$\tau = hu/F \quad (1)$$

where τ = mean residence time, seconds (s)
hu = hold up, kg
F = feed rate, kg/s

and $hu = [\{-0.0095000 + 0.59870\,F - (0.00020000 + 0.17360\,F)\,V\} + \{1.1728 - 0.082300\,V + (2.2093 - 0.15050\,V)\,F\}\,h]\,\rho_p\,A$

where A = reactor area, m^2
V = air velocity, m/s
ρ_p = average product density, kg/m^3
h = weir height, m

It is valid for weir heights in the range 0.04–0.10 m, air velocities in the range 1.7–2.3 m/s, and paddy feed rates in the range 0.025–0.058 kg/s. For a rough calculation, hu is approximately equal to $h\,A\,\rho_p$.

Dividing the paddy bulk into n layers, changes in moisture content of paddy, temperature, and the humidity ratio of air were calculated for each layer. The following basic equations were employed.

2. Equation of drying rate

The empirical equation for fluidised-bed paddy drying in the form of the equation of Page (1949), developed by Sripawatakul (1994), was used. It is written as follows:

$$MR = \exp(-xt^{y}) \quad (2)$$

where $MR = (M - M_{eq})/(M_{in} - M_{eq})$
t = drying time, min
$x = 0.00163100\,T_{mix} - 1.16202\,(m_{mix}/hu) + 0.00415300\,(m_{mix}/hu)\,T_{mix} + 0.147383\,\ln(m_{mix}/hu) + 0.474743$
$y = -0.00322000\,T_{mix} - 0.835960\,(m_{mix}/hu) + 0.0203190\,(m_{mix}/hu)\,T_{mix} - 0.143150\,\ln(m_{mix}/hu) + 0.548493$

Equation (2) is similar to that developed by Soponronnarit and Prachayawarakorn (1994) for higher specific airflow rate (m_{mix}/hu). It is valid for temperatures of 90–140°C and specific airflow rates of 0.03–0.16 kg/s/kg dry matter of paddy. The symbols are defined as follows :

M = moisture content of paddy at time t, decimal dry basis
M_{in} = moisture content of paddy at the inlet of drying section, decimal dry basis
M_{eq} = equilibrium moisture content, decimal dry basis
T_{mix} = air temperature at the inlet of drying section, °C
m_{mix} = airflow rate at the inlet of drying section, kg/s

During calculation, Equation (2) was differentiated with time, and finite difference was employed to obtain the solution. Equilibrium moisture content was determined using the equation developed by Laithong (1987).

3. Equation of mass conservation

$$W_{f1,i} = R(M_i - M_f) + W_{mix} \quad (3)$$

where $W_{f1,i}$ = humidity ratio of outlet air at the i^{th} layer, kg water/kg dry air
W_{mix} = humidity ratio of inlet air at the i^{th} layer, kg water/kg dry air
M_i = moisture content of paddy at the inlet of i^{th} layer, decimal dry basis
M_f = moisture content of paddy at the outlet of i^{th} layer, decimal dry basis
R = ratio of dry mass of paddy to mass of dry air.

4. Equation of energy conservation

$$T_{f1,i} = [Q_l/m_{mix} + C_aT_{mix} + W_{mix}\,(h_{fg} + C_v\,T_{mix}) - W_{f1,i}\,h_{fg} + RC_{pw}T_{mix}]/(C_a + W_{f1,i}\,C_v + RC_{pw}) \quad (4)$$

where $T_{f\,1,i}$ = temperature of outlet air at the i^{th} layer, °C
Q_l = heat loss, kW
C_a = specific heat of dry air, kJ/kg °C
C_v = specific heat of vapour, kJ/kg °C
C_{pw} = specific heat of wet paddy, kJ/kg °C
h_{fg} = latent heat of moisture vaporisation, kJ/kg

Average temperature and humidity ratio of the outlet air from n layers were determined by arithmetic mean.

For other calculations such as mixing of air streams, and consumption of energy at the fan and the heater, solutions can be achieved by the application of first law of thermodynamics [see Soponronnarit and Prachayawarakorn (1994) for details].

The equations were solved by iteration. Firstly, the value of exit humidity ratio of air was assumed. The equations presented by Wilhelm (1976) were used to determine properties of moist air.

The accuracy of the mathematical model was tested and found to be in good agreement with the experimental results. The model was employed to investigate optimum operating parameters such as air temperature, specific airflow rate, and fraction of air recycled. Details are available in Soponronnarit et al. (1996a).

Performance of Fluidised-bed Dryer

Minimum fluidised-bed velocity

From the experimental results reported by Soponronnarit and Prachayawarakorn (1994), the minimum fluidised-bed velocity for paddy was approximately 1.65 m/s and increased with moisture content. The relationship between pressure drop across the paddy bed and bed velocity is presented in Figure 4.

Paddy quality

According to the experimental results on paddy quality reported by Soponronnarit and Prachayawarakorn (1994), for drying temperatures of 100 and 130°C, relative head yield, which is defined as the ratio of head yield to reference head yield (paddy dried by ambient air), dropped rapidly (below 80–90%) when moisture content after drying reached about 23–26% as shown in Figure 5. Initial moisture content was 45.3% dry-basis. Due to the relatively fast drying rate, the grain surface became hard rapidly and resulted in cracking of grain kernels if drying continued. For a drying temperature of 150ºC, relative head yield increased when final moisture content decreased. This was due to a gelatinisation effect. Figure 6 shows the relationship between relative whiteness as measured by Kett meter and final moisture content. The initial moisture content was 45.3%. It could be concluded that relative whiteness was higher than 90% (still acceptable) for all final moisture contents if drying air temperature was 100°C. However, relative whiteness decreased relatively rapidly with decreased final moisture content, particularly at 130 and 150°C. It was believed that decreasing whiteness was due to caramelisation.

Prototype fluidised-bed dryer

The prototype fluidised-bed paddy dryer shown in Figure 7 and described at the beginning of this paper was tested first at the Rice Engineering Supply Co. Ltd for 2 hours (2 passes). The unit was then transported and installed at Koong Lhee Chan, a paddy merchant site, and was tested for 1497 hours during the wet harvest season in 1994. Approximately 1211 t of paddy were dried from different initial moisture contents to approximately 23%. For the analysis, data obtained from 70 hours of use were employed (Soponronnarit et al. 1996b).

Moisture content of paddy

Figure 8 shows the relationship between inlet and outlet moisture content for paddy drying tests conducted at the Rice Engineering Supply Co. Ltd. Feed rate was 1 t/hour, inlet air temperature was 60°C, initial moisture content of paddy was 26% dry-basis and resident time was 1.8 minutes. Moisture was reduced by approximately 4 and 1.5% during the first and second passes, respectively.

At Koong Lhee Chan, the feed rate was 0.82 t/hour, inlet air temperature was 100°C, initial moisture was 45%, and residence time was 2.2 minutes. Moisture was reduced 20% as shown in Figure 9. Other tests gave similar results.

From Figures 8 and 9, it may be concluded that fluidised-bed drying is more efficient at higher paddy moisture levels.

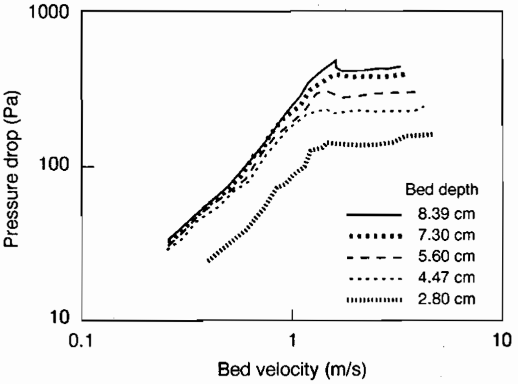

Figure 4. Relationship between bed pressure drop and bed velocity at different bed depths in fluidised-bed paddy dryer.

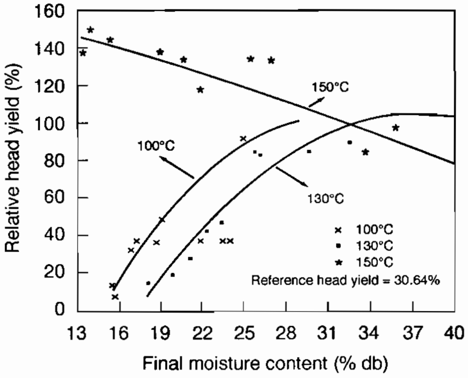

Figure 5. Relationship between relative head yield and final moisture content in fluidised-bed drying at different temperatures (Mi = 45.30% dry basis).

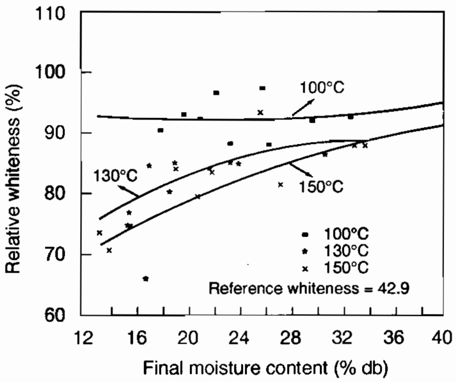

Figure 6. Relationship between relative whiteness and final moisture content in fluidised-bed drying at different temperatures (Mi = 45.30% dry basis).

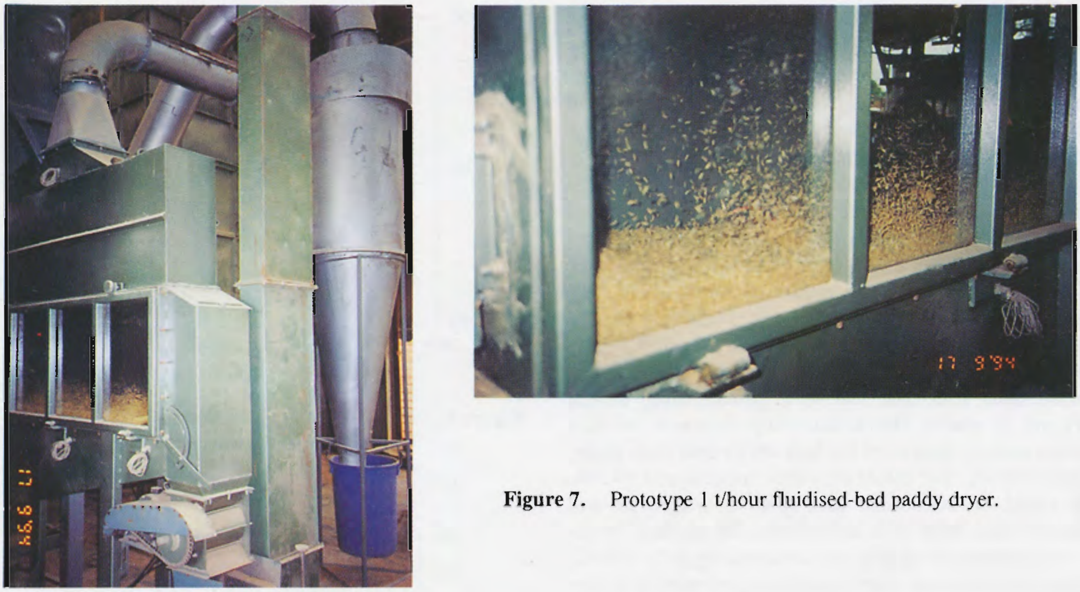

Figure 7. Prototype 1 t/hour fluidised-bed paddy dryer.

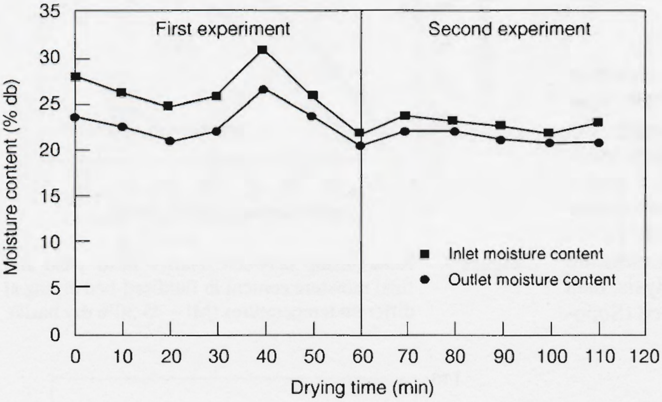

Figure 8. Relationship between inlet and outlet moisture of paddy with fluidised-bed inlet air temperature of 60°C (at Rice Engineering Supply Co. Ltd).

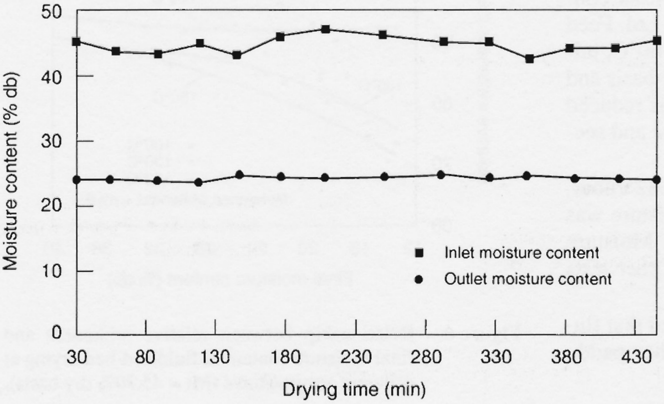

Figure 9. Relationship between inlet and outlet moisture of paddy with fluidised-bed inlet air temperature of 100°C (at Koong Lhee Chan).

Temperatures

For low inlet air temperature (60°C) and low initial moisture content of paddy (26%), average outlet air temperature was close to (just below) outlet grain temperature, as shown in Figure 10. In contrast, the two temperatures were significantly different for high inlet air temperature (100°C) and high initial moisture content of paddy (45%), as shown in Figure 11.

Energy consumption

For drying paddy from 26 to 21% dry-basis with a feed rate of 1 t/hour, specific air flow rate of 0.05 kg/s-kg dry matter, drying air temperature of 60 ºC and fraction of air recycled of 0.66, it required a total primary energy consumption of 5.7 MJ/kg water evaporated, of which 2.45 was primary energy from electricity (electrical energy multiplied by 2.6) and 3.42 was primary energy in terms of heat. During the test, average ambient air temperature and relative humidity were 35.7 ºC and 67.1% respectively.

For drying paddy from 45 to 24% with a feed rate of 0.82 t/hour, drying air temperature of 100–200°C and approximately the same specific airflow rate and fraction of air recycled, it required total primary energy of 2.32 MJ/kg of water evaporated, of which 0.53 was primary energy from electricity and 1.79 was primary energy in terms of heat. During the test, average ambient air temperature and relative humidity were 36.6°C and 59%, respectively.

Electrical power needed for various pieces of equipment was reported as follows: electrical motor for driving fan, 4.93 kW; electrical motors for driving rotary feeders (in and out), 0.72 kW; electrical motor for bucket elevator, 0.79 kW; diesel fuel oil burner, 0.11 kW. In total, the electrical power was 6.55 kW and heating power 60.4 kW.

Paddy quality

Figure 12 shows that head yield of paddy dried in the fluidised-bed dryer with an inlet air temperature of 100–120°C is, on average, approximately 6.5% less than the reference paddy which was dried by ambient air (56.9%). Figure 13 shows the result of whiteness. It indicates that the whiteness of paddy dried in the fluidised-bed dryer or dried by ambient air is nearly the same. The above results confirm the findings of Soponronnarit and Prachayawarakorn (1994) and Sutherland and Ghaly (1992).

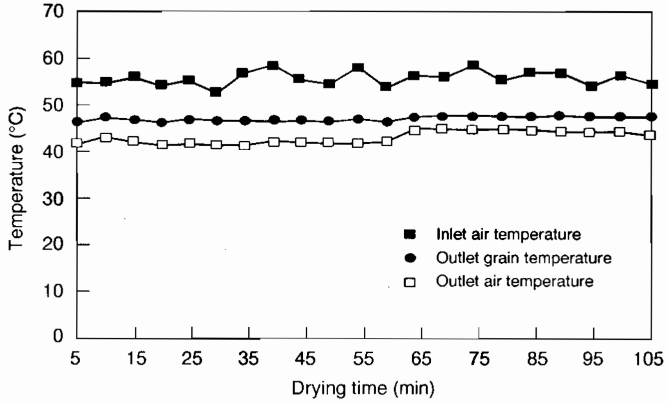

Figure 10. Evolution of temperatures in fluidised-bed dryer at Rice Engineering Supply Co. Ltd.

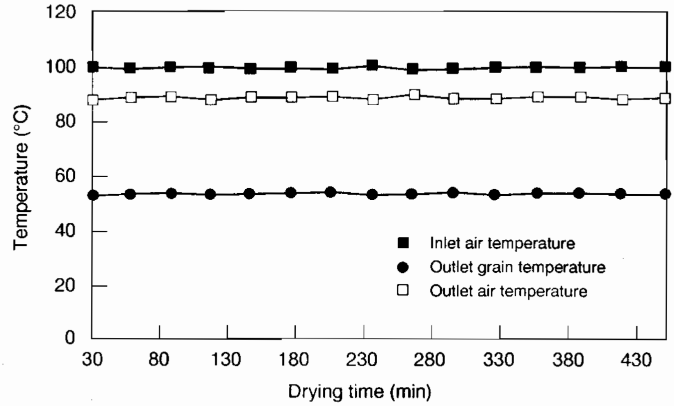

Figure 11. Evolution of temperatures in fluidised-bed dryer at Koong Lhee Chan.

Long term testing

Throughout the wet harvest period of 1994, the prototype fluidised-bed dryer was used for 1497 hours, and approximately 1211 t of paddy were dried. No repair was required. The owner of the paddy merchant site reported that the unit as follows: easy of use; had a very fast drying rate, especially at high moisture levels; consumed less energy in terms of electricity and diesel fuel-oil; and yielded a more uniform product moisture content than the two existing cross-flow columnar dryers at the site.

From Prototype to Commercialisation

As a result of the very successful trial of the prototype fluidised-bed paddy dryer with a capacity of 0.82 t/hour, the owner of the paddy merchant site where the prototype was tested placed an order for a larger fluidised-bed dryer with a capacity adjustable between 2.5 and 5 t/hour. The commercial unit was designed by the research team of King Mongkut's Institute of Technology Thonburi and fabricated by Rice Engineering Supply Co. Ltd. It has been used with success during the main harvesting season in 1995. The unit comprises a drying section, a 11.2 kW backward curved blade centrifugal fan, a diesel fuel oil burner and a cyclone. It costs approximately US$16 000. The bed length, width, and height of the drying section are 2.1, 0.6, and 1.3 m, respectively. The capacity of the burner is 180 kW.

The commercial unit was further scaled up to 10 t/hour capacity during mid 1995. As of August 1995, more than 20 units of both 5 t/hour and 10 t/hour have been installed or are being installed in Thailand. Two units of 5 t/hour were exported to Indonesia.

Conclusion

Field testing of the prototype fluidised-bed paddy dryer with a capacity of 0.82 t/hour during the wet harvest season in 1994 for a total of 1497 hours, indicated that the unit was easy to use, performed efficiently in terms of a very fast drying rate and low energy consumption, and gave uniform product moisture content, compared with the two existing cross-flow columnar dryers installed at the same site. This was reported by the owner of the paddy merchant site, but there are no comparative performance figures.

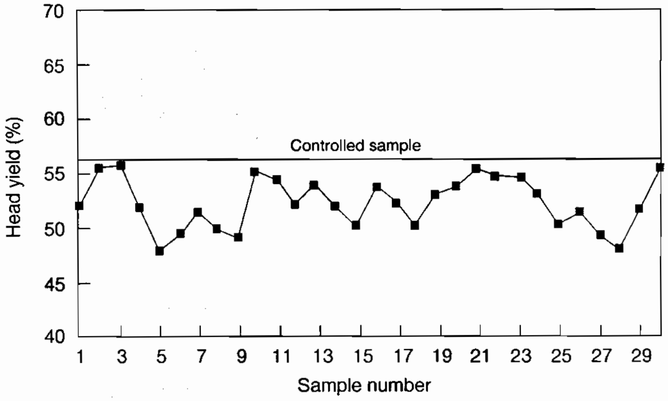

Figure 12. Head yield of paddy after fluidised-bed drying compared with control sample: drying temperature of 100–120°C, moisture content of paddy from 45 to 24% dry basis.

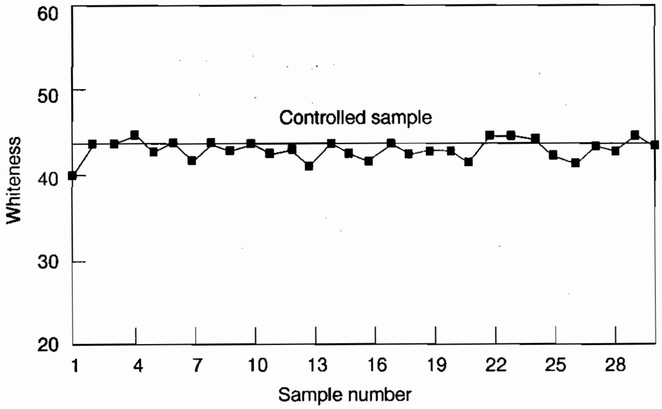

Figure 13. Whiteness of paddy after fluidised-bed drying compared with controlled sample: drying temperature of 100–120°C, moisture content of paddy from 45 to 24% dry basis.

Results from the 70 hours of use of the prototype indicated that the unit operated efficiently and yielded high product quality in terms of head yield and whiteness. In reducing the moisture content from 45 to 24% using an air temperature of 100–120°C, fraction of air recycled of 0.66, specific airflow rate of 0.05 kg/s-kg dry matter, superficial air velocity of 3.2 m/s, bed depth of 0.1 m, total primary energy was 2.32 MJ/kg of water evaporated, of which 0.53 was primary energy from electricity (electrical energy multiplied by 2.6) and 1.79 was primary energy in terms of heat.

Since the beginning of 1995, more than 20 commercial units with capacity of 5 t/hour and 10 t/hour have been sold in Thailand.

Acknowledgment

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References

Driscoll, R.H. and Srzednicki, G.S. 1991. Design for a complete grain drying system under Southeast Asian climates. In: Naewbanij, J.O., ed., Grain postharvest research and development: priorities for the nineties. Proceedings of the 12th ASEAN Technical Seminar on Grain Post-harvest Technology. Bangkok, ASEAN Grains Post-Harvest Programme. Surabaya, 29–31 August 1989.

Laithong, C. 1987. Study of thermo-physical properties of rough rice. Masters thesis, King Mongkut's Institute of Technology Thonburi, Bangkok, Thailand.

Page, G.E. 1949. Factors influencing the maximum rate of drying shelled corn in layers. Unpublished thesis, Master of Science, Purdue University.

Soponronnarit, S. and Prachayawarakorn, S. 1994. Optimum strategy for fluidized bed paddy drying. Drying Technology, 12, 1667–1686.

Soponronnarit, S., Wongvirojtana, P., Nathakaranakule, A., and Prachayawarakorn, S. 1994. Maintaining paddy quality by appropriate ventilation under tropical climate. Proceedings of the 9th International Drying Symposium, Gold Coast, Australia.

Soponronnarit, S., Prachayawarakorn, S., and Sripawatakul, O. 1996a. Development of cross-flow fluidized bed paddy dryer. Drying Technology, in press.

Soponronnarit, S., Yapha, M., and Prachayawarakorn, S. 1996b. Cross-flow fluidized bed paddy dryer: prototype and commercialization. Drying Technology, in press.

Sripawatakul, O. 1994. Study of drying paddy by cross-flow fluidization technique. Masters thesis, Faculty of Engineering King Mongkut's Institute of Technology Thonburi, Bangkok, Thailand.

Sutherland, J.W. and Ghaly, T.F. 1992. Rapid fluid bed drying of paddy rice in the humid tropics. In: Naewbanÿ, S.O., ed., Proceedings of the 13th ASEAN Conference on Grain Postharvest Technology, Brunee Darussalam, 4–7 September 1990. Bangkok, ASEAN Grain Post-Harvest Programme.

Wilhelm, L.R. 1976. Numerical calculation on psychrometric properties in SI units. Transactions of the American Society of Agricultural Engineers, 19, 318–321, 325.

Yapha, M. 1994. Design and testing of pilot continuous fluidized bed paddy dryer. Masters thesis, School of Energy and Materials, King Mongkut's Institute of Technology Thonburi, Bangkok, Thailand.

In-bin Grain Drying Systems

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Abstract

The main categories of in-bin dryer systems are reviewed. For Southeast Asian conditions, research on in-store dryers is discussed, as a component of a two stage drying system for maximum quality preservation and reduced drying cost. Limitations for paddy and maize exist, requiring management of the system to obtain these benefits. Examples of adoption of in-store drying in conjunction with first stage dryers are presented.

IN-BIN drying is drying grain in bins commonly used for grain storage. It is divided into two main classifications: low-temperature (air heated by less than 6°C), and high-temperature drying (air heated to over 50°C).

The objectives of drying are the same as for any other unit operation: to process maximum product at minimum cost whilst maintaining adequate quality. Drying is not able to improve the product quality. Its value is in arresting spoilage by controlling water activity within the product. There are further advantages in reducing the bulk required for transport and in preparing paddy for milling.

Concepts

If drying is performed at an excessive rate, the grain becomes susceptible to fissuring, due to the creation of moisture gradients within the product. These gradients may be due to the drying process directly, caused by too high a drying air temperature, or more commonly to exposure of the product to a readsorption environment. Fast dryers operate at high temperatures, and will tend to cause fissuring if the grain is not allowed to temper. For maize and paddy, once the moisture is reduced below a certain moisture (about 18%, moisture content (m.c.) corresponding to a significant drop in water activity below 1), high-temperature drying becomes inefficient and will tend to cause cracking.

For this reason, forms of drying in two stages have been developed around the world. The basic strategy is to use high temperatures while the grain is still elastic, and low temperatures for removing bound water from the product so that stresses have time to relax within the product. The introduction of two-stage drying to Southeast Asia will be the main topic of this paper.

Theory

In-bin drying in Australia

The technique of in-store drying was adopted early in the history of Ricegrowers' Co-operative Limited, a farmer cooperative in New South Wales, Australia which grows and markets its own grain, and to which over 98% of the farmers belong. In the 1950s, the American technology of in-store drying was adopted, accompanied by conversion from bag handling to bulk handling, in order to solve problems of high paddy moistures and sun cracking (Bramall 1986). The procedure allowed paddy to be harvested at around 21% m.c. (wet basis, w.b.), and then dried in-store to below 14% w.b. for storage and milling.

In-store drying was effective because the ambient conditions in Australia were suitable for this form of aeration, and no supplemental heating was required. Initially, radial bins with mesh walls were used, but based on research at the University of California, ducts at the bottom of the bulk were adopted. Later, under-floor aeration was installed to allow easier access for transport and loaders.

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Over the years the system has been refined, with layer filling, computer controlled bins, supplementary heating, computer-based harvest systems and computer models of drying.

In-bin drying in the United States

Background

In the United States forms of in-bin drying have been used for many decades (since the 1950s), with great success for the maize industry in the central states. Design is based on studies of weather conditions. Experience has shown that both design and careful management are crucial to the success of the system. The main difficulties with implementation in the USA have arisen from the increased time before the grain is dried, increasing the risk of deterioration. Sufficient good quality air must be available at grain collection time to ensure that spoilage can be prevented.

Since in-store drying operates at near ambient conditions, minor changes in ambient conditions can have large effects on the drying rate, and thus careful research is required to ensure that adequate good quality air is available in any year for accomplishing the grain drying objective, which is basically to move the drying front through the grain mass before deterioration is significant in the top layer of the grain. This research has been conducted by the United States Department of Agriculture and by various universities. Much of the research has been conducted by means of computer simulation.

As a result of this research, areas of the United States have been zoned according to the aeration conditions required for full bin drying (Chung et al. 1986). Schedules for different locations are specified, so that the grain is quickly cooled after harvest and to make sure that the grain receives sufficient aeration for drying. Various methods of operating the drying bins have been developed (see introduction). Systems for preventing overdrying and top to bottom moisture gradients, loading and unloading, and rewetting of the inlet layers have been developed.

System types

The appeal of in-bin drying is that it saves on equipment costs, by allowing the same bin used for storage to double as a dryer. In all cases air is passed slowly through the bin of grain, picking up moisture as it does so. Careful design is required to ensure that all of the grain in the bin is adequately dried.

The main types of in-bin drying are (Brooker et al. 1992):

- full bin: bin is filled with grain, and dried, cooled, aerated and stored in the same bin
- full bin with stirring, allowing more uniform grain treatment
- layer filled bin, in which grain is dried in successive layers, new grain being added as the previous layer is dried
- on-floor batch in-bin, used for drying a batch of grain and occasionally for cooling as well, in a method similar to the flat-bed dryer used in Asia
- recirculating, in which grain at the bottom of the bin is picked up by auger, swept to the centre and then augured to the top of the bin, where it is respread, allowing the grain to be recirculated for more uniform treatment and reduced airflow resistance
- dryeration, a specific technique in which grain is dried at high temperature in a bin, to within 2–3% m.c. (w.b.) of the actual final moisture required, then transferred hot into a tempering bin. After the drying stresses have been allowed to equalise, the grain is then cooled using ambient air, the stored heat removing the final 2–3% moisture. This gives a high quality grain with low susceptibility to breakage.

Various other more sophisticated forms also exist. For Southeast Asian conditions we are concerned to find the simplest, most robust drying system for the severe climatic conditions, and so the main concern of this paper is in-store drying, which is typically full-bin drying at low temperature.

Stir augers

Stir augers are devices for vertical mixing of the grain. The augers rotate slowly around the bin, taking 1 to 2 days to complete a circuit (Intong 1995). Two major problems with in-bin dryers are solved by the use of stir augers: moisture gradients caused during drying, and compaction of lower layers by the upper, resulting in decreased airflow.

Stir augers are not often recommended for Southeast Asia due to the high initial cost, wear on the augers from paddy, and lack of supplier support, even though simulation studies indicated a clear benefit (Intong 1995). Other problems are increased mechanical damage to the grain, and reduced air thermal efficiency.

Recirculation of air

Studies on air recirculation were conducted using computer simulation at the University of New South Wales. The results showed that recirculation at about 90% was of marginal benefit for the last period of full-bin drying (after the drying front has reached the top of the bed so that the exit air relative humidity starts to decrease). This is because air comes to equilibrium with the wettest grain in an in-store drying system, and so the system naturally has a high thermal efficiency – there is no need to recirculate the air. In general, air recirculation never justifies its installation costs for in-store dryers.

Dehumidification

Air recirculation becomes more effective if dehumidification is used. Moisture from the bin exit air is extracted by cooling the air, and then re-enters the grain to do additional drying. Again this system has not been applied to any great extent to tropical countries because it depends on cooling equipment and has a high investment cost. An alternative to desiccation of the air by cooling is using a desiccant bed. Due to their cost these have only been applied to high value food products and pharmaceuticals.

Recirculation of grain

Recirculation of the grain on the other hand has proven to be a more successful option, for example:

- partial drying in one bin followed by auguring to a second bin; and
- auguring grain from the bottom of the bin to the top.

This allows tempering, mixing and repacking of the grain to reduce pressure drops. This technique has been applied in Thailand for aerating grain.

In-bin drying in Southeast Asia

Mechanical dryers were promoted in the late 1970s throughout the region, but were generally poorly chosen and unsuitable for humid tropical conditions. Many were rejected by the end users. The first appropriate technology was developed by Dr Dante de Padua, and this was the flat-bed dryer, still extensively used 30 years later. The wet season harvest was increasing the drying load, and many international research agencies were contacted to look for possible solutions. The Australian Centre for International Agricultural Research, through its Postharvest Research Program led by Dr Bruce Champ, suggested studying the application of in-store drying to tropical countries.

The research method adopted was as follows:

- set up research teams in each country;
- study paddy and other grains to determine key thermophysical properties, such as isotherms, thin-layer drying rate, specific heat etc.;
- construct a deep bed drying model (Dung et al. 1981);
- obtain detailed information on harvest practice, times, and weather conditions;
- feed these through the simulation to determine suitable drying conditions;
- test recommendations at three levels in all countries, pilot plant (1–5 t), commercial trials (up to 500 t) and full scale implementation.

This has now been done in the Philippines, Thailand, Malaysia, and Vietnam. Crops studied under the research program include peanuts, soybeans, maize, mung beans and, of course, paddy. A typical recommendation for an in-store drying system would depend on location, grain type, harvest moisture, loading and unloading equipment, and existing storage structures, but a typical recommendation for a humid tropical climate would be a grain height of 4 m, maximum receival moisture of 18% (w.b.), supplementary heating of a few degrees, and an air speed of more than 6 m/min.

Reports on the field trials are available as follows:

- in-store drying commercial trial in Malaysia (Srzednicki and Driscoll 1992);
- field trials in Thailand (Soponronnarit et al. 1994);

Current research topics are:

- improved loading and unloading techniques;
- first-stage drying;
- computer control systems;
- development of small scale in-store dryers;
- quality measurement.

Real bin effects

Computer modelling of drying systems has been of immense benefit in predicting their performance. Three forms of models have competed for dominance:

- The near-equilibrium model, in which thermal equilibrium between the air and the grain is assumed to exist at all points in the bed at all times. Examples are Thompson et al. (1986), Soponronnarit and Chinsakolthanakorn (1990), Driscoll (1986b), and Jindal and Siebenmorgen (1994).
- The non-equilibrium model, in which heat transfer and mass transfer are modelled at all points in the grain mass. As with near-equilibrium models, the drying problem is treated as one-dimensional. Examples are Dung et al. (1981) and Bakker-Arkema et al. (1974).
- The three-dimensional model, in which differential transport equations are used to model moisture and heat movement. An example is Thorpe (1994).

Each approach has advantages and disadvantages, but except for ideal situations, none could claim an accuracy of greater than 10%. The advantages of the near-equilibrium approach are:

- computation is fast;
- real-bed effects can be easily included—a wide range of these effects has now been modelled, and so can be included in the drying system;
- graphical presentation of results can be integrated with the drying program.

The real-bed effects have turned out to be important factors. Some of the effects now included are heat losses through side walls, respiration, pressure energy regain, and quality models. Factors still needing inclusion are grain settling, better thin layer drying models and stress relaxation models.

The near equilibrium model of the University of New South Wales (UNSW) team (Driscoll 1986b) also includes:

- economic analyses for Southeast Asian countries,

- recirculation,
- grain freezing and sublimation drying,
- dehumidification and heat pump operation,
- effect of fines on pressure,
- bin design tools,
- thermophysical data presentation,
- aeration module for developing drying strategies quickly for specific weather conditions,
- four quality models,
- user-friendly (mouse and button) interface,
- a wide range of products,
- weather module for analysis of weather data.

Inclusion of these factors has become necessary to make the simulations robust design, optimisation, and strategy-development tools.

Application

Application to Southeast Asia

The previous section shows that there are many potential in-bin drying solutions. The system which has been most widely researched in Southeast Asia is in-store drying, in which grain is dried in bins (either full or using layer filling) and then stored in the bins under aeration until required for milling. The equipment required is:

- a storage bin able to sustain a small air pressure (i.e. mesh or hessian walls are not suitable, but brick, concrete and timber are)—note, however, that in Thailand bags of grain with a tarpaulin lining have been successfully used!
- a fan and air ducting of suitable size,
- underfloor or ducted above floor aeration (underfloor, the preferred option for handling, may be too expensive for existing sheds, or too difficult to install, especially in the old timber sheds),
- a loading and unloading system,
- a burner if simulation determines that supplementary heating is required,
- a trained operator,
- a weather station capable of determining ambient temperature and relative humidity (for example, an operator with a wet and dry bulb thermometer),
- temperature sensors placed at known heights (1 m separation) in the grain mass are of great benefit in determining the performance of the system,
- a programmable controller is of benefit in improving the control and reliability of the system.

The minimum quantity of grain for returning an economic benefit under Southeast Asian conditions appears to be about 100 t per load. If grain (paddy and maize) is harvested above 18% m.c. (w.b.) in humid climates, a system for reducing the grain moisture to below 19% is required; for example, first-stage dryers (hence this system is often called two-stage drying). The drying time is about 10–15 days for the operating conditions recommended for tropical climates.

Examples of applications

The earliest attempts were mismanaged trials using USA Butler bins. Caking and yellowing considerably damaged the reputation of in-bin drying for Southeast Asian conditions. The fan sizes chosen for these bins were an order of magnitude too small for the tropics. Some rough trials on shallow beds were also made by the Northern Philippines Grain Complex.

Kongskilde bins use a form of in-bin drying (a radial orientation), and have proven very successful due to careful training of operators. Although a *safe* solution, we do not believe that this design exploits the full potential benefits of in-store drying.

In Thailand adoption at Kittisak Wattana mill was on the basis of improved grain quality if aeration of existing bulk bins was implemented. The success of this implementation lead to the installation by the owner of new storage bulk bins designed on in-store drying principles, allowing the owner to purchase paddy at a higher moisture content. Three other mills have tested the system but had major handling problems, suggesting correct design and management are crucial to the success of in-store drying. Several other complexes are testing in-store drying, including Chachoengsao, Tron, and a range of small-scale mills. Seminars by Soponronnarit and collaborators have stimulated interest amongst millers in this technology. The Department of Agriculture will evaluate two-stage and in-store drying with a view to wider adoption by the Thai milling industry.

In the Philippines, NAPHIRE has developed an in-store dryer of 66 t capacity, currently being used by Dayap Multipurpose Development Cooperative, located near Los Baños (Calauan, Laguna) (Tumambing et al, 1995). This is designed to run in conjunction with the NAPHIRE fast dryer, and has a pneumatic loading system. It has operated for only one season, but this was successful with paddy dried to an average of 13.5% in 43.5 hours at P40/tonne. At the same site and time sun drying cost P100/t (mainly in labour cost). The in-store-dried rice was of good quality. A second trial in the dry season gave similar results. No yellowing occurred. Personnel training was an important component of this field trial. In-store technology was used for several years by the NFA and was tested by the Northern Philippines Grain Complex. NAPHIRE now plans to build additional units in 1995–96.

In-store aeration using computer control has been implemented at the BERNAS mill in Kangkong, Malaysia.

Adoption has been more rapid in Vietnam, moving from testing to implementation in one year. Before

1990, many dryers were tested, with adoption of the University of Agriculture and Forestry (UAF) flat-bed dryer (Hien and Hung 1995). Increasing concern for grain quality led to rapid adoption of dryers in the Mekong delta region. An 80 t in-store dryer was built and successfully installed at Song-Hau Farm as part of ACIAR Project 9008. Two-stage drying is currently being tested, with several first-stage dryers currently being evaluated.

China has on its own initiative tested aeration drying similar in concept to Kongskilde drying (cylindrical bins with central aeration duct).

Attempts have been made to in-store dry in one stage in Southeast Asia. Our own computer studies at the University of New South Wales indicate that this is not a suitable or sensible option for humid tropical climates for moistures above 19%, as the air speed required to prevent deterioration of the upper layers is too high for economic operation. Thus, two-stage drying is the preferred option.

Conclusions

In-store drying is a slow drying technique which saves on capital costs by combining the role of dryer and storage bin. Research on its implementation in Southeast Asia has shown that it has an important role to play in the complete drying picture on the basis of producing high quality grain at low cost. Successful adoption is dependent on good design, good management practices, and a large scale of operation for second stage drying. Design of the dryer is strongly affected by local weather conditions.

References

Bakker-Arkema, F.W., Lebrew, L.E., Deboer, S.F. and Roth, M.G. 1974. Grain Dryer Simulation. Research Report 224, Farm Science Technical Information. Michigan State University, Agricultural Experiment Station East Lansing, 23p.

Bramall, L.D. 1986. Paddy drying in Australia. In: Champ, B.R. and Highley, E., ed., Preserving grain quality by aeration and in-store drying. Proceedings of an international seminar held at Kuala Lumpur, Malaysia, 9–11 October 1985. ACIAR Proceedings, No. 15, 219–223.

Brooker, D.B., Bakker-Arkema, F.W., and Hall, C.W. 1992. Drying and storage of grains and oilseeds. New York, Van Nostrand Reinhold.

Chung, D.S., Kanuyoso, B., Erickson, L., and Lee, C.H. 1986. Grain aeration and in-store drying in the USA. In: Champ, B.R. and Highley, E., ed., Preserving grain quality by aeration and in-store drying. Proceedings of an international seminar held at Kuala Lumpur, Malaysia, 9–11 October 1985. ACIAR Proceedings, No. 15, 53–66.

Driscoll, R.H. 1986a. Grain drying strategies for the humid tropics. In: Champ, B.R., Highley, E. and Remenyi, J.V., ed., Technological change in postharvest handling and transportation of grains in the humid tropics. Canberra, Australian Centre for International Agricultural Research, Proceedings No. 19, 26–34.

Driscoll, R.H. 1986. The application of psychrometrics to grain aeration. In: Champ, B.R. and Highley, E. ed. Preserving grain quality by aeration and in-store drying: proceedings of an international seminar held at Kuala Lumpur, Malaysia, 9–11 October 1985. ACIAR Proceedings No. 15, 67–80.

Dung, N.V., Bowrey, R.G., and Fowler, R.T. 1981. An equation for the rate of drying of paddy rice. Food Technology in Australia, 31(1), 20–21.

Dung, N.V., Bowrey, R.G., and Fowler, R.T. 1981. Simulation of drying in ventilated paddy rice stores. Food Technology in Australia. 33, 173–175.

Hien, P.H. and Hung, N.L. 1995. Drying research and application in the Mekong delta of Vietnam. Paper presented at the 17th ASEAN Technical Seminar on Grain Postharvest Technology, 25–27 July 1995, Lumut, Malaysia.

Intong, C. 1995. Paddy rice in-store drying with air recirculation. PhD Thesis, The University of New South Wales, Sydney, Australia.

Jindal, V.K. and Siebenmorgen, T.J. 1994. Simulation of low temperature rough rice drying and rewetting in shallow beds. Transactions of the American Society of Agricultural Engineers, 37, 863–871.

Soponronnarit, S. and Chinsakolthanakorn, S. 1990. Effect of heat and water from respiration on drying rate and energy consumption. ASEAN Journal on Science and Technology for Development, 7, 4, 65–83.

Soponronnarit, S., Wongvirojtana, P., Nathakaranakule, A., and Chinsakolthanakorn S. 1994. Maintaining paddy quality by appropriate ventilation under tropical climates. In: Rudolph, V. and Keey, R.B., ed., Drying 94, 825–832.

Srzednicki, G.S. and Driscoll, R.H. 1992. Results of a field trial on in-store drying in Malaysia. In: Naewbanij, J.O., ed., Proceedings of the 13th ASEAN Technical Seminar on Grain Postharvest Technology, 4–7 September 1990, Brunei. Bangkok, ASEAN Grains Post-Harvest Programme, 197–212.

Thompson, T.L., Peart, R.M., and Foster, G.H. 1968. Mathematical simulation of corn drying - a new model. Transactions of the American Society of Agricultural Engineers, 11, 582–586.

Thorpe, G.R. 1994. Modelling heat and mass transfer phenomena in bulk stored grains. In: Highley, E., Wright, E.J., Banks, H.J., and Champ, B.R. ed., Stored Product Protection. Proceedings of the 6th International Working Conference on Stored-product Protection, Canberra, Australia 17–23 April 1994, 359–367.

Tumambing, J.A., Manelito, C.B., Miranda, L.N., and Daquila, R.E. 1995. Commercial application of in-store drying in a farmer cooperative in the Philippines. Paper presented at the 17th ASEAN Technical Seminar on Grain Postharvest Technology, 25–27 July 1995, Lumut, Malaysia.

Renewable Energy Sources for Grain Drying

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Abstract

This paper examines existing and potential systems which enable the use of renewable energy sources for grain drying. The scale and distribution of process drying operations in Asia is reviewed and the various mechanisms for obtaining heat and power from renewable resources are identified. The need to focus on smaller-scale systems is highlighted. An alternative system to traditional sun drying, which has been implemented in Indonesia, is described. This involves use of auxiliary solar heating to provide technical and financial benefits in performance of commercial, induced-draught mechanical-dryers. Available biomass resources are considered together with the implication for supply and pre-treatment. Some specific types of biomass burners are described including various options for rice husk combustion. The significance of combustion control on rice husk ash quality for effective by-product use is examined through work that has been carried out with co-workers in Sri Lanka. Combined heat and power (CHP) options are reviewed including recent work on a technology under development by the Natural Resources Institute. This will use low cost vehicle turbocharger components as elements of an indirect biomass-fired heat exchanger/air turbine cycle for power systems at around 100 Kw_e output and with scope for small-scale CHP applications.

THERE are various technical options for application of renewable energy to grain drying. The extent to which they have been or may be adopted is ultimately dependent upon economic factors, but a number of important issues can be identified. Use of renewable energy will generally reduce running costs compared with fossil fuel usage. It may also give a degree of operational independence, e.g. from price variations or from supply restrictions. Environmental benefits can be associated with the use of renewable energy at local and/or global levels but these may not be easily measured in cash terms. This paper will aim to present options that may be considered for specific applications rather than make overall recommendations. These options can be grouped into basic routes for either heat or power. Also, as some opportunities exist where technical options for combined heat and power need to be considered, these are examined.

Heat—sun drying, solar assisted mechanical, biomass fuelled

Grain drying is in fact already largely achieved through renewable energy by direct sun drying. This is a topic on which there has been substantial study and it was covered in detail at an FAO conference in 1993 (Bakker-Arkema and Suhargo 1993). A step beyond this basic technology is solar drying and the technology associated with this and the variety of systems appropriate to postharvest processing has been dealt with elsewhere in a way that fully covers the particular aspects relating to grain drying (Brenndorfer et al. 1985). A particular system of solar assisted mechanical drying for rice will be described in this paper by way of an example.

The other important renewable route to provision of heat is the combustion of biomass fuels. These need to be considered in terms of basic fuel characteristics and pre-treatment. Technology exists for major renewable biomass fuels such as wood and straw; also, there are routes for combustion of particulate forms of biomass that may be considered separately. The specific issues relating to the combustion of rice husks are important.

Power—renewable electricity, direct biomass-fuelled power systems

Grain drying as a process operation invariably requires power input. This may be solely human labour but, for the purpose of this paper, consideration is given to needs for shaft-power, either for direct mechanical application or for electricity production. Electricity may be generated locally or centrally, so theoretically hydro-power or wind-power come into this category. Electricity once produced by renewable

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means is available to generate shaft power and/or heat. More emphasis will be placed in this paper on routes involving thermal processing, e.g. biomass, since this creates also waste heat, thereby offering scope for combined heat and power. The various routes to heat and power are illustrated by Figure 1.

Need for focus on smaller-scale requirements

Knowledge of the size distribution of process operations such as grain drying is important when considering potential for use of renewable energy sources. For rice, the major grain crop of Asia, some information has been collated in Table 1.

From this information it is evident that by far the majority of rice processing is currently performed in small-scale operations. For this reason the emphasis in this paper is on the smallest scale of processing technology that can be envisaged. Normally this excludes the direct application of commercial systems from fully industrialised countries although there is often scope for scale-down. Also, in order to keep costs down the use of local equipment and construction must be maximised.

Solar-Assisted Mechanical Drying

A prototype paddy drying system utilising both solar energy and waste heat from an engine with a throughput of 10 t/day of paddy was designed, constructed, and evaluated at a rice mill in West Java, Indonesia. The dryer is inherently similar to a conventionally heated flat-bed dryer, except that the air for drying is partially heated by a solar collector. There are three separate components to the dryer, all of which are located within an open-sided building, as shown in Figure 2. The components are:

(a) a bare plate solar collector integral with the roof of the building;
(b) a combined engine and fan unit collectively termed a moisture extraction unit (MEU); and
(c) two drying bins positioned adjacent to each other with a common manifold duct.

Solar collector

The cost of a solar collector can be minimised if it can be incorporated within the roof of a building. There are many versions of roof-type collectors; the basic distinguishing feature between them being the configuration of the flow path of the air through the collector. The bare plate collector is the simplest version of the roof-type collector. The air flows from one end to the other of a rectangular duct, the upper side of which is the blackened metal roof sheeting (absorber), and the lower side a thin wooden ceiling fixed to the roof timbers. The performance of bare plate collectors with corrugated iron sheeting as the absorber has been investigated (Trim and Fish 1996). The orientation of the building and the slope of the roof are the major factors determining the heat output from the collector. So that the collector surface is exposed to insolation throughout the day, the dryer building should be constructed with its longitudinal axis running from east to west. It is generally the case that the roof slope should be such as to maximise the angle of incidence of insolation upon the roof and hence the heat output from the collector during the peak harvesting period.

Table 1. Size distribution for rice processing in some Asian countries.

Indonesia[a]	About 2 million registered 'large' rice mills with average production of about 1000 t/year; unknown number of smaller mills.				
Malaysia[a]	Nos vs capacity, tonnes paddy/hour				
	< 1	1–2	2–3	> 3	Total
	99	107	66	107	379
Philippines[a]	Nos vs capacity, tonnes paddy/hour				
	< 2	2–3	3–5	5–10	> 10
	n.a.	108	35	22	19
Thailand[a]	Nos vs capacity, tonnes paddy/hour				
	< 1	1–4	4–6	6–10	> 10
	20,000	1,500	102	42	17
Sri Lanka[b]	Nos vs capacity, tonnes paddy/hour				
	> 0.5	0.5–2	≥ 2	Total	
	5,600	1,600	n.a.	> 7,000	
	Paddy produced (1993) — 2680 × 10^3 (total rated capacity — 2640 × 10^3 t/hour)				

[a] Girard 1993
[b] Palipane, personal communication, 1995

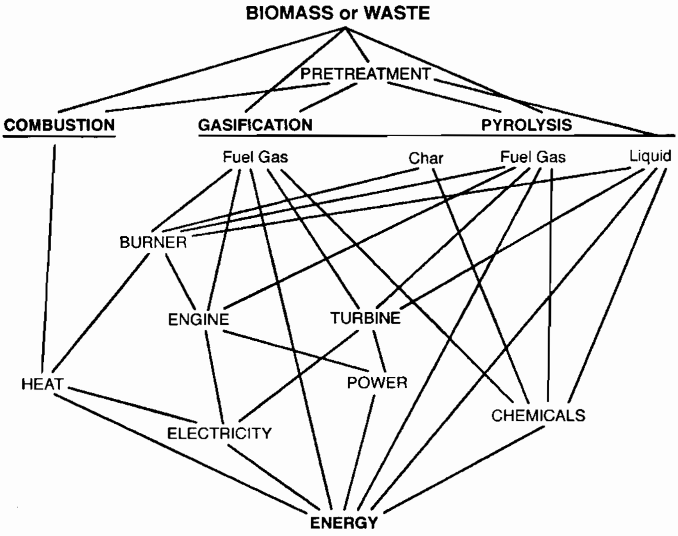

Figure 1. Routes for conversion of biomass or waste to energy.

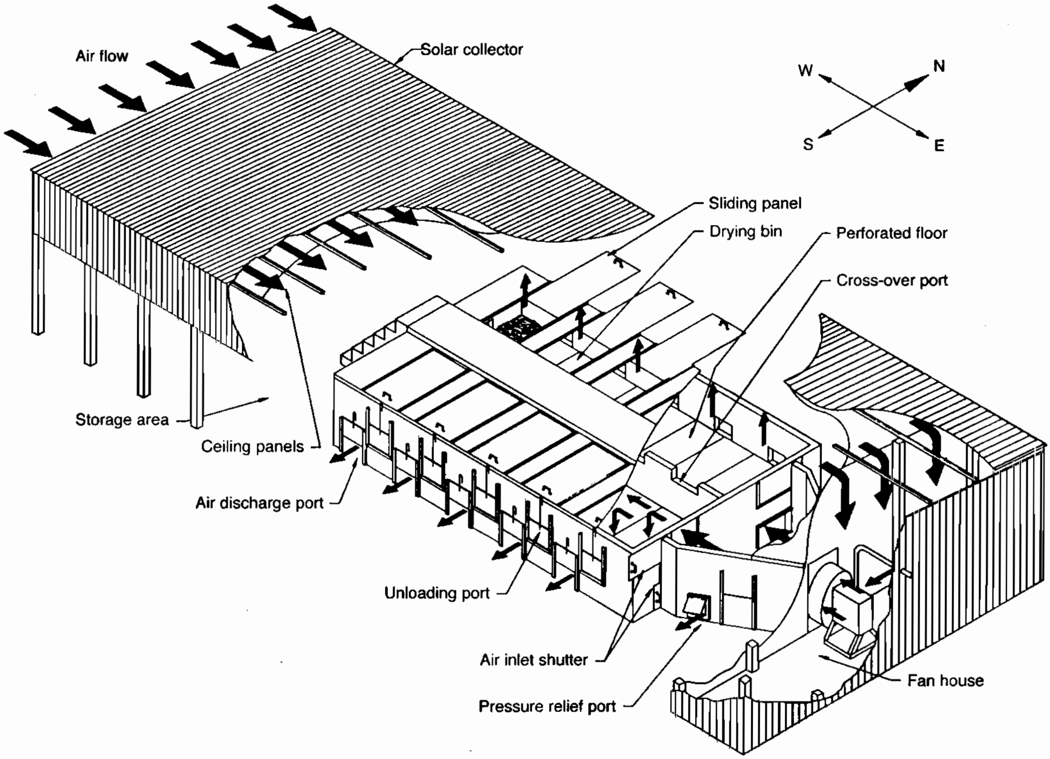

Figure 2. Schematic of paddy dryer. For illustration, air is shown passing up through the right-hand bins and (separately) down through the left-hand bins.

Moisture extraction unit (MEU)

The MEU consists of an axial-flow fan directly driven by a diesel engine, as used with conventional flat-bed dryers. Before passing through the fan the air flows over and around the engine block thereby absorbing the waste heat produced by the engine. The MEU is positioned centrally within the fan house at one end of the building. It is connected via a canvas coupling and flange to the manifold duct. The exhaust gases from the engine are piped outside the fan house to avoid contamination of the paddy with combustion by-products.

Drying bins

The two bins, positioned next to each other with a common side wall, are each internally 10 m long, 3 m wide, and constructed of rendered brick. The drying chamber within each bin is 1.25 m deep with a floor of perforated metal sheeting. Each bin is fitted with five moveable plywood covers through which paddy is loaded, and six unloading ports in the outer side and end wall of the bin.

The flow of air into a bin is through ports, either into the plenum chamber (for the up-flow of air through the bed of paddy), or into the top of the drying chamber (for down-flow of air). Air is exhausted from the bin through the loading ports or through outlet ports along the bottom of the side wall of the bin. The common side wall between the bins contains cross-over ports to permit the flow of air from one bin to the other.

Operating principles

Air is drawn through the solar collector and into the fan house by the MEU and thence into one or both of the drying bins. There are three different modes of operation:

(i) air is blown through the lower inlet ports into the plenum chamber of one (or both) bin and flows up through the paddy, exhausting through the loading ports;

(ii) with the loading ports closed, air is blown through the upper inlet ports into the top of the bins before passing down through the paddy and exhausting through the outlet ports;

(iii) air is blown into the plenum chamber of one bin, up through the paddy, then—as the loading ports are closed—through the crossover ports into the second bin, before passing down through the paddy and exhausting through the outlet ports of the second bin.

Changing from one mode to another is carried out simply by opening and shutting the requisite ports and covers. Three labourers are required for this changeover operation.

Conclusions

It was found that, in addition to the dryer providing increased drying capacity compared with sun drying, the solar-dried paddy provided both an increase in milling yield and rice of improved quality for which premium prices were paid. Fuel consumption of the dryer was 29% less than that of a conventional flat-bed dryer. Financial analysis showed that the improvements in milling yield and rice quality more than compensated for the high fixed and variable costs of the dryer, with a payback period of three years.

Biomass

General considerations

Fuel characteristics and pre-treatment

The physical form in which biomass fuels are supplied can vary considerably, and moisture content, particle size, and bulk density, in particular, are important basic parameters. The consequence of variation in these properties can have far-ranging effects on the energy density of the material. These effects are illustrated by the data in Table 2 where typical values are used to calculate the volume of fuel with the same energy as that contained in 1 m^3 of fuel oil, for straw and wood as available in different forms.

Straw lying in the field is normally recovered by baler and this greatly reduces its volume. An alternative process of in-field compaction to produce compressed wafers has been developed to a prototype stage and will further increase the density. Still higher density pellets are also available from various types of compaction equipment.

With wood, the range of materials that must be considered includes forestry waste, i.e. logging residues, thinnings, etc., through to timber as either unseasoned (green) or seasoned (air dried), and in solid or chipped form. Also, there are various forms of processing wastes, and such materials can be specially converted into fuel pellets using compaction equipment.

It will be seen from Table 2 that the various forms of wood and straw have energy contents from 4 to 100 times lower than fuel oil. This points to the importance of collection and supply of such fuels. These and the broader aspects of material handling are key elements in the supply of such materials as economic alternatives to fossil fuel.

Apart from the physical properties mentioned, complete fuel characterisation requires measurement of the key variables such as: calorific value; volatile matter; thermogravimetric analysis; ash content; moisture content; elemental analysis; and fusion temperature. Requirements for these measurements are appropriate sampling techniques and sufficient analyses to provide statistical means and averages.

Table 2. Energy content for straw and wood as fuel.

	Moisture (wet basis) (%)	Bulk density (t/m^3)	GCV (GJ/t)	Energy content (GJ/m^3)	Vol of fuel (1 m^3 oil) (m^3)
Straw					
Loose (unchopped)	15	0.03	13.5	0.4	102
Loose (chopped)	15	0.06	13.5	0.8	50
Large bales	15	0.15	13.5	2.0	21
Compressed wafers	15	0.30	13.5	4.0	10
Pellets	12	0.50	14.0	7.0	6
Wood					
Forest waste	50	0.3	8.4	1.7	24
Unseasoned timber (solid)	50	0.8	9.3	7.4	6
Unseasoned timber (chips)	25	0.35	15.0	5.2	8
Seasoned timber (solid)	50	0.65	9.3	6.0	7
Seasoned timber (chips)	25	0.23	15.0	3.5	12
Process waste (solid)	12	0.63	16.5	10.4	4
Process waste (chips/ etc)	12	0.12	16.5	2.0	21
Pellets	12	0.7	16.5	11.5	4
Coal	9	0.85	28	24	1.7
Oil	0	0.9	46	41	1

After collecting such data it is necessary then to substantiate the conclusions from analysis by means of proving trials in which practical aspects need to be assessed. Such considerations are smoke levels, ease of handling, boiler fouling, ash clinker, particulate emissions, silo blockage, and fuel delivery preparation.

Straw and wood burners

Development work in the U.K. to realise the potential use of both straw and wood as commercial fuel has been similar in that in both cases there has been initially a systematic attempt to identify any existing coal-burning equipment which could be readily adapted to alternative fuel firing. This has initially involved proving trials on such equipment with wood or straw either as an alternative fuel or in a co-firing mode. Various systems were examined and, for both straw and wood, the same general conclusion was reached—namely that the different fuel characteristics of coal were such that while straw and wood could be burnt with varying degrees of success in coal-fired plant there was usually a marked down rating of the plant, especially when using fixed or moving grate systems. Thus, unless for some reason the existing equipment of this type was grossly oversized for its duty there was no real point in attempting 100% alternative fuel replacement.

Some success was found in trials with straw co-firing by means of suspension conveying of chopped straw into the furnace in a secondary combustion air stream. One option for 100% fuel substitution with straw was potentially more successful and involved burning in a cyclone furnace such as can be retrofitted to shell boilers

With wood, the same range of options was essentially examined but while there was a rather better performance in the various grate systems the same general conclusion about severe downrating was reached. The prospect of lean phase conveying for co-firing is not available for most forms of wood, apart from sawdust or wood shavings.

The general conclusion reached was that specialised burners are required for these materials. Extra investment can, however, often be minimised by retrofitting of cyclone combustors. Most of the straw currently used for on-farm fuel purposes is burnt in low-technology, manually stoked whole bale burners of which there is a full range of U.K. equipment available. These are typically in the range of 20 to 300 kW thermal output.

For larger ratings, such as are commonly required in industrial and commercial applications there are various arrangements that are available or under development. One development funded by the U.K. Department of Energy was a boiler unit capable of taking whole large Hesston bales for direct feed to a furnace. Other examples of commercial systems are available in Denmark. There are also possibilities for high-capacity utilisation of these materials and these include fluidised-bed combustion and suspension firing of particulate materials for co-firing with pulverised coal.

Particulate biomass combustion

Types of particulate biomass

Work was done by the Natural Resources Institute (NRI) to identify the quantities of key biomass residues that occur in particulate form in Asia since it was considered that these materials were more amenable to design of generic equipment. Information was gathered for rice husk, coconut shells, palm shells, sawdust, and peanut shells (Table 3). This showed the high amounts of rice husk, particularly in Asian countries. Also, some information on the quantities of grain residues available was derived which showed how widely this could vary depending upon the crop yield (Table 4).

Following this background study, work was focused on burner development for rice husk and sawdust combustion (Robinson 1991). The rice husk combustion system developed under this program is described below.

Burner development for rice husk

Initial design and development work was conducted at the NRI laboratories in the U.K. on a pilot unit. Results obtained from the pilot unit were promising and the project progressed to the field-testing stage. The test site chosen was a commercial rice processing mill in Sri Lanka. The mill, Richard Pieris Agricultural Enterprises Limited, situated in the rice growing region of Anuradhapura, has a milling capacity of 2 t/hour and a parboiling capacity of 4 t/hour. The rice husk combustion system was installed and connected to the mill's boiler to raise steam for associated parboiling operations. The system was scaled-up from 250 kW thermal to 750 kW thermal to meet an increased heat demand and, with a few other modifications which included an external ash collection chamber, it has worked very well for the past 4 years. Another unit was installed at the Rice Processing Research and Development Centre (RPRDC), Anuradhapura for experimental use with a fluidised-bed paddy drier. The field demonstration trials were carried out in collaboration with RPRDC.

Table 3. Estimated production of biomass residues in Asia (NRI 1991).

Country	Rice husk		Coconut shells		Palm shells		Sawdust		Peanut shells	
	'000 t	%	'000 t	%	'000 t	%	'000 t	%	'000 t	%
Afghanistan							69			
Bangladesh	4,561	4.9	13	0.2					7	
Bhutan	17									
Burma	2,813	3.0	28	0.5			84		208	4.9
China	36,189	38.9	12	0.2	89	1.7	4,566	5.3	1,257	29.0
India	15,982	17.2	735	12.5			3,026	3.5	1,135	26.5
Indonesia	7,929	8.5	1,740	29.5	359	6.9	1,581	1.8	152	3.6
Iran	394	0.4					28			
Iraq	31						718	0.8		
Kampuchea	349	0.4	7	0.1						
Korea DPR	1,271	1.4								
Korea Rep	1,557	1.7							6	
Laos	243	0.3							1	
Malaysia	384	0.4	270	4.6	2,338	44.8	1,089	1.3	720	16.8
Maldives			2							
Mongolia							81	0.1		
Nepal	486	0.5								
Pakistan	977	1.1					10		157	3.7
Philippines	1,780	1.9	1,530	26.0	9	0.2	214	0.3	181	4.2
Sri Lanka	436	0.5	263	4.5			3		118	2.8
Thailand	3,618	3.9	2,035	3.4	53	1.0	190	0.2	274	6.4
Turkey	57	0.1							498	11.6
Vietnam	3,137	3.4	91	1.5	61	0.1			194	4.5

Table 4. Crop residue production under different yield situations (NRI 1991).

	Yield	Country	Crop yield (t/ha)		Crop: residue ratio	Residue yield (t/ha)	
Rice	Low	Guinea	0.9	0.9	1.75	1.6	1.6
	Medium	LDC Average	3.0	3.4		5.3	6.0
	High	China	5.1	5.5		8.9	9.6
Wheat	Low	Tunisia	0.7	0.8	1.75	1.2	1.4
	Medium	LDC Average	2.0	2.2		3.5	3.9
	High	Egypt	3.5	5.0		6.1	8.8
Maize	Low	Zaire	0.8	0.9	2.5	2.0	2.3
	Medium	LDC Average	1.9	2.2		4.8	5.5
	High	Egypt	4.6	5.8		11.5	14.5
Sorghum	Low	Niger	0.3	0.3	2.0	0.6	0.6
	Medium	LDC Average	1.2	1.0		2.4	2.0
	High	Mexico	3.4	2.9		6.8	5.8
Millet	Low	Chad	0.4	0.6	2.0	1.8	1.2
	Medium	LDC Average	0.7	0.8		1.4	1.6
	High	China	1.7	2.6		3.4	4.4
Groundnuts	Low	Zimbabwe	0.2	0.2	2.3	0.5	0.5
	Medium	LDC Average	1.0	1.0		2.3	2.3
	High	Egypt	1.9	2.2		4.4	5.1

A diagram of the system is shown in Figure 3. The burner operates on the principle of suspending the husk in air during combustion. This helps ensure an intimate mix of air with the husk and facilitates complete and efficient combustion. The furnace is sized to provide a heat output of approximately 900 MJ/hour (equivalent to approximately 250 kW thermal) with a husk consumption of 60 kg/hour at 10% moisture content. The burner is suitable for both unbroken husk from a rubber huller or broken husk mixed with bran from a steel sheller. Ash can be collected in the furnace chamber or in an external ash collection chamber, depending on user requirements.

The temperature of the combusted gases can be maintained at around 1200°C, which allows effective heat transfer in any connected boiler or other system, such as heat exchanger for indirect air heating in a mechanical dryer. The furnace has a thermal efficiency of approximately 95%. Overall system efficiency largely depends on husk moisture content and heat exchanger efficiency—typical values are 60 to 70%. Flue gases vented to atmosphere contain no smoke and reduced ash emissions.

The components of the system comprise:

Vibratory feed hopper. A 0.3 m^3 capacity vibrating hopper of basic design (see Fig. 3) is fitted with a small out-of-balance motor to produce a steady vibrating action. At the bottom of the hopper an adjustable gate is installed to regulate the flow of husk. The system operates satisfactorily and delivers a steady flow of husk.

Injector feeder. This device, developed by NRI (Tariq and Lipscombe 1992), is used in conjunction with the vibratory feed hopper described above. It consists of two different diameter pipes connected in series to the outlet of the fan. The flow of air through the contraction caused by the smaller diameter pipe produces a region of negative pressure in the larger diameter pipe. Connected to the larger pipe is an inlet pipe and funnel to feed the husk. Husk and air is sucked into the pipe by the negative pressure.

Paddle fan. A mild-steel centrifugal paddle fan of 380 mm paddle diameter, driven by a 0.6 kW electric motor and capable of delivering air up to 13 m^3/min at NTP is used for the development trials. The optimal excess air value for the efficient combustion of husk is approximately 80%, equivalent to a delivery of approximately 350 m^3/hour of air at a husk feed rate of 60 kg/hour.

Brick-built furnace. The furnace is built with four layers of brick to provide necessary durability and insulation. An arched roof avoids the need for lintels and other supporting structures associated with flat roof construction. The furnace chamber is partitioned to direct the travel of husk in an up-and-down path, thus increasing its residence time. A central partition divides the furnace into a primary combustion chamber and ash collection chamber. Access to each chamber is by insulated hinged doors. Husk is blown into the lower region of the primary combustion chamber and the hot gases exit the upper region of the ash collection chamber.

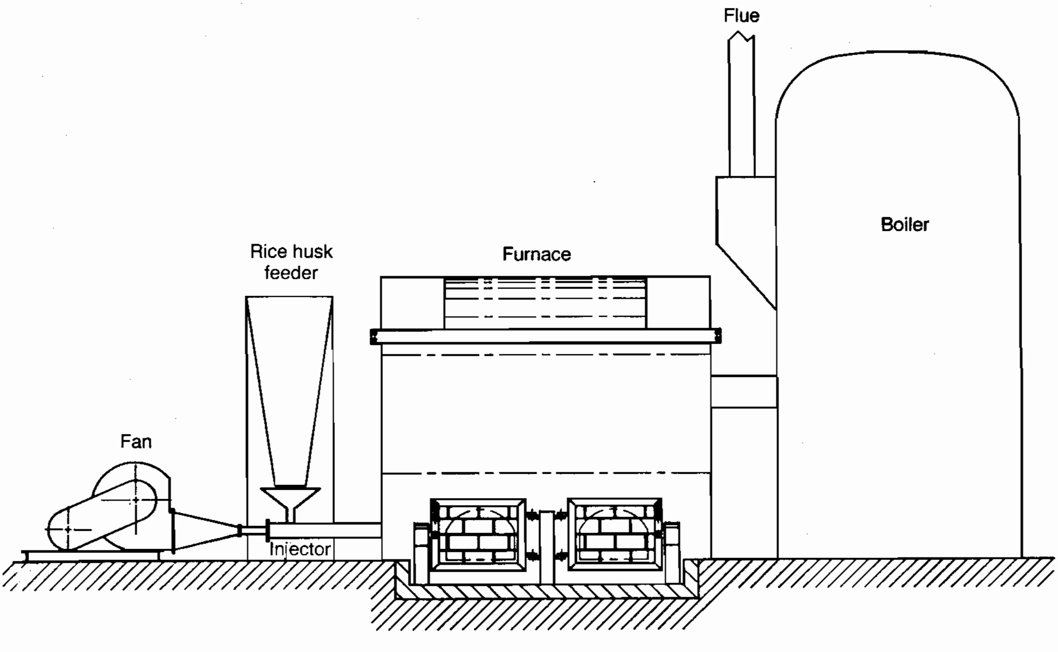

Figure 3. NRI brick-built suspension burner.

Heat exchanger system. The system should have a thermal rating to at least match the furnace gross thermal output of 900 MJ/hour (equivalent to 250 kW thermal) and be capable of withstanding hot combustion gases at a temperature of up to 1200°C. The corresponding mass flow of combustion gases at the typical operating conditions described above is approximately 500 kg/hour. While the ash collection chamber will trap the majority of the ash, a small but significant quantity will be entrained in the combustion gases. It should be noted therefore that some ash deposition, fouling, and wear of heat exchanger surfaces are likely to occur, the extent of which will largely depend on the type and design of the heat exchanger. This needs to be considered in the maintenance schedules for the various applications of the system.

Where rice-processing mills adopt this system, various heat and/or power applications are possible either with steam, hot water, air, or a thermal fluid as the heat transfer medium. In addition, the furnace system could be used in conjunction with an existing solid-fired system to supplement energy needs. For example, the husk burner could be connected to a furnace operating on fuelwood. In this case, fuelwood consumption could be reduced at a rate proportional to the amount of husk burnt. On a typical 8 hour/day husk burner operation, 280 days a year, some 110 t of air-dry fuelwood could be saved annually.

Work has been carried out by NRI and RPRDC on this furnace to define the limits of operations for feed rates and excess air levels on this equipment. An experimental design was established and a matrix of tests completed for three rice-husk feed rates of 50, 85 and 120 kg/hour, and for four sets of excess air values from 20% to 200% inclusive. Systematic ash quality evaluation from these trials was investigated based upon X-ray diffraction techniques. This has shown the control conditions necessary for optimal rice husk ash (RHA) characteristics (K.B. Palipane, unpublished data, 1993).

Rice husk combustion

Use as a by-product

Disposal of rice husk is a problem sometimes addressed by indiscriminate dumping and burning. However, rice husk is increasingly being burnt with recovery of heat and/or power. Combustion results in a high yield of RHA which contains around 95% silica. This silica is potentially a valuable by-product, depending on its quality specification and, in particular, the extent to which it has retained its non-crystalline or amorphous characteristic. NRI has examined methods to devise equipment and operational conditions for combustion of rice husks in a manner capable of supplying energy for industrial processing and of providing a high grade rice husk ash for by-product use as a silica source.

Commercial initiatives for use as a building material component are widespread and well documented. While there is a potentially large market for such products they attract only a low market price. Other applications of RHA, many of proven commercial status, include: insulation uses, refractories, reinforcing agents and fillers, fertilizers, filter mediums, and as a silica chemicals raw material (Beagle 1978). These generally demand lower volumes but a tighter specification and thus have the potential to attract a higher market value.

Quality control of the RHA is the main problem with existing combustion systems and even with RHA use in cement, probably the least sensitive to changes in quality, serious product specification problems exist. Greater control over the combustion process allows closer specification of RHA properties.

The crystalline properties of silica in RHA are strongly affected by the temperature of formation and the duration of heating. There is also evidence that the level of impurities has a significant influence upon change of crystalline structure with temperature. This subject has been comprehensively reviewed recently (James and Subba Rao 1992).

The particular amorphous crystalline characteristic of silica in rice husk which derives from its role in plant structure can be maintained only through the combustion process if the temperature of combustion is kept low. Precise temperatures vary but above 500°C it seems some significant degradation will commence. However, it appears that even at temperatures of over 1000°C the amorphous structure will be retained provided the ash is quickly cooled. With increasing temperature the silica structure progressively changes into cristobelite, tridymite, and quartz crystalline forms.

A high degree of amorphous structure of silica is known to give it a high reactivity in terms of its use for cement. The amorphous structure is very porous and has high surface area so this also gives a high activity for chemical treatment and in absorption. In general, silica in this condition has far more potential for commercial utilisation than mineral sources of silica which are characterised by higher temperature crystalline forms.

Types of system

Techniques for thermal processing of rice husk to derive energy and/or provide RHA for subsequent use are commercially available. Some key systems are described below with an emphasis on potential small-scale processing.

Brick incinerators. The status of these devices has been detailed through reports (Smith and Tait 1989; Cook 1985). Development of these low-cost incineration systems has been limited to the use of RHA in cement production. Through this work the importance of thermal processing techniques upon the physical properties of the ash has been established and although for this application there is some latitude on product quality it has been found necessary to draw-up a specification for RHA masonry cement. RHA for use in cement requires grinding in ball mills and the energy input for this operation is minimised with a high degree of amorphous silica in the ash. The time for milling may vary by a factor of seven and, being an energy intensive operation, it is a key consideration for process economics of RHA cement production.

Traditional step-grate boilers. Inclined-step grate boilers are the traditional design for rice husk burning. There are various configurations and the range has been fully described (Beagle 1978). In normal use these units burn the husk at high temperature (above, say, 700°C) under conditions which result in the formation of crystalline ash. In general, it appears that the ash from traditional step-grate furnaces does not retain an amorphous characteristic.

Fluidised-bed combustion. Fluidised-bed combustion of rice husk is a technique with intrinsic potential for producing amorphous ash since it enables low combustion temperatures. This route was applied for a large capacity application in USA in 1976 of 7.5 t rice husk/hour. Also work on 2 t/hour rice husk, fluidised bed, combustion units is reported to have been carried out in India and Australia (Cook 1985). NRI work on a fluidised-bed combustion and carbonisation test rig for particulate biomass indicates a need to evaluate 1/2–1 tonne/hour systems for application in developing countries (Hollingdale et al. 1990).

Vortex gasifiers. Renewed emphasis has been placed on biomass thermal gasification in recent years since it can provide a high conversion efficiency route to derive shaft power from the thermal energy of biomass. In some preliminary collaborative work by Biomass Energy Services and Technology (BEST) and the National Building Technology Centre (NBTC) attempts have been made to generate a consistent amorphous ash from a 30 kg/hour rice husk feed rate vortex gasifier (Hislop 1991).

Pyrolysis/steam gasification. The Indian Institute of Technology has advocated a thermal processing route for conversion of rice husk to process recovery of silica from the ash. The technique proposed is controlled pyrolysis followed by steam gasification of carbon present in char and it is said to be economically attractive at a system capacity of 6 t/day rice husk feed with output of 120 kW electrical power and 1 t/day silica (Grover 1992).

Brick suspension burner. Suspension burning with waste heat recovery offers good temperature control of combustion and commercial systems at 6 t/hour feed rates are available. The NRI low-cost brick-built suspension burner operates at 180 kg/hour rice husk feed rate and produces 33 kg/hour of ash. Ash analyses by X-ray diffraction has indicated a high amorphous content though it is recognised that more work is required to establish design and operation procedures which would ensure a consistent ash to a market specification (D. Nicholas, pers. comm., 1995).

Implications of ash quality

In order to develop an understanding of the benefits that would accrue from a burner that provided a high grade amorphous rice husk ash, cost models were examined based on experience of the NRI 180 kg/hour furnace in Sri Lanka. The results show that the production costs of rice husk ash are considerably lower if a heat production component is included into the project. Without heat production the cost of producing 1 t of ash is US$32 compared with $18 if heat production is included. This production cost of RHA in Sri Lanka is only about one eighth of the price ex-factory in Europe, without considering the value of the by-product heat. Clearly this is attractive but it is essential that the quality specifications be examined to establish a full comparison for its use. Also, there are particular aspects in relation to various products as described below.

Cement. Production cost models for lime/RHA cements have been published for India (Cook 1985). Production costs were competitive with standard cement at $60/t when the rice husk was costed at a nominal figure of $1/t. However, it was projected that if the rice husk costs increased due to its use for fuel, as has now happened in some situations, then production costs for these processes would become too high for the product to compete. In 1992 the estimated production cost of 1 t of cement using RHA in Sri Lanka was between $37 and $45, depending on the quality. This compared with bags of Indian cement being sold then at a price equivalent per tonne of $106.

Refractories. By far the most important end market for refractories is the iron and steel industry. Trade has indicated that there is a European market for 20,000 t/year of RHA for refractory bricks in the cement and steel industry. The kiln products, glass, and non-ferrous metals industries represent most of the remaining demand for refractory products and will have a smaller but nonetheless important impact. In the context of a specific developing country it has to be examined which among the above industries are prevalent in the national economy. Only a preliminary assessment of potential cost savings from use of RHA in refractory bricks has been possible. This suggests that use of local RHA in Sri Lanka as a substitute for an imported raw material could reduce production costs by 25–30%.

Sodium silicate. Sodium silicate solutions (water glass) have properties similar to those of organic colloids like gums and resins, but with the advantage of being colourless, odourless, heat resistant, and of becoming insoluble. The major uses of sodium silicate are connected with its adhesive, wetting, binding and detergent properties. It is widely used in the washing soap industry to improve the foaming capacity of soap. In addition, water glass is used to putty glass and china, to conserve foodstuffs such as eggs, to impregnate paper, and as a fire-resistant paint.

Indian workers have analysed low cost routes to sodium silicate from RHA (Andiappan 1981). These schemes relate to low outputs in the region of 1–3 t/day and the method of production described is primarily intended for sodium silicate used for soap making. It is not clear that they could meet raw material specifications for major users of sodium silicate but the route involved does benefit from the use of amorphous silica and is therefore of interest in the context of this exercise. Thus, 1 t of sodium silicate produced in India would cost $148. In November 1992, the trade list price of sodium silicate on the international market was between $456 and $978/t depending on the quality and quantity.

Other products. Sodium silicate is a raw material for production of a range of products with a variety of overlapping uses, known generically as fumed silica and precipitated silicates. Other silicon products that have been identified and which could be derived from amorphous rice husk ash are silicon carbide, silicon tetrachloride, silicone nitride, silane, semi-conductor/metallurgical grade silicon, and catalyst supports. Each involves particular production techniques which have been ascertained to varying degrees. In these, the use of a high quality amorphous silica is generally advantageous.

Prospects for product development

RHA cement does not offer a high value-added use of RHA since the price must be competitive with standard cement products. Previous studies on RHA cement have been re-examined and it is concluded that this product is only likely to be profitable with large-scale operations.

Sodium silicate and RHA refractory bricks are two products to which more attention should be applied. These would sell at higher cost than RHA cement and might be produced more cheaply than comparable products not using RHA as a raw material. Reduced production costs would arise partly from the fact that RHA is an intrinsically cheap material but also from the technical benefits stemming from the amorphous structure.

In view of the market potential for commercial products from RHA there should be further development of a furnace/combustor that provides energy in association with a high grade RHA. Parallel work on quality assessment of RHA is required. Experimental work should be focused on low cost and simple construction which makes it directly applicable to less-developed countries (LDCs).

Market evaluation for silica production derived from RHA should be extended and commercial collaborative links established with a view to encouraging joint venture operations in LDCs where a degree of added-value production can be anticipated.

Small-scale combined heat and power

Energy balance in a typical rice-processing mill

A summary of the energy requirements of a typical 2 t/hour rice processing mill with a husk-fired steam boiler is shown diagrammatically in Figure 4. It is assumed for this mill that mechanical drying is not required on receipt of paddy and that the paddy is stored in sacks—therefore there is no energy input at these stages.

Based on the following assumptions:

(a) 2- t/hour rice processing mill, generating 440 kg/hour of rice husk
(b) husk net calorific value of 13.5 MJ/kg
(c) furnace efficiency of 90%; boiler efficiency of 65%
(d) overall steam turbine or steam engine efficiency of 6%.

A Sankey diagram of a theoretical combined heat and power installation is shown in Figure 4.

The electrical power of 99 kW available approximately matches the mill's electricity requirement of 95 kW, made up of 20 kW for drying and 75 kW for milling. Should, in practice, there be an excess of electricity production, consideration could be given to earning revenue by supplying the grid, if connected, or adjacent/local industry or local community. In the event of insufficient electricity production to meet the mill's demand, grid electricity or some other form of back-up generation system would be required.

The energy from the turbine or engine exhaust steam broadly matches the energy requirement for the hot water soaking, parboiling, and drying operations—2792 MJ in the exhaust steam versus 2700 MJ required.

Gasifiers

The equipment available for the steam-based systems at this scale is limited and suffers from low efficiencies and high costs which are of the order of GBP1600/kW$_e$ (during October 1995, ca65 pounds sterling (GBP) = US\$1). In many countries, considerable effort over a long period has been put into the development of a marketable gasifier system. Despite this effort such systems have not progressed beyond prototype stages. The efficiencies of the small-scale gasifier systems can be of the order of 20%. The projected costs of gasifier based systems are in the range GBP1000–1200/kW$_e$. The gasifier systems also suffer from the drawback that they produce a noxious by-stream of liquor and tar. This con-

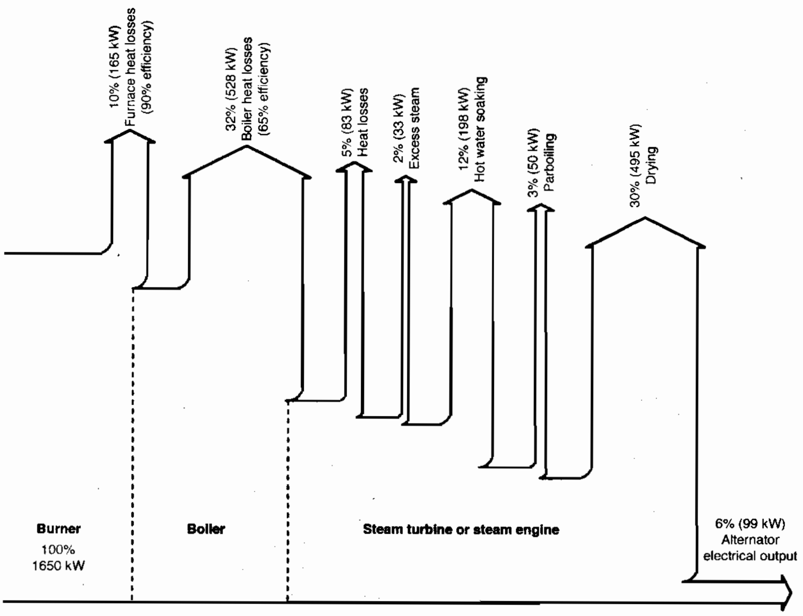

Figure 4. Energy flow in a combined heat and power system.

sists of known carcinogens and disposal costs for this material are not often included in the financial appraisal of these systems. Due to the large water content and toxic nature of the wood tars/liquor, their disposal costs are not likely to be insignificant. The waste heat in the gasifier systems is of low grade. Furthermore, the gasifier systems are not very tolerant of changes in the fuel properties. The biomass fuels are inherently of variable quality, particularly their moisture and ash content are determined by the ambient conditions, harvesting, and handling history. Therefore, a need exists for a small-scale power generation system which can provide efficiencies comparable to the gasifier systems, is cheaper, and does not suffer from the drawbacks of the gasifier systems. The work described in this paper is an attempt to address this need.

Indirect turbine

Recent work by the NRI funded through the EU's JOULE II Non-nuclear Energy program, has identified the attractiveness of energy cropping for power generation systems at around 100–300 kW for on-farm generation. Based on preliminary design studies an indirectly-fired gas turbine system was identified as a potentially attractive option at scales of around 200 kW. The commercial viability of this type of system is enhanced if operated in combined heat and power mode. In addition to on-farm systems, considerable scope for applications of a system of this size exists where biomass residues are available, as in small- to medium-sized processing industries. Such applications arise in both developed and developing countries and may include rice mills with drying and parboiling heat requirements.

Earlier studies on indirectly-fired turbine cycles have concentrated on large, high-efficiency systems which have necessitated the use of expensive materials for construction and/or sealed systems filled with gases such as helium. The systems investigated were based around turbines developed for direct firing. On the scale considered here, the approach is to focus on the economic viability and financial return of the unit—not simply to concentrate on higher efficiencies alone—since it has been shown that competitively priced electricity, from biomass, can be produced only from a system with low capital, operating, and maintenance costs; and high 'availability'. Indirect-fired gas turbine offers a potential to meet both of these criteria as it uses clean air as a working fluid and is based on rotating turbo-equipment with inherently long service intervals and greater reliability.

The indirectly fired cycle has the potential to produce electricity at efficiencies of 20% at modest turbine inlet temperatures and low turbine pressures. In the past, aero-derivative engines have been used which are optimised for a high power to weight ratio and operate at high inlet temperatures. This has resulted in a requirement for heat exchangers made from ceramic materials. This project presents a new approach tailored to the requirements of small-scale stationary power generation under 500 kW_e particularly for combined heat and power applications.

The technology will use low-cost turbine and compressor systems based on automotive turbo-charger technology. The thermodynamics of a number of variants of indirectly heated turbine cycles have been evaluated with realistic values for various component efficiencies. A cost-effective system with an overall efficiency of 20% is possible using a single heat exchanger instead of two; as normally associated with recuperative indirectly heated turbines. The size of this single heat exchanger is less than the combined size of a separate heat exchanger and recuperator. Also, a cycle operated in this mode encounters lower heat exchanger temperatures and operates at a lower pressure ratio (3–4). The combination of lower temperatures and pressures results in requirements for the materials of construction which can be met with stainless steel rather than ceramics or nickel-based alloys. The system is illustrated in Figure 5.

The following parameters were used in the calculations:

Polytropic efficiencies of compressor and turbine: 0.85
Effectiveness of heat exchanger: 0.85
Pressure losses in the heat exchanger (for both hot and cold sides): 3% of inlet pressure
Losses in gearbox and alternator: 10% of turbine net work
Temperature at inlet of turbine: 750°C
Temperature at outlet of combustor: 900°C
Combustor losses: 5% of total heat input into the combustor
Fuel:
  Moisture content 25% (wet basis)
  Ash content 1% (wet basis)
  Gross calorific value 19 900 kJ/kg (daf basis)
  Net calorific value 13 140 kJ/kg (as fired basis)

Most of the components for the proposed system are available but will require some modification and development work. The turbine, compressor, furnace, and low-temperature recuperator would be derived from existing technologies. However, there is a need for some development work on combustion systems to reduce potential fouling of the heat exchangers; on higher temperature heat exchangers and on turbomachinery, especially the turbine side. Application of high-speed generator technology which has the potential for simpler control and to eliminate gearbox losses, is also to be investigated.

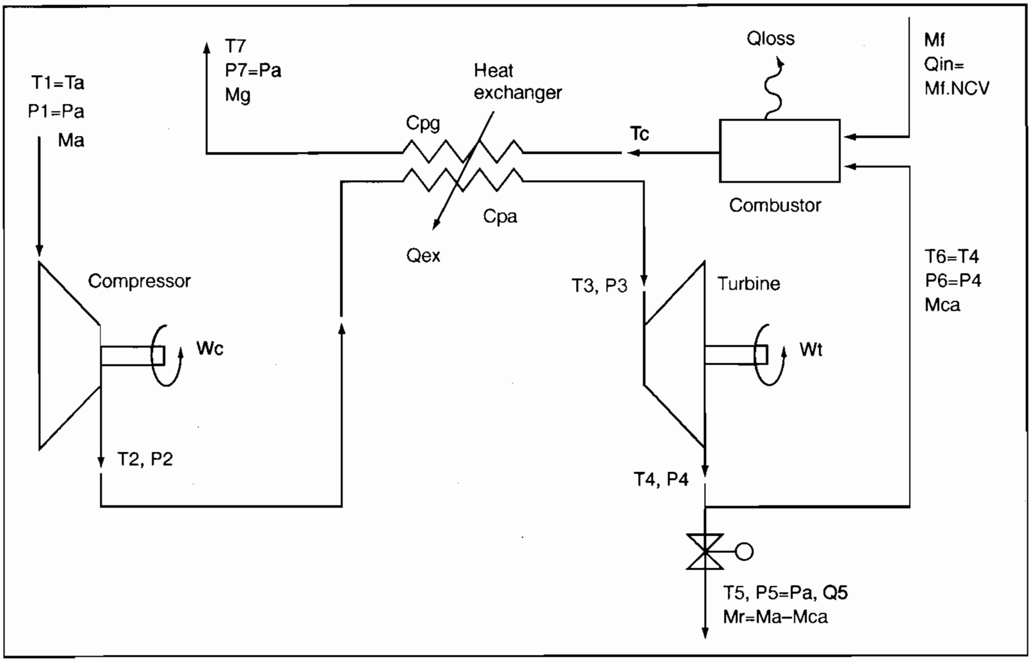

Figure 5. Indirectly fired exhaust heated cycle.

It is anticipated that a system could be developed which would cost less than GBP800/kW$_e$ when in production. Using this figure electricity from such a system could be produced at a break-even price of 5.6p/kWh (100p = 1GBP). This is based upon the following assumptions:

Size of the system 250 kW$_e$
Installed cost GBP800/kW$_e$
Cycle efficiency 20%
Use of thermal energy (450 kW at 1.8p per kW)
Heat rejection from the system at 100°C

It is planned that an optimised prototype system will be designed and costed as the next stage of this work.

Acknowledgments

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References

Andiappan, A.N. 1981. Manufacture of sodium silicate from rice husk ash. Proceedings of National Seminar on Utilization of By-Products from Rice Milling Industry, New Delhi, India, September 1981.

Bakker-Arkena, F.W. and Suhargo 1993. Sun drying of grain. Proceedings of FAO/CESA International Symposium on Grain Conservation, Canela-RS-Brazil, 19–22 October 1993.

Beagle, E.C. 1978. Rice husk conversion to energy. Rome, FAO Agricultural Bulletin No. 31.

Brenndorfer, B., Kennedy, L., Oswin-Bateman, C.D., Trim, D.S., Mrema, G.C., and Wereko-Brobby, C. 1985. Solar dryers—their role in post-harvest processing. London, Commonwealth Science Council, 337.

Cook, D. 1985. Rice husk ash cements. UNIDO Monograph.

Girard, P. 1993. Opportunity for energy generation in rice mills. EC–ASEAN COGEN Programme Report, The Asian Institute of Technology, PO Box 2754, Bangkok 10501.

Grover, P.D. 1992. Recovery of value added products and energy from biomass. Proceedings of Biomass Energy Conference, Forestry Research Institute of Malaysia.

Hislop, D. 1991. Preliminary investigation on a vortex furnace and gasifier for the continuous production of heat and amorphous rice husk ash. Biomass Energy Services and Technology and National Building Technology Centre.

Hollingdale, A.C., Tariq, A.S., and Kemp, J. 1990. Continuous carbonisation of particulate agriculture and forestry residues. Phase I Project Report, NRI Internal Report.

James, J. and Subba Rao, M. 1992. Rice husk ash cement— a review. Journal of Scientific and Industrial Research, 51, 383–393.

NRI (Natural Resources Institute) 1991. Best bets— a strategy for better utilisation of biomass for energy. NRI internal publication.

Robinson, A.P. 1991. The design and development of a suspension burner system for particulate forestry and agricultural residues. Chatham, U.K., Natural Resources Institute, Bulletin No. 41, v+24.

Smith, R.G. and Tait, G. 1989. Rice husk ash cement in Guyana. Third CIB/RILEM Symposium, Materials for Low Income Housing, Mexico, November 1989.

Tariq, A.S. and Lipscombe, R.J. 1992. Application of air injectors to biomass combustion systems. Conveyance of rice husks and other particulate biomass materials. Chatham, U.K., Natural Resources Institute Bulletin No 52.

Trim, D.S. and Fish, D.M. 1996. Investigation of the performance of corrugated bare plate solar collectors. Tropical Science, in press.

Non-conventional Grain Drying Technology

Francis Courtois*

Abstract

Drying is probably the oldest method for preparing grain for long-term storage. Many scientists are seeking to understand the underlying phenomena, the influence of drying on quality, and to optimise the design and/ or control of industrial dryers. Many technologies exist (air drying, freeze-drying, steam drying, etc.) but most of them are restricted to specific products and developed countries. Some of them are designated 'non-conventional', mainly due to their high investment cost and the level of technology required. In most cases, they are not well suited to developing countries.

Many constraints have to be considered in developing countries when designing a dryer. Thus, the global optimisation of the drying operation requires advanced knowledge. Even the precise definition of the objectives of drying can be complex. Objectives are contradictory (e.g. energy efficiency is generally opposed to drying capacity). Quality and moisture content must also be considered. The complexity of the interactions between the different objectives is difficult to resolve, but the modelling approach can help here. The automatic control approach appears to increase the global performance of existing dryers. These tools can be invaluable to engineers and operators even if they are mostly used in laboratories.

DRYING is one of the oldest methods for enhancing the 'storability' of biological products. For cereal grains, we can say that it is the oldest and only solution applied. Depending on the level of industrialisation, the drying may be natural or artificial, or a combination of the two.

It is difficult to define what is a 'non-conventional' drying technology since what is conventional in Europe may not be so in Asia and vice versa. As we will discuss, non-conventional often means 'unacceptable cost'.

Our aim here is not to review unusual technologies for drying. Of more interest from our point of view is to focus on the physical goals and constraints of grain drying and then propose some solutions.

As we will see, drying involves many different products and goals, and is applied in so many technological environments that we need to use a general approach close to the level of microscopic phenomena.

First, we may say that we are all interested in optimising grain drying. That is, we want the drying to be inexpensive (investment and running costs), multipurpose, maintain grain quality, be under automatic control, etc.

We will focus on each goal in an endeavour to understand how to optimise the drying process.

Methodology

Dryer optimisation can be studied at three levels:

- The design level, if the dryer is not yet built. We need to make a choice between a diversity of technologies, materials, dimensions, etc.
- The set-up level, if the dryer already exists. We need to find the best setpoint to optimise the objectives.
- The control level during drying. We need real-time corrections of the setpoint to avoid perturbations and reduce the overall standard deviation in the outlet moisture content.

Whatever the level of optimisation we seek, the objectives remain the same. We need to define the objectives with precision, in terms of an equation.

Defining Objectives

Grain drying generally has several objectives. Figure 1 shows the most common ones. Each problem is specific and thus has a specific objective map. As can be seen, objectives may be contradictory. For example, maximising the product flow rate generally involves the highest energy cost.

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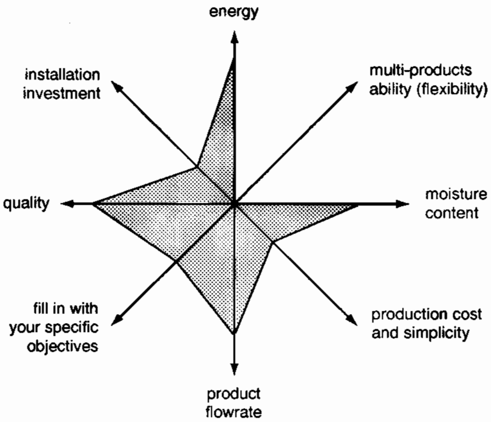

Figure 1. Drying objectives can be contradictory.

Since we are going to use some mathematics, we prefer to group all objectives in a single cost function J:

$$J = \int_{0}^{total\ time} \begin{bmatrix} a_1 (energy\ cost)^2 + \\ a_2 (invest\ cost)^2 + \\ a_3 \left(X_{\exp} - X_{obj}\right)^2 + ... \end{bmatrix} dt \qquad (1)$$

This cost function J has very general use. To fit particular objectives, we need to set the values of the a_i coefficients. Choosing these values is equivalent to finding the correct compromise between energy cost, quality, investment, etc. Note that the investment cost can be treated separately, since it is incurred before the dryer is operational.

This cost function is obviously an integral of time since none of the variables are constant. In particular the third term is subject to large variations and thus leads to consideration of automatic control as an optimisation solution.

Primary Objectives

Energy

First there are some physical limits to energy efficiency. When using air as a drying medium, the energy consumption is at least 2.3 MJ (550 kCal) per kilogram of water, the latent heat of vaporisation. Dryers in western countries generally have energy efficiencies of 700–1200 kCal per kilogram of water, and it would be quite difficult and expensive to reduce this energy requirement.

Generally, good energy efficiency is associated with higher investment costs (more complex construction) and may thus be incompatible with constraints encountered in the developing countries.

It can also run counter to the drying capacity, since the highest energy efficiency is obtained with cribs in western countries at a very low cost but a very low production capacity.

How is energy lost during drying? As we will see later, exhaust air is rarely saturated and thus still has drying capacity. Even if it is completely saturated, its temperature is generally higher than that of the ambient air. But the main loss comes from the vapour produced in the air. This contains a great deal of energy which could be retrieved if we could condense it (Fig. 2).

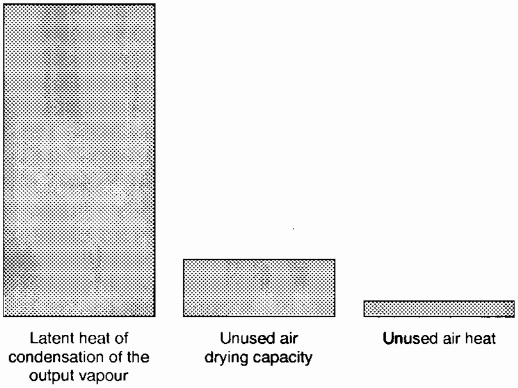

Figure 2. Comparison of the different kind of energy losses.

Some numerical values illustrate this point.

- The energy required to heat 100 kg of maize from 20 to 70°C (the highest grain temperature encountered in French dryers) is 5.6 MJ.
- The energy required to vaporise 20 kg of water (100 kg of maize dried from 35 to 15% moisture content, wet basis) is 50 MJ.

It is clear that vaporisation of water consumes about 90% of the energy for drying.

This is the basic idea that led to consideration of steam rather than air as a drying medium. Since the drying medium and the gas produced are the same, it offers some interesting possibilities:

- the steam produced, when recompressed or heated, is able to replace the condensed drying medium (closed loop)
- there is no rejection of fines (no air wastes)
- a higher drying rate is possible (mainly due to the high temperature)

However, steam drying also has a number of disadvantages:

- much higher cost (boiler, high technology dryer, etc.)

- quality degradation due to the high temperature (reverse conclusion in certain cases).

It is important to note that drying with superheated steam implies boiling of the water in the product. The dried products thus differ from those obtained by hot air drying.

We may say that, due to its high investment cost, steam drying is reserved for very high production capacities and convection-limited products (i.e. diffusion is *not* the limiting factor of the drying rate).

It is important to categorise the energy optimisation possibilities:

- conception level—choice of the drying medium (air, steam, microwaves, etc.), heating device (electrical, fuel, etc.), design of the dryer;
- tuning level—settings of the dryer (temperature, flow rates, etc.)
- control level—control algorithm (setpoints, desired performance)

The first level (conception) differs from the others in that the dryer does not exist yet at this point. The choices must be made by considering the environment constraints: what is the cheapest energy available? Do we have the technological environment to produce and use steam?

How does one tune an existing dryer for optimal running? The best answer would come from simulation tools (model based computer aided design (CAD) software; see section on modelling) and the dryer design. In the more general case, the answer comes from previous knowledge and thus can be considered to be sub-optimal.

Figure 3 shows theoretical curves comparing performance using manual and automatic control. Is has been widely verified that automatic control leads to a narrower distribution of the moisture content of the product at the output. Thus, the setpoint is approached more closely and the energy consumption is reduced.

Drying capacity

As previously discussed, both the drying capacity and the energy efficiency must be considered. For a continuous dryer, drying capacity is inverse proportional to the residence time (i.e. drying time) of the product. For a discontinuous dryer (e.g. a crib), it is proportional to the size of the dryer since the residence time is very long.

As an example, typical production capacities in France (for a maize mixed flow dryer operating to reduce moisture content from 35 to 15% wet basis) ranges from 30 to 100 t per hour.

Clearly, the production capacity should be defined at the design level, considering the requirements and the effective (decreasing) drying rate of the product. Best solutions are obtained with the help of a simulation tool (model-based CAD software).

If we consider a deep bed of grain, dried by hot air flowing from the bottom to the top, where the input air characteristics are 100°C and 1% relative humidity (r.h.), two contrasting cases can be considered for the output air characteristics (Fig. 4):

- either we want the best production capacity (lowest drying time)—airflow rate should be as high as possible to maintain the same drying capacity everywhere in the bed; or
- we want the best energy efficiency—airflow rate should as low as possible to use completely the drying capacity of the air (100% r.h. and 10°C at the output)

It is obvious that increasing the airflow rate will increase the global drying efficiency of the bed (including the production capacity) while considerably decreasing its energy efficiency. Conversely, a low airflow rate will ensure high energy efficiency and better quality while greatly reducing the production capacity (due to long drying time).

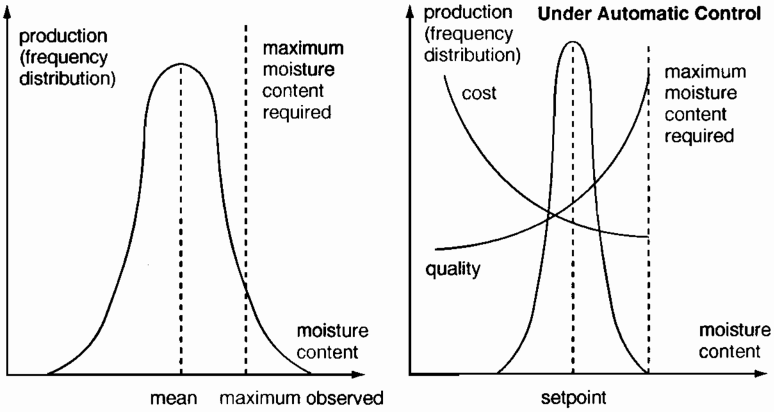

Figure 3. Automatic control reduces the moisture heterogeneity and thus better fits the requirements.

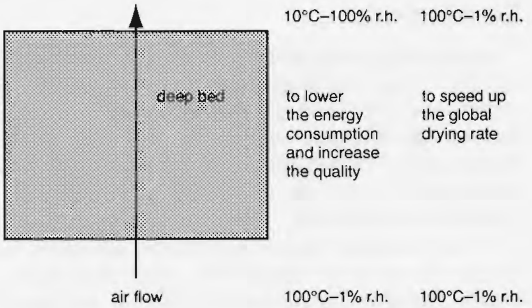

Figure 4. Energy and drying rate can be considered as opposite objectives. It is totally related to the characteristics of the output air.

Quality

During the 1970s, energy efficiency was the most important factor to consider when designing and operating dryers. Today, quality is becoming increasingly important, perhaps more important than energy when drying rice in western countries.

Rice is a good example, since broken kernels cannot be used for human food markets and thus their value is only one-tenth that of whole kernels for the same production cost.

Many authors have studied phenomena associated with the degradation of the quality of rice kernels (Kunze 1979, 1996). The wet-milling quality of maize (Courtois et al. 1991), the baking characteristics of flour, and the viability of wheat seed (Nellist 1981; Nellist and Bruce 1987) have also been studied. These last studies have developed models describing the relation between quality degradation and drying variables (grain moisture and temperature).

We have shown (Courtois 1991; Courtois et al. 1994) that the wet-milling quality of maize is mainly influenced by the thermal treatment, independently of any drying phenomena. Using water baths, after one hour at fixed temperatures, the quality was considerably reduced for temperatures above 50°C (Fig. 5).

Bonazzi et al. (1994) describe an interesting comparison between two different kinds of experimental treatment:

- one hour drying of rice; and
- one hour of thermal shock without drying (see above).

Quality was measured as head rice yield (in a processing unit). Results are presented in Figure 6.

Obviously, the quality is not affected if no drying occurs even at high temperatures. This quality criterion is a physical one, as opposed to the biochemical criterion used for the wet-milling quality of maize.

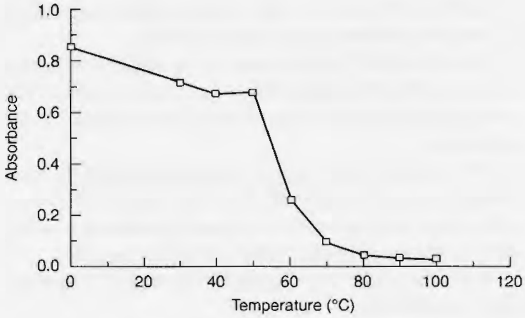

Figure 5. Wet-milling quality (absorbance units) of maize in vacuum-sealed bags after one hour in water baths at different temperatures (Courtois 1991).

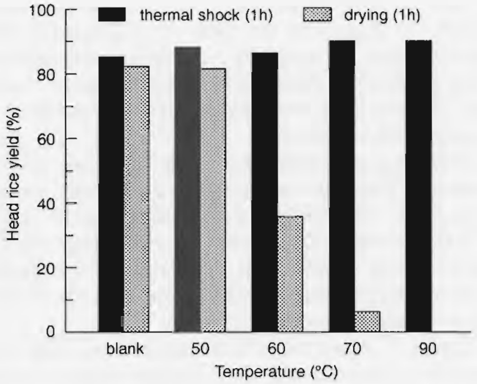

Figure 6. Comparison between drying and thermal shocks on final rice quality (Bonazzi et al. 1994).

Unfortunately, there are only a few products for which quality models are available. This is partly due to the high cost of the experimental work required for this purpose. Another important reason arises from the fact that quality is more a constraint than a real objective to maximise. Generally, the operator chooses a quality limit below which the dryer should not operate.

General-purpose dryers

A major component of the cost of a dryer is attributable to its limited use: about one month from the beginning of the harvest. As an example, in France, grain dryers work only 3–4 months a year for an approximate investment of US$400000. It is thus obvious that research on grain drying should focus more on the multi-purpose capabilities of industrial dryers. Realistically, however, we must admit that there is no industrial dryer available that could dry grains, pet foods, or flours equally well.

The Modelling Approach

It is difficult to say if there might be a universal solution to all the problems listed above. In particular, we did not consider the additional constraints specific to developing countries. From our point of view, the gain in performance will be achieved more by the use of modern tools such as models and automatic controllers, than by specific technologies. An interesting illustration of this is the superheated steam widely used for liquid concentration (evaporators) but very poorly used for the drying of solids in western countries. This is mainly because of the very high cost of these technologies. These remarks can also be applied to several other technologies, such as freeze-drying and vacuum-drying.

Models are useful for a number of reasons. First, there are many good drying models in the literature for most cereals (Toyoda 1988; Bakker-Arkema et al. 1974). Moreover, it is not expensive to adapt existing models to other products.

Second, models allow the testing of the best design of a dryer reducing the development cost and optimising the performance obtained. This is particularly useful since the drying time varies widely with the air characteristics (Fig. 7).

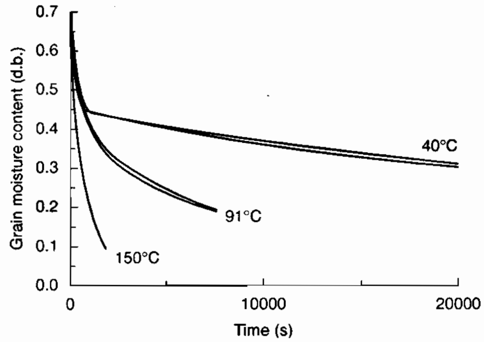

Figure 7. A model allows the prediction of the drying time at any air temperature and humidity (comparisons experiment/simulation) (Courtois 1991).

Third, combining drying and quality models enables the global optimisation of the design and settings of the dryer. It provides online assistance to the operator to determine the best settings for the desired performance (Fig. 8).

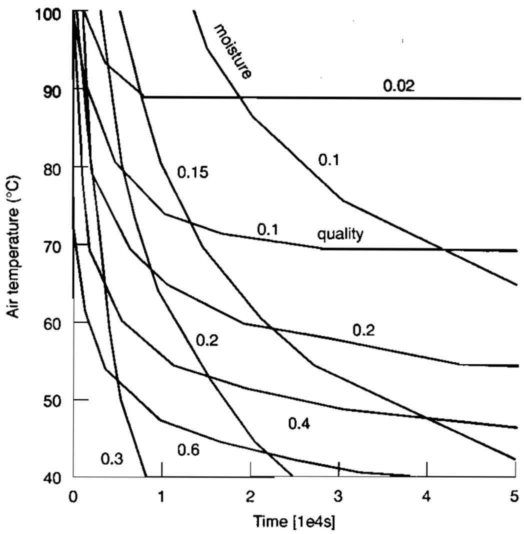

Figure 8. Normograph of thin layer drying of maize (obtained by simulations) (Trelea et al. 1995a).

For practical reasons (mainly the destructive methods used for quality measurements), the confidence intervals on quality predictions are much larger than those for drying. As shown in Figure 9, the validation of the quality model gives a poorer agreement between experiments and simulations compared with those observed for the drying model.

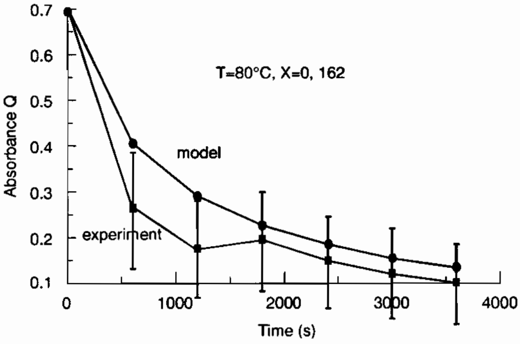

Figure 9. Comparison between experiment and simulation of maize wet-milling quality during one hour drying at 80°C (Courtois et al. 1994).

The Control Approach

It would be difficult to list all the possibilities that would flow from the availability of a good model combining drying and quality (Trystram and Courtois

1994). We will emphasise here the use of a model in a model-based predictive control algorithm used to control a fixed-bed maize dryer.

A study in progress (Trelea et al. 1995a) concerns the optimisation of batch drying. The study focuses on the fixed-bed drying of a thin layer of maize. The wet-milling quality of the maize is considered as well as its moisture content (Fig. 10).

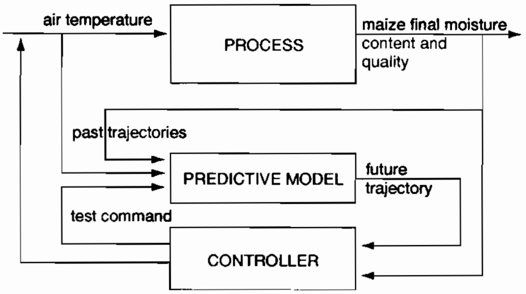

Figure 10. Bivariable non-linear model based predictive control scheme.

Two recurrent neural networks have been identified to speed up the online prediction of moisture content and wet-milling quality of maize (Trelea et al. 1995b). These models are coupled with optimisation techniques to determine the best air temperature to achieve the correct final moisture content at the desired drying time, and to ensure that the quality stays within required boundaries. Uncertainties in the state variables are taken into account.

Figure 11 plots the results of an experiment conducted to observe the efficiency of the controller during a simulated disturbance (heating resistors were decoupled for one hour). Despite this, the algorithm has succeeded: final moisture content is under the desired value and the quality is maintained above its limit.

The interest in this method lies in its generalisation ability. The lack of assumptions concerning the model, the general formulation, and the very good performance are important advantages to consider.

Conclusion

Grain drying remains open as a domain for researchers. There is a multitude of publications to support this assertion (e.g. proceedings of drying symposiums). However, these studies may diverge from developing countries' considerations and needs. They generally do not take into account either practical constraints encountered in developing countries or the multi-purpose ability required.

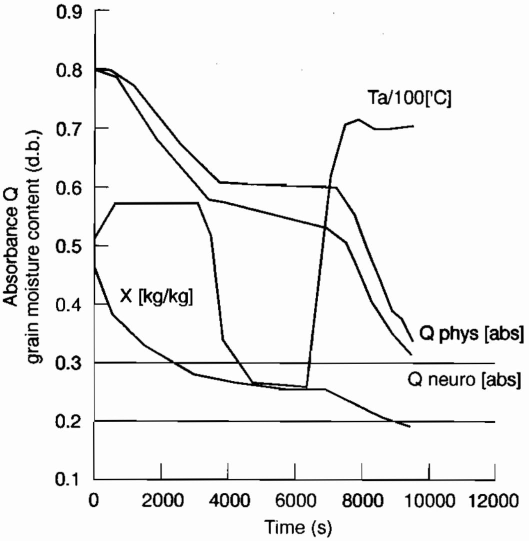

Figure 11. Simulated and experimental maize moisture content and wet-milling quality during a thin-layer batch drying with a temporary failure of the air heating device. Predicted (neural network) quality is compared to reference model simulation.

Knowledge of underlying phenomena is increasing and several models are available. Despite this, there are few CAD tools available to help people design and set up their dryer for their specific requirements. Moreover, knowledge of the linkages between drying and quality is still more practical than when they are formulated as a model.

Solutions are specific to each problem and thus it is very difficult to propose a general solution. Despite this, the modelling approach may be of great help through:

- CAD software, to design and tune;
- model in a predictive control algorithm; and
- simulators to train users at a low cost.

From a technological point of view, it is clear that the use of superheated steam (at or below atmospheric pressure) is a very promising area for many reasons to do with energy transfer, but it has high investment costs. It is thus restricted to high production capacity dryers.

Acknowledgments

The author wishes to thank FAO and M. François Mazaud for their invitation and valuable help.

References

Bakker-Arkema, F.W., Lerew, L.E., DeBoer, S.F., and Roth, M.G. 1974. Grain drying simulation. East Lansing, MI, USA, Michigan State University, Agricultural Experiment Station.

Bonazzi, C., Courtois, F., Geneste, C., Pons, B., Lahon, M.C., and Bimbenet, J.J. 1994. Experimental study on the quality of rough rice related to drying conditions. In: Rudolph, V. and Keey, R.B., ed., Drying 94, B, 1031–1036.

Courtois, F. 1991. Amélioration de la Qualité Agro-Industrielle du Mais par la Modelisation Dynamique du Séchage. Massy, France, ENSIA, France, 100p.

Courtois, F., Lebert, A., Duquenoy, A., Lasseran, J.C., and Bimbenet, J.J. 1991. Modelling of drying in order to improve processing quality of maize. Drying Technology, 9(4), 927–945.

Courtois, F., Lebert, A., Lasseran, J.C., and Bimbenet, J.J. 1994. Corn drying: modelling the quality degradation. In: Developments in Food Engineering, Part 1. Blackie Academic and Professional, 334–336.

Kunze, O.R. 1979. Fissuring of the rice grain after heated air drying. Transactions of the American Society of Agricultural Engineers, 22(5), 1197–1201, 1207.

— 1996. Effect of drying on grain quality. These proceedings.

Nellist, M.E. 1981. Predicting the viability of seeds dried with heated air. Seed Science and Technology, 9, 439–455.

Nellist, M.E. and Bruce, D.M. 1987. Drying and cereal quality, aspects of applied biology. Cereal Quality, 15, 439–455.

Toyoda, K. 1988. Study on Intermittent Drying of Rough Rice in a Recirculation Dryer. Versailles, France, 171-178.

Trelea, I.C., Courtois, F., and Trystram, G. 1995a. Modélisation de la cinétique de séchage et de la dégradation de la qualité amidonnière du maïs par réseaux de neurones. In: Automatique et maîtrise des procédés complexes. Lavoisier, 40, 135–140.

— 1995b. Non-linear optimal control of a cereal dryer. Iasi.

Trystram, C. and Courtois, F. 1994. Food processing control; reality and problem. Food Research International, 27, 173–185.

CONTRIBUTED PAPERS

Grain Drying as a Means of Reducing Harvest Losses

Yahya Abawi*

WHEAT and sorghum are major winter and summer crops grown in north-eastern Australia. Bad weather during harvest can cause considerable delays to harvesting, resulting in substantial yield and quality losses. On average some 10% of Australian wheat is downgraded to feed quality because of summer rains. Harvesting of sorghum is normally carried out in late autumn and early winter. Overnight dew, high relative humidity, and shorter day length prevent rapid drying of the grain in the field. Clearly, high moisture harvesting and drying of the grain can reduce weather-related damage and yield losses. A simulation model of grain harvesting and drying was developed to examine the economics of high moisture harvesting and drying. The results show that the optimum harvest moisture content for wheat is between 14 and 18% (wet basis) and for sorghum is around 18% (wet basis). This paper outlines some strategies for minimising grain losses caused by adverse weather during harvest.

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Minimum Daily Temperature as a Predictor of Dewpoint Temperature

Yahya Abawi*

PSYCHROMETRIC data, such as relative humidity, dewpoint temperature, wet-bulb temperature, and vapour pressure, are used in the simulation of many grain drying and aeration systems. However, availability of such data is limited to a few meteorological stations, and records are often short and incomplete. On the other hand, long-term records of daily minimum and maximum temperatures, from which hourly values of dry-bulb temperature can be generated using published models, are widely available. In this paper, regression analysis is used to relate dewpoint temperature to daily minimum temperature. Once the dewpoint temperature is known, all remaining properties of air can be computed from the dry-bulb temperature and the psychrometric equations.

Materials and Methods

Seven meteorological stations in Queensland and New South Wales were selected to represent contrasting climatic conditions for this study (Fig. 1). The minimum data set used in the analysis included daily minimum and maximum temperatures, rainfall, and dry- and wet-bulb temperatures at 0900h and 1500h. For each location, a minimum of 15 years of data was available for regression analysis. At each location, daily dewpoint temperatures were calculated at 0900h and 1500h. If the difference in dewpoint temperatures between the 0900h and 1500h was greater than 6°C, the data were discarded and assumed to have measurement errors (this accounted for about 4% of all available data). Daily variations of more than 6°C in dewpoint temperature are extremely rare and could occur only with sudden change in atmospheric conditions such as a storm.

To establish a relationship between the dewpoint temperature and the minimum daily temperature, the average daily dewpoint temperature (mean of 0900h and 1500h) was correlated with daily minimum temperature, for each location. Regression coefficients were derived for each month, to determine the seasonal variability of the correlation. Separate regression coefficients were derived for dry and wet days so that the effect of wet days on the relationship between the dewpoint and minimum temperature could be found.

Results and Discussion

Correlation between daily minimum temperature and average dewpoint temperature

Significant correlations were found between the daily minimum temperature and the average dewpoint temperature. More details of the results and the monthly regression coefficients for each location are given in Abawi (1994). The correlation was generally higher ($R^2 = 0.70$, $P < 0.01$) during the southern winter, when the differences between the daily minimum temperature and the dewpoint temperature are smaller. The correlation was lower ($R^2 = 0.3$, $P < 0.01$) during the southern summer, particularly for the drier regions (Charleville and Roma) where the differences between dewpoint temperature and minimum air temperature are larger. During summer, the correlations were generally lower for wet days than for dry days, partly because of the subjective definition of what constitutes a wet day, as discussed later.

For each location, daily value of dewpoint temperature was calculated from 1957 through to 1973. The calculations were based on the daily minimum temperature, state of the day (dry or wet), and the regression coefficients. The average daily dewpoint depressions (minimum temperature minus dewpoint temperature) for Charleville, Emerald and Dalby (as representative locations) for dry and wet days are shown in Figures 2 and 3.

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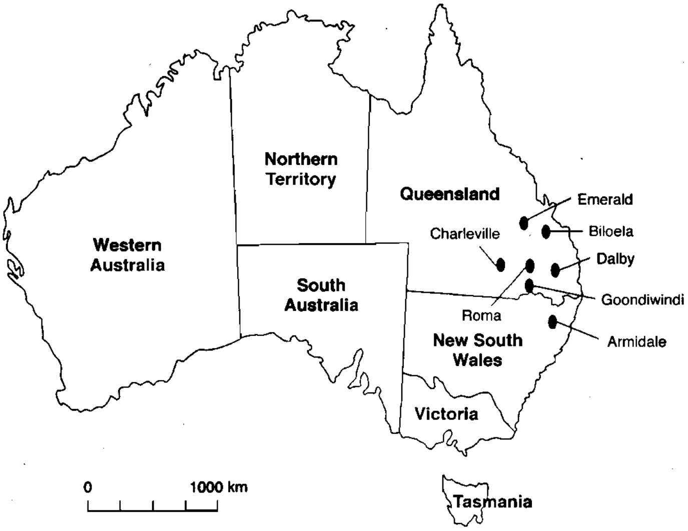

Figure 1. Locations used in the study.

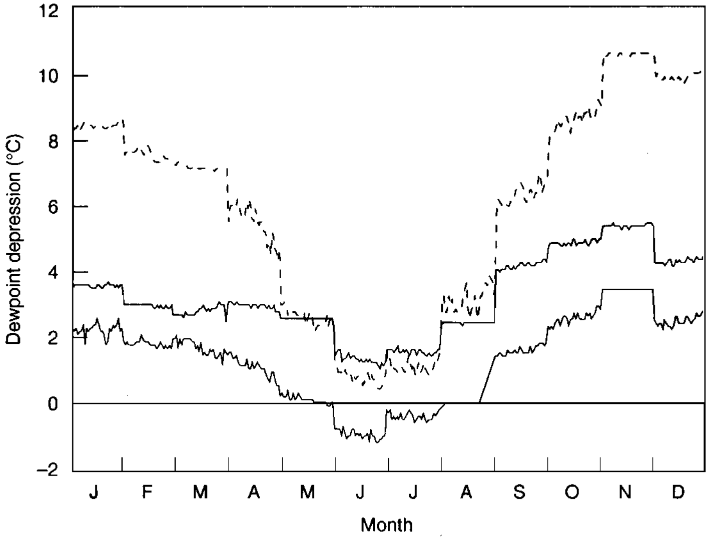

Figure 2. Seasonal and locational variability in dewpoint depression. Data points are average daily depression (1957–1973) for days without rain.

The results show that dewpoint depressions are spatially and seasonally dependent. Dewpoint depressions increase with the distance from the coast and show a distinct seasonal trough with the minimum occurring during the cool winter months.

For fine days, the average daily depression during summer ranged from 2°C for Dalby (200 km inland) to 10°C for Charleville (1000 km inland) (Fig. 2). During winter, the dewpoint depression was about 1°C for all locations more than 200 km inland. For Dalby, the dewpoint depression was negative during winter, indicating that dewpoint occurs before minimum daily temperature is reached.

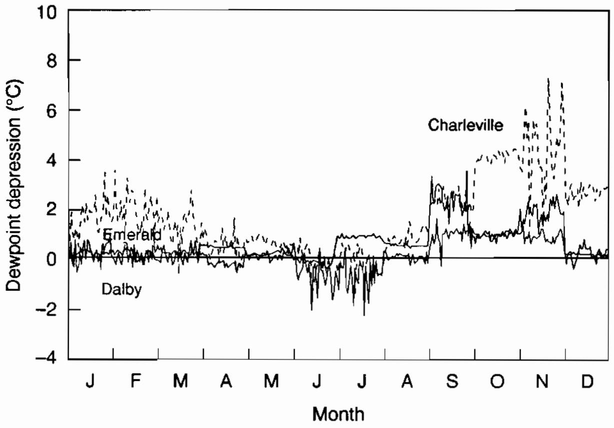

Figure 3 Seasonal and locational variability in dewpoint depression. Data points are average daily depression (1957–1973) for days with rain.

For wet days, the dewpoint depression was close to 1°C for most locations, particularly during winter (Fig. 3). The results for wet days showed considerable scatter, especially during summer at inland locations such as Charleville. This is largely because wet days were defined as days with more than zero mm of rain and, consequently, many days with less than 1 mm of rain were classified as wet days. Dewpoint temperatures are up to 10°C below the daily minimum temperature on dry days and only 2–3°C below on wet days.

In the absence of direct data on dewpoint temperature, researchers have often assumed that the dewpoint temperature occurs at minimum daily temperature and, based on this assumption, have predicted agroclimatic data such as relative humidity, wet-bulb temperature and vapour deficit (Carberry and Bristow 1991). The results from this study show that the general assumption of minimum daily temperature as a substitute for the dewpoint temperature is not valid and could lead to significant errors, particularly for arid regions where the difference between the daily minimum temperature and the dewpoint temperature could be up to 10°C.

Besides seasonal and spatial effects, other variables such as altitude and the daily temperature range may influence the relationship between the daily minimum temperature and the dewpoint temperature. This is currently being examined.

Correlation between 0900h and 1500h dewpoint temperature

Calculation of hourly psychrometric values from the dewpoint temperature is usually based on the assumption that the dewpoint temperature remains relatively constant throughout the day (Kimball and Bellamy 1986; Campbell 1977; Bristow and Carberry 1991). This assumption was tested by plotting the calculated dewpoint temperatures at 0900h against the dewpoint temperatures at 1500h. The data for one year for Goondiwindi are presented in Figure 4 as a representative sample which shows that dewpoint temperatures were generally higher at 0900h than at 1500h, particularly on fine days. During wet days the dewpoint temperatures were nearly the same at 0900h and 1500h. These results suggest that in certain applications, such as in the simulation of grain aeration and drying systems, where hourly values of air properties are needed, the relationship between the 0900h and 1500h dewpoint temperature needs to be taken into consideration.

Prediction of hourly psychrometric data from daily temperatures

To assess the reliability of the method for predicting hourly data, 29 years (1957–1985) of daily minimum and maximum temperatures and rainfall for Goondiwindi and Dalby were used to generate hourly dry-bulb temperatures using the algorithm proposed by Kimball and Bellamy (1986). The regression coefficients were then used to predict daily dewpoint temperature from minimum air temperature and daily rainfall. Dewpoint temperature during the day was assumed to remain constant. The psychrometric equations were then solved to compute hourly values of wet-bulb temperature and relative humidity. The average monthly values of these parameters at 0900h and 1500h and the published historical averages recorded by the Bureau of Meteorology (1957–1985) for Dalby are presented in Table 1. There is a close agreement between the predicted data, based on the regression coefficients, and the published historical data, particularly at 1500h.

Table 1. Comparison of historical and predicted air temperatures and relative humidity for Dalby (1957–1985). Station 041023: Latitude 27°11'S; Longitude 151°16'E.

	Mean temperatures (°C) and relative humidity (%) at 0900h								Mean temperatures (°C) and relative humidity (%) at 1500h							
	Dry-bulb		Wet-bulb		Dewpoint		r.h.		Dry-bulb		Wet-bulb		Dew-point		r.h.	
Jan	25.1	22.9	20.4	19.0	18	17	64	70	30.6	31.3	21.8	21.6	17	17	44	44
Feb	24.7	22.3	20.4	18.9	18	17	66	73	30.3	30.9	21.7	21.6	17	17	44	45
Mar	23.2	20.0	19.1	17.1	17	16	66	75	28.7	29.3	20.3	20.2	15	16	44	44
Apr	20.2	15.5	16.5	13.5	14	12	67	80	26.1	26.5	18.1	17.5	12	12	43	42
May	15.5	10.6	12.7	9.5	10	9	71	88	21.7	22.3	15.1	14.5	10	9	46	43
Jun	11.7	7.2	9.7	6.9	8	7	76	96	18.7	19.2	13.1	12.4	8	7	50	45
Jul	10.5	6.0	8.2	5.4	6	5	72	92	17.9	18.4	11.8	11.3	5	5	44	42
Aug	13.0	8.1	10.0	6.9	7	6	66	84	19.7	20.2	12.8	12.4	6	6	41	40
Sep	17.0	12.1	12.8	9.5	9	7	59	72	23.2	23.6	14.8	14.3	7	7	36	36
Oct	20.7	16.7	15.9	13.1	12	11	59	67	26.2	26.7	17.3	16.9	11	11	37	38
Nov	23.5	20.3	18.1	15.8	14	13	57	63	29.0	29.5	19.5	19.0	13	13	38	38
Dec	25.0	22.2	19.6	18.1	16	16	59	67	30.4	31.0	20.7	20.9	15	16	39	41

Notes:
Values in shaded columns are calculated from historical daily minimum and maximum temperatures and the regression coefficients.
Value in remaining columns are from: Climatic Averages Australia, Bureau of Meteorology, 1988.

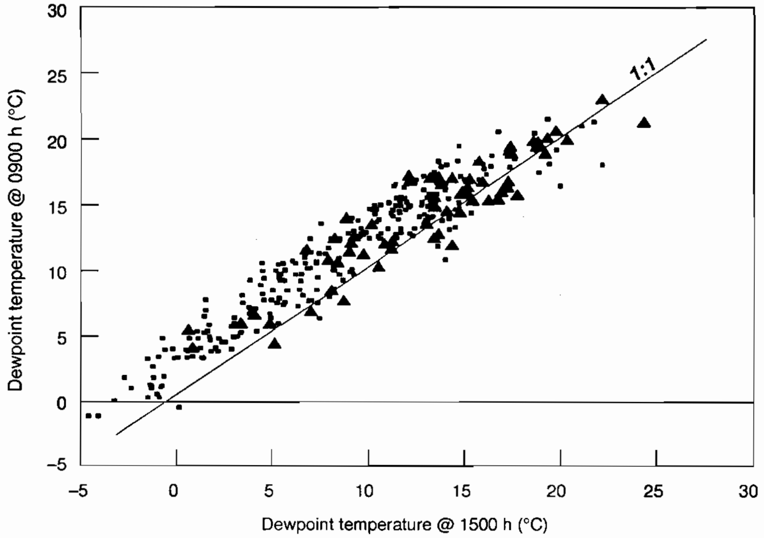

Figure 4. Correlation between 0900h and 1500h dewpoint temperatures. Daily data for Goondiwindi. s = wet days; n = fine days.

The predicted dry-bulb temperatures at 0900h are 2–3°C below the published data, particularly during the winter months of May–August. This difference arises from the assumption in the Kimball and Bellamy (1986) model that minimum air temperature occurs shortly after sunrise. A slight lag between the predicted and actual time that minimum temperature occurs results in a large prediction error because of the steep gradient in the temperature rise early in the morning. Since the wet-bulb temperature and the relative humidity records are derived from dry-bulb temperature, an error in the dry-bulb temperature would also influence the values of these parameters. Another explanation for the difference between published and predicted data, particularly for relative humidity and wet-bulb temperature, may lie in the assumption that the dewpoint temperature remains constant during the day. Dewpoint temperature is 1–2°C higher at 0900h than at 1500h (Fig. 4) and because this bias is not corrected in these calculations, it could explain some of the differences between the observed and published data at 0900 h.

Conclusions

The assumption that minimum daily temperature can be substituted for the dewpoint temperature is not valid. However, significant correlation exists between the daily minimum temperature and the dewpoint temperature. In eastern Australia, the regression parameters vary with the season, location, and the state of the day (wet or dry). The dewpoint depression (minimum temperature minus dewpoint temperature) ranged from about −1°C for coastal areas during the southern winter (May–August) to 10°C for inland locations during the southern summer (November–January). On wet days, at all locations and times of the year, the dewpoint depression was close to zero. These results can be used to predict a wide range of agroclimatic data from daily minimum and maximum temperatures and rainfall records.

References

Abawi, G.Y. 1994. An operations research model of wheat harvest management in northern Australia. Unpublished PhD thesis, University of Queensland.

Bristow, K.L. and Carberry, P.S. 1991. Minimum air temperature as a predictor of daily mean vapour density. Conference on agricultural meteorology, Melbourne, 301–304.

Campbell, G.S. 1977. An introduction to environmental biophysics. New York, Springer-Verlag.

Carberry, P.S. and Bristow, K.L. 1991. Sensitivity of crop yield to errors in daily vapour deficit. Conference on agricultural meteorology, Melbourne, 297–300.

Kimball, B.A. and Bellamy, L.A. 1986. Generation of diurnal solar radiation, temperature and humidity pattern. Energy in Agriculture, 5, 185–197.

Design and Development of a Rotary Semi-fluidised System Dryer for Paddy

T.F. Anchiboy and R.E. Manalabe*

THE advent of flash dryers has been brought about by the two-stage drying technology, a proven way of minimising grain quality deterioration after harvest. The first stage of drying entails the rapid removal of surface moisture that will otherwise cause rapid quality deterioration. The successful development of mechanical dryers involves both technical and socioeconomic considerations. The latter have often been overlooked in the past, thus resulting in technologies that failed. Most Filipino farmers cannot afford a mechanical dryer no matter how simple and inexpensive the unit might be, but they are willing to pay for farm services such as threshing and harvesting. They might also be willing to pay for custom drying if an appropriate service and equipment were available. This study examines the factors considered in the design and development of a rotary semi-fluidised system dryer, or RSSD, for first-stage drying of paddy.

Methodology

Ex-ante socioeconomic survey

To analyse the various social and economic parameters that served as bases for the development of the RSSD, an ex-ante socioeconomic survey was conducted with farmers as respondents. Drying systems applicable to their operations were identified and quantified in terms of gross income, for the computation of an affordable drying fee and investment cost for the developed technology.

Experimental model of the RSSD

In parallel with the survey, an experimental model of the RSSD was built for laboratory testing (Fig. 1). The optimum exhaust door opening, which affects the moisture extracting capability of the drying system, was established in the test. The effect of initial moisture content of the paddy to be dried, the inflow rate, the drying air temperature, and the airflow rate on the performance of the dryer were also investigated. Paddy at 1 t/hour flowrate was dried using a temperature of 150–170°C and an airflow rate of 57 m^3/minute. In another experiment, airflow was reduced to 37 m^3/minute in order to investigate the possibility of reducing blower capacity and thereby its cost.

Prototype model of the RSSD

The prototype model of the RSSD was designed and developed based on the results of the drying experiments using the experimental model and the findings of the ex-ante study on the preferred investment cost, drying cost, and drying strategy. The prototype was performance tested. Important parameters such as the moisture extracting capability and input and output flowrates were established in the tests. A bill of materials was determined in order to evaluate the investment cost of the dryer, particularly whether it remained within the affordable investment cost limitation established in the first part of the study. Fuel consumption and labour requirements of the dryer were also recorded.

Results and Discussion

Seven existing and proposed drying systems were identified in the ex-ante survey as shown in Figure 2. The gross incomes from the different systems were computed, without deducting the drying fee. The results are shown in Figure 3. SVI has the advantage over the rest, followed by SIII and SVII. However, SIII is difficult to achieve during the wet season, hence SVI and SVII were compared for the calculation of affordable drying fee. The difference in gross income between the two systems was computed and divided by the volume available for drying to arrive at the affordable drying fee of approximately PHP10.00 per cavan (during October 1995, ca 25 Philippines pesos (PHP) = US$1; 1 cavan = 50 kg). Cost data of a 1 t/hour mechanical thresher were used as a starting point in determining the cost for the RSSD. Investment cost was computed by dividing the net income by the assumed payback period, and was found to be approximately PHP46,000.00.

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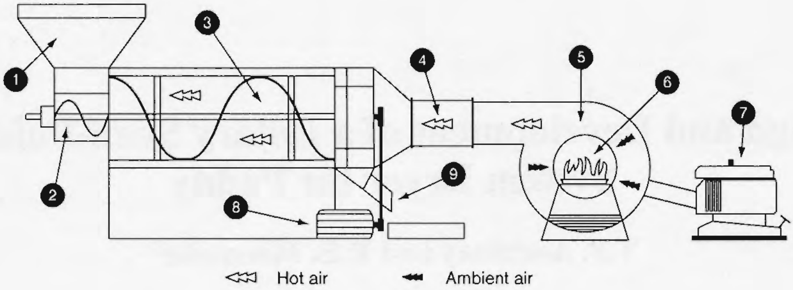

Figure 1. Schematic drawing of the experimental model of the RSSD. Parts of the model are as follows: 1, loading hopper; 2, screw auger; 3, perforated cylinder drum; 4, air duct; 5, blower; 6, kerosene pot type burner; 7, gasoline engine; 8, electric motor and; 9, unloading port.

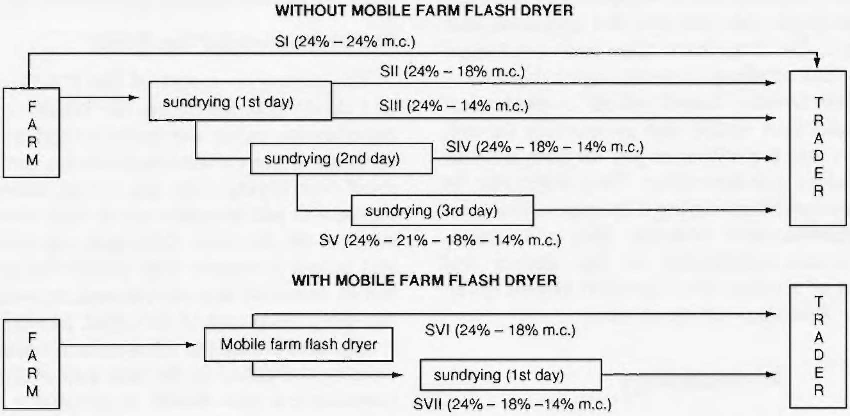

Figure 2. The seven identified drying systems.

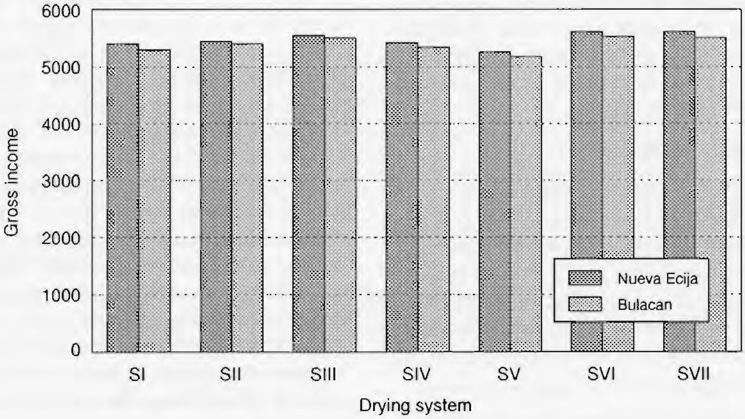

Figure 3. Gross income for the seven identified drying systems.

An experimental model of the RSSD was fabricated and used for preliminary testing. Table 1 summarises the results of the first laboratory test. At a residence time of 20 seconds, the resulting moisture extraction averages 3.8% resulting in an input capacity of only 0.58 t/hour, well below the target capacity of 1 t/hour.

Table 1. Performance testing of RSSD experimental model at varying exhaust door opening.

	Exhaust door opening			
	1/4	1/2	3/4	1
Drum ang. vel., mps	1.61	1.61	1.61	1.61
Blower speed, rpm	2705	2695	2712	2705
Drying air temp. °C	100	100	110	110
Grain temp, uncooled, °C	*	50	*	56.5
Cooling duration hr	1	1	1	1
Grain temp., °C (cooled)	*	33.5	*	32.5
Airflow, m^3./min	56.68	56.68	56.68	56.68
Res. time, sec.	18.70	19.61	20.86	21.19
Initial m.c., % w.b.	22.07	21.88	24.23	25.35
Final m.c., % w.b.	18.40	18.52	20.18	21.29
Moist. reduction	3.67	3.36	4.05	4.06
Total drying time, sec	110.8	118.0	133.3	138.5
Capacity, t/hour	0.65	0.61	0.54	0.52

With the loading hopper regulator fully open, the highest grain input flowrate of 0.83 t/hour was achieved. Decreasing the drum speed from 78 to 60 rpm decreased the residence time to only 7 seconds, thus increasing the grain output flowrate (Fig. 4). With the decrease in the grain residence time, the moisture extracting capability of the dryer also falls (Fig. 5). Figure 6 shows that as drum speed decreases, grain flowrate increases to a peak at 50 rpm, then gradually falls again as drum speed continues to decrease. It was also observed during the drying experiments that the highest possible drying air temperature, without resulting in a kerosene odour in the exhaust, ranged from 150–170°C. Quality analysis done in terms of brown rice, milled rice, and headrice recovery showed no significant differences between samples taken before and after drying.

The combined effect of high drying-air temperature and low airflow at 1 t/hour flowrate in the preceding experiment was not very encouraging in terms of moisture extraction (2.1% per pass). For this reason, another experiment was conducted, using 57 m^3/minute airflow instead of 37 m^3/minute. The results are summarised in Table 2. At 150–160°C drying air temperature and approximately 57 m^3/minute airflow, the resulting moisture extraction was 3.9%. The initial moisture content of the sample used was relatively low at 22.0% (wet basis), and the actual output capacity was calculated to be 0.90 t/hour. Results of the quality analyses done on samples before and after drying paddy with high drying-air temperature and high airflow showed no significant difference in brown rice and milled rice recovery but for the headrice recovery, the initial sample (before drying) had a relatively lower headrice yield than samples after drying (Table 3). This could be attributed to the gelatinisation effect of using high drying-air temperature and high airflow during the flash-drying operation.

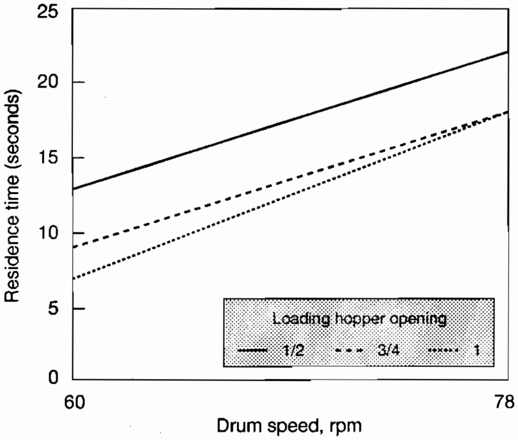

Figure 4. Exposure time of paddy at different drum rotation speeds of the RSSD.

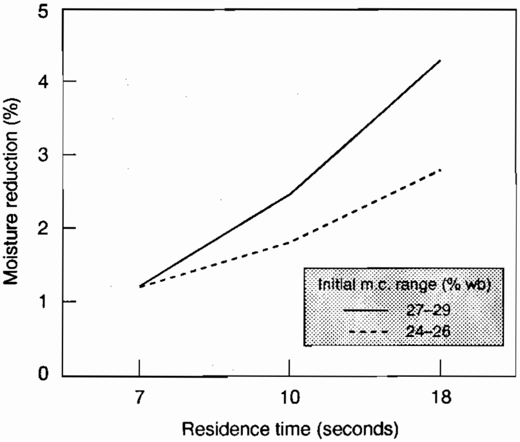

Figure 5. Moisture reduction of paddy at different initial moisture contents and residence times.

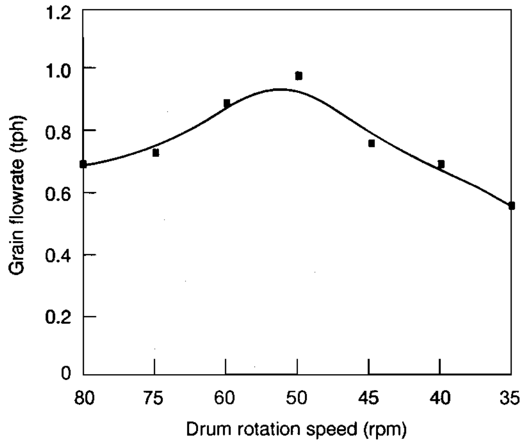

Figure 6. **Grain flowrate at varying drum rotation speed.**

Table 2. The effect of flash drying paddy with 150–160°C drying air temperature and 57 m^3/minute airflow on moisture extraction of paddy.

	Trial 1	Trial 2	Trial 3
Initial m.c. (% w.b.)	22.0	22.4	22.5
Ambient temp. (°C)	32.5	32.2	33.6
Grain temp. (°C)	55.0	55.0	55.0
Final m.c. (% w.b.)	18.1	18.3	18.8
Moisture reduction (%)	3.9	4.1	3.7
Grain flowrate (t/hour)	0.894	0.888	0.923

Table 3. Summary of the quality analysis of flash dried paddy using 150–160°C drying air temperature and m^3/minute airflow.

	% Brown rice	% Milled rice	% Head rice
Initial sample	76.3	64.4	83.9
Trial I	75.8	64.4	88.0
Trial II	76.5	64.6	88.0
Trial III	76.7	64.8	88.4

The prototype model of the RSSD (Fig. 7) was designed and fabricated based on the results of the various drying experiments. The loading hopper of the developed dryer is provided with a regulator to control the input flowrate of the grain. Likewise, a separate auger pulley is provided to make the auger speed independent to the speed of the rotating drum. Thus, the optimal drum speed could be set to achieve fluidised-drying of grain at 1 t/hour input flowrate (as can be regulated separately through the auger speed).

A plenum air manifold is provided with air diverters to achieve equal distribution of drying air to the entire length of the rotating drum. Exhaust air is vented through a duct with a 10 × 20 cm opening at the side opposite the plenum air duct. An axial fan was used in the dryer rather than a centrifugal blower because the resulting static pressure of the dryer is less than 1 inch of water gauge. Also, axial fans are cheaper than centrifugal blowers. The computed bill of materials for the RSSD prototype was PHP42,927.50.

Results of the performance testing of the prototype model showed that the average moisture reduction of paddy is 4.1% per pass, at a residence time of 40 seconds. The average kerosene consumption was 5.6 L/hour and the average gasoline consumption of the engine used for the blower 1.5 L/hour. Input capacity was maintained at 1 t/hour, with a drying air temperature of 160°C, and an airflow of 57 m^3/minute. The labour requirement for the entire drying operation was at least 3 persons.

Conclusions and Recommendations

1. The RSSD was designed and envisioned to give the highest return in the wet season, especially during days of continuous rain when one day of sun drying is not sufficient to completely dry the paddy to a safe moisture level.
2. The mechanical drying fee affordable to farmers was estimated to be approximately PHP10.00 per cavan of paddy.
3. The investment cost affordable to farmers for the RSSD is estimated at PHP46,000.00
4. As drum speed decreases from 80 revolutions per minute, grain flowrate increases up to its peak at 50 rpm, then decreases again as drum speed continues to decrease down to 35 rpm. A 1 t/hour input capacity can be obtained with 50 rpm drum speed and 14.2 % moisture content of the paddy
5. The optimum drying air temperature for the RSSD was in the range 50–170°C. With this drying air temperature and a 37 m^3/minute airflow, the resulting moisture extraction was only 2.1%. When an airflow of 57 m^3/minute was used, the resulting moisture extraction increased to 3.9 %, without significantly affecting grain quality.
6. Based on the conclusions drawn from the drying experiments conducted, the prototype model of the farm flash dryer must be operated with a fully open loading hopper. The drying air temperature to be used for flash drying paddy at 1 t/hour flowrate must not exceed 150–170 °C.

Figure 7. The prototype model of the rotary semi-fluidised system dryer.

7. The total material cost of the dryer developed was PHP42,927.50. The drying cost can be ascertained only after pilot testing of the technology. This has yet to be done.

8. Further studies should also be done to investigate the possible use of the dryer in drying crops other than paddy, such as maize and other cereal grains, soybean, and mungbean.

Chilled Aeration/Storage of Grain in Southeast Asia

F.W. Bakker-Arkema*, D.E. Maier†, and A. Sebastianelli§

Abstract

The storage of grains under tropical conditions requires close supervision. This is true even for grains dried properly and uniformly to 13–14% moisture content. A major problem is the resistance of the major grain pests to the few chemicals still permitted for use. *Grain chilling* may be a solution to this problem.

Thailand and Malaysia are among the countries in the Southeast Asian region in which grain chillers are operating successfully. Indonesia, the Philippines, and Vietnam are researching the new technology and are expected to adopt on a limited scale the chilled aeration/storage of grains in the near future.

Experience with commercial grain chillers in the tropics has thus far shown the following:

- A chilling unit can maintain a constant temperature and relative humidity of the air entering a grain bin regardless of the ambient conditions.
- The cool-down of a bin of grain is a rapid process, and thus a chiller can be used for a series of bins.
- The re-chilling of grain by chilled aeration is required relatively infrequently due to the favourable thermal properties of the grain.
- The electrical energy use of long-term chilled-grain storage is low.

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Promoting Grain Storage Technology and Best Practice through Short Courses

R.J. Banyer* and J.H. Kent†

FOR businesses to remain competitive and sustain profitability, staff must possess the competencies required to carry out best practice. One significant impediment to staff development is the lack of suitable or accessible training of high quality. Educational institutions have an important role to play in the provision of such training.

Over the past six years, Charles Sturt University, a nationally and internationally recognised provider of distance education, has successfully conducted an industry short course dealing with all aspects of preservation of grain quality in storage. Emphasis is given to promoting the latest technology in the protection of stored grain. The course, based on self-paced learning on-the-job, attracts supervisors and operators of grain storages throughout Australia. Industry leaders service a follow-up skills training workshop and field excursion. Modified for Asian conditions, the course could service specific training needs of internationals.

Course Structure and Mode of Delivery

The course has two main parts:

- a knowledge component presented in a manual form designed for self-paced learning at home; and
- a practical component presented by visiting experts, either in Australia or off-shore.

Course Requirements

- Total time required to complete course requirements will vary according to an individual's program.
- Assessment of learning outcomes is based on open-book questions submitted as assignments.
- Assessment of the practical component is conducted immediately following each discrete session.
- The cost for course tuition will vary according to an individual's training program and location of the practical component.
- Sources of financial assistance are currently under review.

Award

- A Charles Sturt University Certificate of Achievement detailing competencies gained is issued on completion.

Main Features of the Course

- Quality learning materials are presented in a user-friendly format.
- Modules are designed for self-paced study at home.
- The course is structured and delivered to suit individual specific training needs.
- Expert instruction and personal tuition are provided for practicals.
- Learning materials are supplemented with up-to-date technical references including visual aids.
- A University Certificate of Achievement is awarded.
- The main topics of study are presented as discrete but interrelated modules.

Course Content

Participants may select a program of training from the following main areas:

- *Grains industry in perspective*—an overview of organisational structure, marketing and standards.
- *Storage types and systems*—design, maintenance, problems, and modifications.
- *Grain characteristics and behaviour in storage.*

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- *Hygiene and sanitation–first line of defence*—principles and practices.
- *Grain pests–vertebrates and invertebrates*—problems caused, characteristics, identification and control; resistance management.
- *Grain quality monitoring and standards*—inspection and detection methods, sampling theory and practice, quality assessment and testing, identification of grain defects and contaminants; mycotoxins.
- *Controlled atmospheres, drying, aeration, and refrigeration.*
- *Fumigants and fumigation.*
- *Grain protectants*—choice; strategic use; application; safety and regulation.
- *Integrated management programs*—total quality management strategies; integrated pest management.
- *Occupational health and safety.*

Rice Hull Furnaces for Paddy Drying: the Philippine Rice Research Institute's Experience

E.U. Bautista, R.E. Aldas, and E.C. Gagelonia*

RICE hulls constitute 14–26% of the harvested weight of paddy. With the current annual Philippine paddy production of around 9 Mt, some 1.8 Mt of rice hulls are produced each year. Although some of the hulls produced by small rice mills are used as domestic fuel or as a livestock feed (when mixed with rice bran), vast quantities of husks are not utilised and are disposed of in vacant areas or along roadsides.

The energy content of rice hulls ranges from 14 to 16 MJ/kg (6000–6800 BTU/lb); a tonne of hulls is thus equivalent to about 84 gallons of heating oil having 140,000 BTU/gal (Beagle 1978). In the Philippines, the best potential use for rice hulls, aside from domestic fuel, is in paddy drying. Paddy drying is commonly accomplished by a combination of field and direct solar drying on a pavement or open road. Mechanical drying is employed when the harvesting occurs during the monsoon season. Most millers using batch dryers fire them with kerosene furnaces, but are beginning to shift to rice-hull-fired furnaces due to cost constraints. Other sophisticated dryers of several private traders/millers in the country are equipped with rice-hull-fired boilers which generate steam for drying.

This paper discusses the rice-hull furnaces adopted by the Philippine Rice Research Institute (PhilRice) in its dryer studies, their performance when fitted to dryers, and the dissemination work conducted to popularise and commercialise the dryers and furnaces.

Furnace Designs and Drying Performance

There is already available in the country a wide range of furnace systems designed for the direct combustion of rice hulls. PhilRice adopted three furnace designs in its paddy-drying studies and is in the process of refining one design for dissemination of dryers in the country.

1. Grate-type furnaces

The first design utilised in flat-bed dryers is the IRRI BD-2 flat-grate furnace (Fig. 1) which is an up-draft type, flat-grate, rice-husk furnace. It consists of a hull feeding component, a combustion chamber, and an ash precipitation chamber. It is simple in construction and operation. The air for combustion is supplied by the suction of the dryer fan, while the fuel supply is facilitated by the vibration of a feeder connected by a wire to the fan shaft. At a feed rate of 10 kg/hour, furnace efficiency is 68–70% (IRRI 1979). However, it has incomplete combustion and inefficient ash separation so that ash and sparks are partially sucked by the fan into the dryer plenum (Phan Hieu Hien 1993).

Similar to the flat-grate furnace is the inclined grate furnace design (Fig. 2) from the University of Agriculture and Forestry (UAF), Vietnam and was based on the IRRI design. It has similar performance to that of the IRRI furnace but has more durable steel parts than the former, particularly the grate, which is made of mild steel. At 34 kg/hour rice hull feed rate, the drying air temperature at the plenum could ranged from 40 to 54.3°C, with a 484 to 509°C exhaust temperature; with a higher feed rate, drying air temperature can be pushed up at 80°C. Efficiency ranged from 48.4 to 86.1%. Combustion takes 10–20 minutes and is characterised by the production of much smoke. The hopper needs to be loaded with husks every 10–15 minutes. Once ignited, combustion is maintained while there are rice hulls. The ash has to be manually raked from the furnace.

Technical evaluation of the performance of the Vietnam-adapted 6 t/batch Maligaya flat-bed dryer (with concrete bin) using the inclined-grate furnace was conducted in Nueva Ecija and Davao del Norte, in order to establish parameters for its optimum operation. Parameters such as grain depth, fan speed, and drying air temperature were examined to determine their effects on drying rate, uniformity of moisture content, milling and head rice recoveries, and germination rates. Results (Table 1) indicate that the improved dryer performed best at 26 to 34 cm grain depth, and maximum air temperatures of 43 and 47°C for seed and milling

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purposes, respectively. Fan speed had no significant effect on headrice yield and germination.

Other problems formerly associated with earlier flat-bed dryer designs—such as the need to mix the grain during drying and the excessive moisture gradient between top and bottom grain layers—could be avoided because of the UAF dryer's efficient fan and if the recommended grain depth was adhered to. With systematic management of operations, even unloading problems could be minimised. However, the operator could be exposed to heat from the furnace, especially as rice hulls have to be loaded and ash removed every 10 to 15 minutes.

At present, PhilRice is refining or testing other designs to go with future installations of flat-bed dryers. The modifications are focusing on better ash separation (which causes the dryer's perforated screen to be plugged with continuous use), lighter weight (for mobility), better durability, and lower cost. The UAF, Vietnam has recently developed an improved furnace using an inclined grate with a more efficient cyclonic ash separation (Fig. 3). This was to be tested during the 1995 wet season.

2. Combustor furnace

Another design tested for batch drying and later commercialised for flash drying is the gasifier combustor designed by the Industrial Technology Development Institute (ITDI) for brick kilns. Its components include an air delivery and metering system utilising a separate blower, fuel inlet and hopper, which is actually the topmost section of the reactor, the reactor, and the grate-ash removal system at the lowest section (Fig. 4). It operates on the principle of an open-core, batch-type gasifier. Air from a separate blower flows downward through the fuel bed. The gasified products are burned to produce a bluish-to-light orange flame at the lower exhaust port.

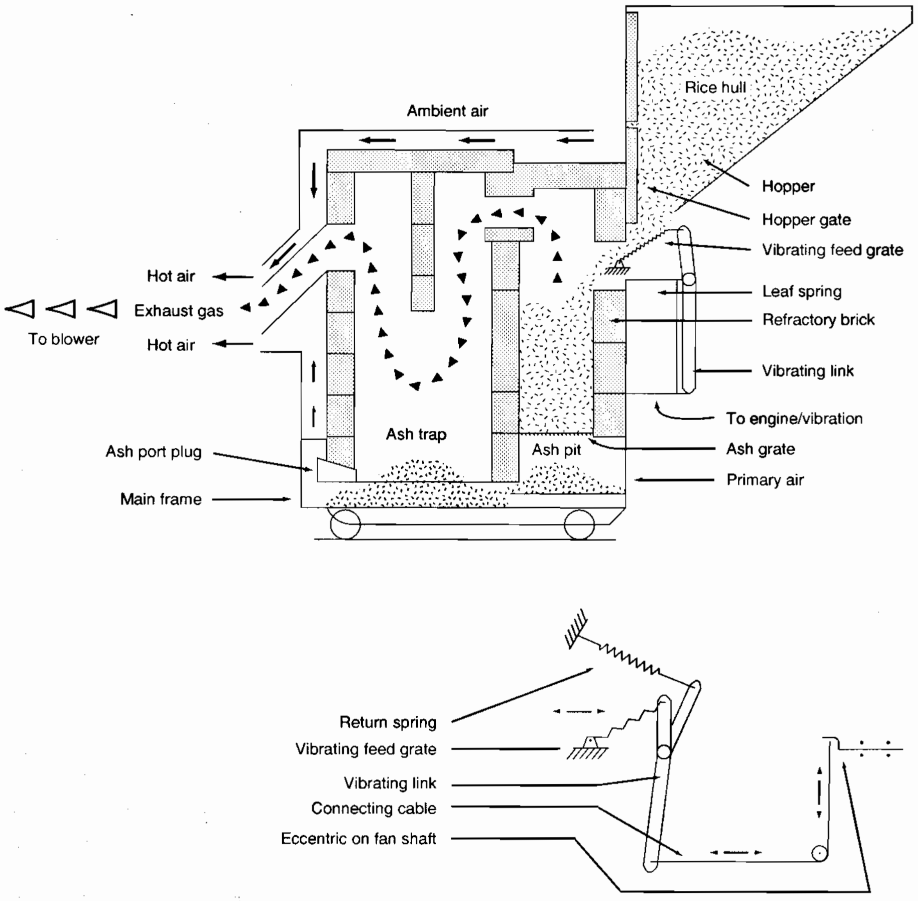

Figure 1. Schematic diagram of the IRRI BD-2 flat grate furnace (IRRI 1979).

Table 1. Results of drying tests at different grain depth, fan speed and drying air temperature for the Maligaya 6-ton flat-bed dryer-cum-inclined grate furnace. Philippine Rice Research Institute, 1994 wet season.

Test no.	FBD1	FBD2	FBD3	FBD4	FBD5	FBD6	FBD7	FBD8	FBD9	FBD10
Date	26 Aug.	7 Oct.	10 Oct.	11 Oct.	25 Oct.	4 Nov.	10 Nov.	23 Nov.	24 Nov.	26 Nov.
Crop conditions										
Variety	IR64	Rc14	BPIRi10	BPIRi10	IR72	Mix	Mix	Burdagol	Burdagol	Burdagol
Initial moisture content, %	23.2	22.5	22.5	22.9	22.7	17.5	17.5	22.3	18.6	25.1
Final m.c., %	15.3	14	14.1	13.4	13.8	12.3	14.2	13.8	12.7	13.8
Initial weight, t	4.75	3.50	2.92	4.79	4.80	4.22	4.41	5.09	3.30	3.61
Final weight, t	4.31	3.15	2.63	4.26	4.30	3.97	4.24	4.59	3.08	3.13
Grain depth, cm	27.0	24.3	19.9	29.8	29.6	26.1	27.9	31.3	20.5	22.6
Ambient conditions										
Temperature, °C	31	33.5	32	31	33	31	30	30	30	31
Relative humidity, %	75	64	67	75	60	60	56	80	75	72
Drying results										
Drying air temp., °C	43	43	41	43	51	49	43	49	49	49
Drying time, hours	3h45	3h00	5h30	5h00	4h00	2h30	2h30	4h00	2h45	3h30
Drying capacity, kg/hour	1149	1053	479	853	1076	1590	1695	1148	1119	895
Top & bottom m.c. diff, %	2.1	1.8	0.5	2.0	1.8	1.7	0.8	1.4	0.5	0.9
Moisture removed, kg	443	346.4	285.5	525.5	495.6	250.5	169.5	502.5	223	472.8
Drying rate, % m.c./hour	2.1	2.8	1.5	1.9	2.2	2.1	1.3	2.1	2.1	3.2
% m.c. reduction	7.9	8.5	8.4	9.5	8.9	5.2	3.3	8.5	5.9	11.3
Ricehull consumption, kg	145	105	137	160	130	65	55	150	100	115
Feeding rate, kg/h	44.5	35.0	27.4	35.6	37.1	32.5	27.5	42.9	40	35.4
Fan operation										
Speed, rpm	1750	1500	1450	1630	1620	1770	1770	1740	1610	1630
Static pressure, mm H_2O	19	16	15	17	17	20	20	22	15	15
Airflow rate, $m^3/s\text{-}m^2$	0.22	0.19	0.195	0.19	0.19	0.22	0.22	0.21	0.22	0.22
Airflow, m^3/s	6.19	5.35	5.49	5.49	5.49	6.19	6.19	5.91	6.19	6.19

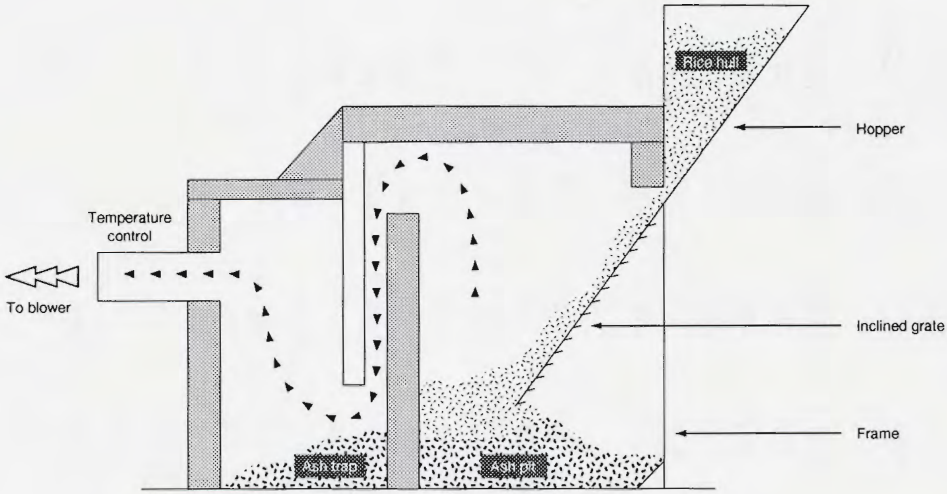

Figure 2. The UAF-designed inclined grate furnace (Tam et al. 1995).

Figure 3. Inclined grate furnace with cyclonic ash separator.

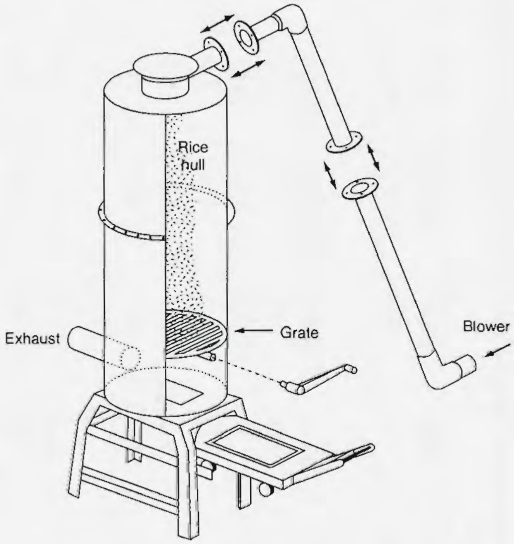

Figure 4. The ITDI rice-hull gasifier–combustor (Gagelonia 1993).

The gas generated in the reactor has a heating value of 3000–4000 kJ/m^3 with a conversion efficiency of 70 to 80%. Ash is removed after every batch by tilting the grate and manually scraping the ash out of the ash port. Phan Hieu Hien (1993) noted several features of this furnace as follows: simple construction, easy control of the heating rate, and the production of a clean-burning flame which is essential in direct-heat drying.

The ITDI combustor could be coupled with a 2 t batch dryer for paddy seed drying. Because of the high heat generated at the exhaust (360–500°C), however, it is necessary to use an expansion duct between the fan and the plenum and to install and regulate a baffle plate at the exhaust to reduce the drying air temperature to 40 to 50°C. With such an arrangement, the drying system efficiency ranges from 20 to 31.4%, depending on the grain depth at the bin, at an airflow rate of 0.8 m^3/sec and static pressure of 20 to 26 mm water. An average moisture reduction of 1.3 to 1.5%/hour, equivalent to 20–31 kg water removed per hour, was obtained during tests.

Because of its capacity to generate high-temperature drying air, the ITDI combustor was also recommended to a manufacturer to be coupled to the NAPHIRE flash dryer design. Tests indicated a drying air temperature within the plenum chamber from 80 to 90°C; this temperature could be attained within 15 minutes after combustion. Drying rate (from 27.9 to 19.0% m.c. grain) was 9%/hour at a plenum air velocity of 0.6 m/second.

The main problems with this system are its slow ignition (which can take from 30–60 minutes with some units) and the excessive smoke produced, which is directed at the drying bin during ignition. Also, being a batch-type furnace, it could pose a problem for unskilled operators in a continuous drying system.

3. Zeta furnace

The latest design developed in collaboration with IRRI and GTZ is the Zeta furnace which is designed for low-temperature drying systems. Low-temperature drying is a process which utilises either natural air or air heated by only a few degrees (6 to 9 K above the ambient temperature) for drying, depending upon the ambient relative humidity. Unlike the other drying methods which use drying air temperature of around 43°C or higher, low temperature drying is a slow process which takes 7–15 days or more depending on the weather. It is also referred to as in-storage drying since the same bin can be used for both drying and storing. Its advantages over high temperature drying include modest investment, minimum energy consumption and labour requirement, and uniform drying (Muhlbaüer et al. 1992).

The furnace designed for such a system (Fig. 5) is a box-type, with an air-sweep floor inclined at 30°, similar to the inclined-grate system. The air-sweep floor was a sheet of metal with rectangular shaped slits where air passes to convey the rice hulls. On the lower side of the floor is a rectangular opening which leads to a cyclonic compartment where the ash falls to the bottom and is separated from the heated air which is sucked into the dryer by the dryer fan. During operation, the hot air, together with the ash, are conveyed to the second compartment through the combined action of air-sweep floor, gravity, and suction from the blower. It uses a feeding system which is adapted from the Colombian furnace.

Tests of the furnace with a 5 t/batch in-store drying bin indicated that, at a feeding rate of 4 to 10 kg/hour, the furnace had burning efficiency of 90–95% and drying air efficiency of 40–80%. Drying tests resulted in the desired moisture reduction and better milling recovery and germination capacity compared with shade-dried samples (Table 2). The dried grain was observed to be clean, which indicated that the furnace had been effective in burning the rice hull and in separating the ash from the heated air. The furnace was also capable of maintaining a nearly uniform fuel bed. No accumulation of a thick layer of rice hull was observed. Thus, there was uniform distribution of air throughout the rice husk fuel mass which led to better performance compared with other existing designs.

Aldas et al. (1995) noted several advantages of the Zeta furnace, including its compactness, lightweight design, and continuous automatic feeding of rice hull with its piston mechanism. However, the furnace is still in prototype stage and will have to be adapted together with the in-bin drying storage system in the country.

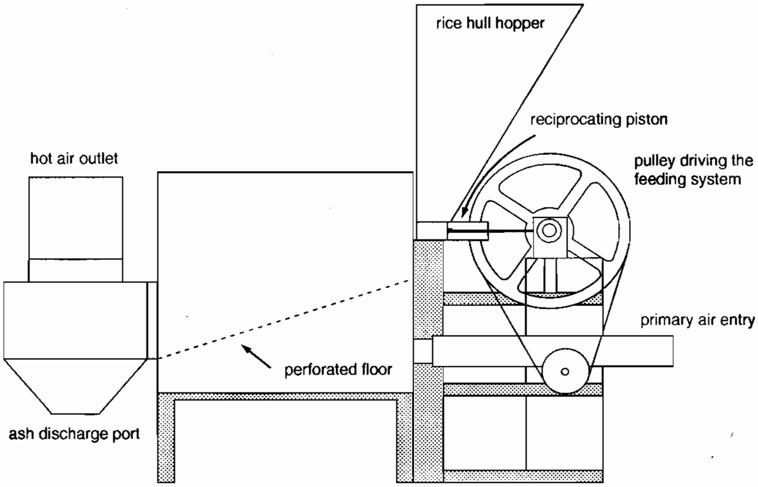

Figure 5. Schematic diagram of the Zeta furnace for low-temperature drying (Aldas et al. 1995).

Table 2. Summary of drying data for 5-ton in-bin dryer and storage system using Zeta furnace.

Test no.	1	2	3
Date and time begun	16 Mar., 1135	20 Apr., 1545	28 Apr., 1545
Date and time ended	28 Mar., 1100	26 Apr., 1100	4 May., 1520
Duration, h	287.4	142.3	143.6
Bulk depth, m	2.2	2.0	1.7
Crop data			
Variety	841	Sinandomeng	PSBRC 10
Initial weight, kg	6135.6	5923.0	5615.0
Initial moisture content, %	28.8	19	22
Operation			
Motor power, hp	3	3	3
Blower operating time, h	136.2	88.6	84.2
Air velocity, m/s	0.09	0.11	0.13
Static pressure, Pa	600-700	450-550	400-500
Airflow power, W	327.6	308.0	327.6
Energy delivered, kWh	44.6	27.3	27.6
Energy used, kWh	410.9	209.0	255.1
Furnace operating time, h	40.97	17.25	17.88
Increase in temperature, K	10	13	11
Fuel consumed, kg	127.9	61.5	59.0
Fuel consumption rate, kg/h	3.12	3.57	3.30
Heat available, MJ/h	44.038	50.305	46.560
During furnace operation			
Average relative humidity, %	80	75	80
Drying air temperature, °C	35	40	38
Air density, kg/m^3	1.119	1.101	1.107
Heat supplied, MJ/h	20.466	31.994	32.169
Results			
Final weight, kg	5034.4	5297.2	4787
Final moisture content, %	13.1	11.8	12
Water removed, kg	1101.2	625.8	828
Drying rate, kgH$_2$O/h	3.83	4.40	5.77
Motor and blower efficiency, %	10.86	13.06	10.82
Drying air efficiency, %	46.47	63.60	69.09
Spec. energy requirement, kWh/kgH$_2$O	0.828	0.719	0.587

Source: Aldas et al. (1995).

Furnace and Dryer Dissemination at PhilRice

PhilRice, in its dryer research and dissemination activities, focused only on tapping dryer designs and models which could be fitted with rice-hull furnaces rather than kerosene burners for economy purposes and which local adopters seem to prefer.

Since total investment cost is also one of the constraints in the wide adoption of dryers in the country, another strategy PhilRice has adopted is to encourage farmers and traders adopters to construct some of the parts of the dryers to further reduce the cost (following PhilRice specifications). This is one major reason for the adoption in the design of a concrete bin (utilising hollow blocks and cement) which ordinary farmers can construct or which others may already have (i.e. pig pens that could be converted during periods when drying is needed). The use of existing prime movers, normally diesel engines from hand tractors, is also being encouraged to further reduce farmer investment. Thus, only parts such as fan assembly, furnace, and the perforated screen are purchased at the recommended PhilRice cooperators.

In the dissemination of the Maligaya flat-bed dryer design, the following are important aspects being considered:

1. *Training operators* is an important component of dissemination that must always accompany installation of new dryer set-ups. At PhilRice, this training includes familiarisation with drying procedures and furnace operation, adjustment procedure for drying temperature, briefing on critical factors such as effect of temperature, and moisture content determination.
2. *Technical assistance* in the construction and manufacture of dryer components and in the initial operation. With the 6 t flat-bed dryer, assistance is needed in the construction of the furnace and in provision of jigs for the construction of the fan assembly. Testing of every set-up is also part of the dissemination strategy in order to monitor the performance of newly-installed set-ups in the sites, as well as assuring adopters of the presence of technical assistance.
3. *Monitoring of the performance of the dryer* is an important component of dissemination in order to determine if adjustments are needed, to meet problems, and to assure users of its good performance.

Factors to be considered in the introduction of furnaces include:

1. *Time taken for ignition/combustion.* Normally, operators and dryer users are particularly interested in the time for ignition for such rice-hull furnaces, especially if this time is characterised by exposure of the operator to heat and excessive smoke. To shorten ignition time, training for operators should be included in the dissemination of the system.
2. *Smoke generation.* Smoke during ignition cannot be avoided, but it is important that it be minimised and not directed to the grain in the bin to prevent any undesired odour in the product which may, in turn, reflect poorly on the whole system.
3. *Continuity of feeding.* Farmers normally prefer rice-hull furnaces (and dryers) which can be operated continuously for maximum efficiency and to minimise ignition. This is one constraint of the gasifier–combustor which has to be fed and cleared of ash in batches (although ignition is a lot faster with succeeding batches).
4. *Temperature control.* Because of varying paddy condition and desired operating requirements for the paddy output, e.g. seed drying, it is essential that furnaces should have some degree of control of temperature output. It is important that every dryer installed be fitted with a temperature gauge.

Strategy of promotion

With the flat-bed dryer cum inclined grate furnace. During the initial promotion activities, the target group was the seed growers and cooperatives who could afford the dryer and who have an incentive for drying. Initial information dissemination activities included the following:

- print material development and dissemination (bulletin, leaflet);
- video development (with an NGO and Philippine Channel 5) and a feature shown on TV;
- promotional briefings and actual demonstration (whenever practical) during seed grower trainings and farmer visits which are regularly done at PhilRice; and
- custom drying at PhilRice to make seed growers in the adjacent community aware of its advantages.

The focus of PhilRice at present is to set up demonstration units for each of the 14 regions of the country. It is expected that with actual units operating in the sites, farmers will become more aware of the improved flat-bed dryer.

In addition, PhilRice has chosen the Maligaya flat-bed dryer design for equipment loan (without interest, 5 years to amortise on seasonal payments) to farmer cooperatives and paddy seed growers. The loan program has already started with the promotion of the technology to regional and local extension engineers in the country.

With the combustor coupled with the flash dryer. Another agency, NAPHIRE, does the dissemination of the flash dryer-cum-combustor (in addition with other commercial furnaces) which was linked by PhilRice to one cooperating manufacturer who has mass produced the system. NAPHIRE has included the flash dryer with combustor in the Department of Agriculture's Grain Production Enhancement Program which selects farmer cooperatives for grants or loans in the form of postharvest equipment such as the dryer.

In commercialising the dryer-cum-gasifier, one concern being attended to by the manufacturer is the need to closely monitor the quality of mass-produced combustors (and dryers), which is perceived to be a constraint to wide acceptance, and the follow up training of cooperative operators. Another concern is the reduction of its ignition time, which with earlier prototypes took at most 15 minutes only but now takes up to 1 hour.

Local adoption

The dryer is being promoted to adopters who finance the whole dryer but with technical assistance from PhilRice.

The adoption of the dryer has peaked this season, with new installations in Northern and Central Luzon, Southern Tagalog, and Mindanao. There are several units that were installed last year by two seed growers, one local government unit (for demonstration), and one university (for commercial seed production). The university unit is also being used for seed maize drying while another local government unit, located in the middle of large banana plantations, was used on one occasion for drying banana chips (one farmer entrepreneur is planning to set up the same dryer solely for such purpose).

New installations are being made this season for private paddy traders (three units with one for both paddy and maize), two farmer cooperatives (one plans to explore its use for copra drying also), three progressive farmers, and two other seed growers. Inquiries are still pouring in this season. Because it is still the cheapest available dryer (in terms of investment cost/unit of paddy) and the simplest to operate and maintain, it is expected that the design will continue to become popular in the coming years with careful introduction from PhilRice.

Summary and Conclusions

Rice hulls offer the best fuel potential for paddy drying during the wet season harvesting in the Philippines. Several rice-hull furnaces were adapted and modified at PhilRice for this purpose. The inclined grate furnace, a modification of the IRRI BD-2 furnace, coupled to a 6 t capacity flat-bed dryer, has a feeding capacity of about 35 kg/hour and furnace efficiency of 50 to 80%.

The ITDI gasifier combustor, adapted for flat-bed drying and flash drying, operates on the principle of downdraft gasifier and, with a feed rate of 40 kg of rice hulls per batch, can generate heat output of 200,000 kJ/hour. Coupling with a 2 t flat-bed dryer resulted in a drying air temperature of 40 –45°C and drying air efficiency of 20–31%.

The Zeta furnace jointly developed with IRRI for low-temperature drying operates on the principle of thin layer of combustion. Its feed rate of 3–10 kg/hour resulted in a burning efficiency of 90–95% and drying air efficiency of 40 –80% when coupled with a 5 t in-bin drying and storage system.

Adaptation and commercialisation of the first two furnaces for paddy drying have already been implemented and their increasing acceptance is encouraging. Numerous units have already been installed in various localities. Promotion of these technologies included information, demonstration in pilot areas, and training and technical assistance to prospective farmer owners.

References

Aldas, R.E., Gummert, M., Lantin, R.M., and Herrera, A. 1995. Rice hull furnaces for low temperature drying. Paper presented at the 17th ASEAN Technical Seminar on Grain Postharvest Technology, 25–27 July 1995, Lumut, Perak, Malaysia.

Beagle, E.C. 1978. Rice husk conversion to energy. Rome, FAO Agricultural Services Bulletin No 31.

Gagelonia, E.C. 1993. Adaptive and optimization tests of the Industrial Technology Development Institute (ITDI) rice hull combustor for palay drying. Unpublished MS thesis, Central Luzon State University, Muñoz, Nueva Ecija.

IRRI (International Rice Research Institute) 1979. Rice hull furnace development and testing. In: Annual Report for 1978. IRRI, Los Baños, Laguna, Philippines, 429–430.

Muhlbaüer, W., Maier, G., Bergotz, T., Esper, A., Quick, G.R., and Mazaredo, A.M. 1992. Low-temperature drying of paddy under humid tropical conditions. In: Proceedings of the International Agricultural Engineering Conference, Asian Institute of Technology, Bangkok, Thailand, 7–10 November 1992.

Phan Hieu Hien 1993. Rice husk combustion systems for crop drying. Unpublished PhD Dissertation, University of the Philippines, Diliman, Quezon City.

Tam, N.H., Gagelonia, E.C., Regalado, M.J.C., and Bautista, E.U. 1995. Optimizing the performance of the Maligaya flat bed dryer. Paper presented at the 8th National R&D Planning Workshop, Philippine Rice Research Institute, Muñoz, Nueva Ecija, 1–3 March 1995.

Drying Maize and Maize Seed in Vietnam

Bui Huy Thanh and Le Doan Dien*

In recent years, maize production in Vietnam has expanded, especially hybrid maize. Drying maize and maize seed are urgent problems in Vietnam because the crop is harvested in the rainy season, and dryers have not yet been accepted by farmers.

Our research has sought to determine the most suitable practical designs of facilities for farmers drying maize and maize seed. In this paper, we present some designs of flat-bed dryers for maize and maize seed. These dryers are locally manufactured and were installed at 15 locations in the north of Vietnam in 1995.

The capacity of flat-bed dryers for maize on the cob is 45 t per batch and for grain is 25 t per batch. The drying bin is made of brick, timber, and bamboo. The perforated floor is made from timber and bamboo. Coal was used as fuel for the burner.

The airflow rate was 660 m^3/t.hour with a drying air temperature of 38–42°C. The fan was driven by a 20 kW electric motor. It took 62–70 hours to dry cobs from 32–35% moisture content (wet basis) to 18%, and 50 hours to dry grain from 18 to 10.5% m.c. The drying cost was about US$3.30/t of seed. Total investment for this dryer was about US$1700.

A flat-bed dryer for maize grain with an airflow rate of 1250 m3/t.hour took 4 hours to dry maize from 19 to 14% m.c. at a drying air temperature of 75–80°C. Specific energy consumption was about 7.29 MJ/kg water evaporated. Drying cost was US$1.80/t. Total investment was about US$1100.

These dryers, with their low operating cost and low initial investment have been accepted by farmers for drying maize and maize seed, especially by the small-scale private sector and seed-processing plants in Vietnam.

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Commercialisation of a Mobile Flash Dryer for Farmer Cooperatives

Manolito C. Bulaong, Renita Sm. Dela Cruz, and Silvestre C. Andales*

DRYING of wet grains has been a problem besetting the Philippines' postharvest industry. Farmers and other sectors in the industry often suffer because of failure to immediately dry wet season crops. This is because the peak of the harvest season coincides with the rainy months when sun drying cannot be depended on.

Mechanical drying offers an alternative for drying grains, especially during uncertain weather conditions. However, the practice did not gain ready acceptance, for reasons such as the high cost of fuel and other operating expenses, incompatibility of dryer operation to the volume of paddy to be dried, and the lack of knowledge on dryer operation and maintenance (Cardiño et al. 1989). To address this problem, the National Postharvest Institute for Research and Extension (NAPHIRE) and the Australian Centre for International Agricultural Research (ACIAR) collaborated to develop a drying technology—the mobile flash dryer (MFD)—that will be accessible and compatible with the level of operations on farms.

Technology Generation

A project funded by ACIAR and conducted by NAPHIRE resulted in the development of a two-stage drying strategy using the 'flash drying' technique in the first-stage, and in-store drying in the second-stage (Tumambing and Bulaong 1988). This technique dries the paddy to a more manageable moisture content (m.c.) of 18% using high drying air temperature, enabling fast drying rates and more efficient heat energy utilisation. At this moisture level, paddy can be stored for about three weeks, allowing enough time to wait for either the availability of sunlight for sun drying or for the second-stage of mechanical drying to completely dry the grains to 14% m.c.

In 1990, a prototype batch-type model of a mobile flash dryer (MFD) was developed and, after preliminary field tests and using feedback from farmers, an improved model was built in 1991. The enhanced model is a continuous-flow type with cooling and heat recycling systems and an elevator to facilitate loading of grains. After a satisfactory result from the pilot testing, the technology was promoted and commercialised in 1992 (Bulaong et al. 1992).

Improvements were further identified in the continuous-flow type model at its early commercialisation stage. All possible design improvements were introduced to some of the cooperating manufacturers who have the capability to do machinery design and development. As a result, the continuous-flow flash dryer underwent further improvements from the cooperating manufacturers. Thus, a model with enhanced overall performance and versatility is now available.

The latest model can be used as a flash dryer or as a recirculating batch dryer heated by either a pot-type kerosene burner or a rice-hull furnace.

Technology Package

Features and components

The MFD allows on-farm and off-farm drying of paddy. Its main components are (see also Fig. 1):

- rice-hull furnace—used for stationary drying operations;
- kerosene burner—used as an auxiliary burner for mobile drying operations;
- centrifugal blower—powered by a 5 h.p. gasoline or diesel engine;
- drying section—composed of an upper and lower drying section with heat recycling mode;
- cooling system—cools the grain before discharge, and recycles heat into the drying section;
- loading system—composed of a loading hopper and a bucket-type elevator;
- unloading system—oscillating hopper;
- recirculating chute—recycles undried grain back to the drying section.

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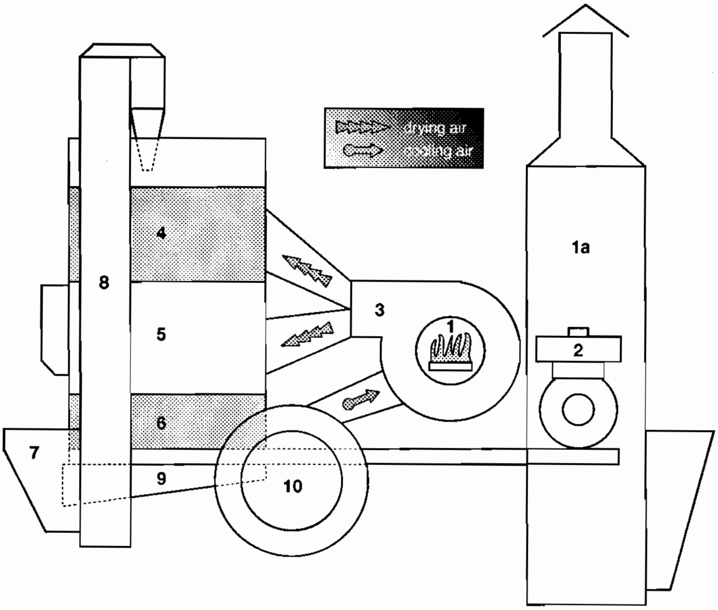

Figure 1. Schematic diagram of the Mobile Flash Dryer showing the principal components. (1) kerosene burner; (1a) rice-hull furnace; (2) engine; (3) centrifugal blower; (4) upper drying section; (5) lower drying section; (6) cooling section; (7) loading hopper; (8) elevator; (9) unloading hopper, and; (10) pneumatic tyre.

The dryer is simple in construction and uses locally available materials. This makes its cost relatively low and it can be fabricated by local manufacturers. Table 1 presents the design features and specifications of the dryer.

Principles of operation

Flash dryer. The wet paddy is continuously fed from the loading hopper and is subjected to temperatures of 80–90°C for 15–20 minutes. As the grain passes through the drying column, heated air crosses both sides of the grain column, outwards in the upper section, and inwards in the lower section (Fig. 2). This minimises the moisture content gradient common to high temperature drying. The grain is cooled in a cooling section before being discharged at the unloading hopper. Heat retrieved in the cooling section is recycled to the drying section, resulting in more efficient heat utilisation. Grain is fed into the dryer continuously, at the same time as semi-dried grain is being discharged.

Recirculating batch dryer. Wet grains are continuously recirculated into the drying bin until semi-dry or dry. Flash drying using drying temperatures of 80–90°C is applied to grains with an initial moisture content above 18%. When drying grains of 18–19% m.c., the drying temperature is reduced to 40–60°C. When drying from 18 to 14% m.c., exhaust air from the lower drying section can be optionally recycled to the system, resulting in greater heat efficiency in the drying operation.

Dryer operation

The dryer is powered by a 5 h.p. gasoline or diesel engine or a 2 kW electric motor which drives the blower, bucket elevator, and the unloading hopper. In operation, the grain is fed into the unloading hopper where it is picked up by the bucket elevator and poured into the drying column at a rate of at least 1 t/hour. Once the drying column is full, the engine is temporarily shut off to allow firing of the kerosene burner or rice-hull furnace for 5 or 15 minutes, respectively. With a steady flame from the burner or furnace, the engine is again started and the blower is engaged. The blower is set to operate at 2500 rpm.

The fuel feed rate is increased until the desired drying air temperature is reached, as indicated by a dial thermometer placed along the hot air duct. The required drying temperature depends on the initial moisture content of the paddy to be dried. When used as a ‘flash dryer’ (drying wet paddy to 18% m.c.) the air temperatures used for paddy with various ranges of moisture content are as follows: 80–90°C for 25–30% m.c. (very wet); and 70–80°C for 23–24% m.c. (wet). Drying 18–20% (skin dry) paddy to 14% m.c. will require 40–60°C. When drying paddy for seed, the temperature should not exceed 43°C for all moisture content levels.

Table 1. Design features and specifications of the mobile flash dryer.

Type	Continuous flow or recirculating batch
Height	2.5 m (without elevator)
	3.5 m (with elevator)
Width	1.0 m grain bin only
	1.5 m including wheels
Length	3.0 m overall length
	1.25 m bin only
Drying bin	Vertical, columnar mixing type with heat recycling system
Capacity	10–12 cavans (1 cav = 50 kg) of palay/hr at 70–80°C at 6% moisture extraction/hr
Power requirement	Minimum 5 h.p. engine
Heating system	Evaporating pot-type kerosene burner or rice-hull furnace
Blower	Centrifugal backward inclined, 3000 CFM at 1" stat. pressure
Temperature indicator	Dial thermometer
Elevator	1 t/hr, bucket-type
Engine (fuel) consumption	1.2 to 1.5 litres regular gasoline/hr
Burner (fuel) consumption	3–4 litres kerosene/hr at 70–80°C
	18–20 kg/hr rice hulls at 80–90°C
Labour requirement	At least 3 persons
Other features	a) Exhaust air recycling system
	b) Cooling section
	c) Grain recycling system

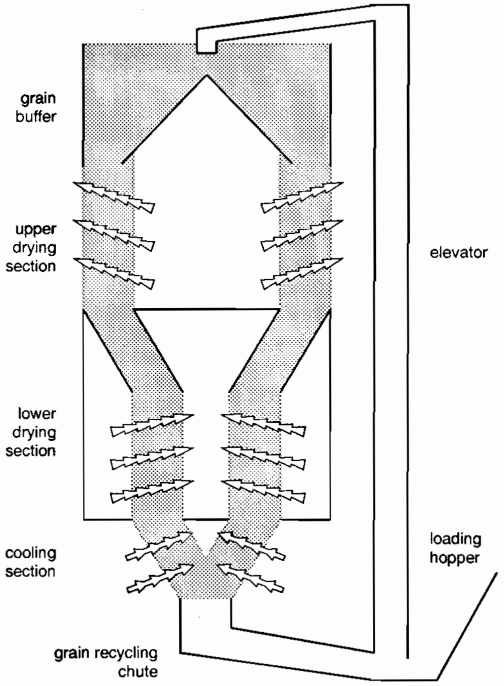

Figure 2. Schematic diagram of the Mobile Flash Dryer drying column.

The grain can be automatically recycled to the drying column if the required final moisture content has not been reached. This is done by closing the unloading hopper and diverting the grain back to the elevator by means of an oscillating sliding chute. For recirculating or multipass operation, the drying air temperature is correspondingly decreased as the grain moisture content decreases.

Once the desired moisture level is reached, the unloading hopper is opened slowly to start discharging the grain. The retention time of the grain inside the drying column can be controlled by the discharge rate. Discharge rate can be varied by means of a crank which adjusts the opening of the discharge hopper.

Viable drying scheme

The technology is cost-effective to operate as a two-stage drying scheme (MFD + sun drying, or MFD + in-store drying). Using MFD as the sole means of drying cuts its capacity by half and results in higher operating costs due to lower output.

Economic returns

The MFD with a convertible kerosene burner and rice-hull furnace (because of its bulk, use of the latter necessitates operation of the dryer as a stationary unit) costs approximately PHP110,000 (during October

1995, ca 25 Philippine pesos (PHP) = US$1), including a 5 h.p. gasoline engine. Table 2 gives a cost and return analysis for the MFD considering two utilisation rates and based on a custom-drying scheme at a drying fee of PHP12.00/cavan (1 cavan = 50 kg). The data indicate a reduced unit cost of drying and a correspondingly higher return on investment with an increase in annual utilisation rate. Using a rice-hull furnace, although it has a higher investment cost, results in the lowest drying cost of PHP5.51/cavan for 120 days use each year.

The data imply that the operation of the technology will be more profitable in areas with relatively long wet seasons which will require a longer dryer utilisation.

Table 3 illustrates the various options of a farmer in selling his paddy. He can either sell it wet, sell it dry using the MFD, or wait for the sunshine and risk deterioration. Using the MFD and sun drying combination gives the farmer greater profit than selling wet or selling dry but damaged grain.

Table 2. Cost–and–return analysis of the mobile flash dryer at varying utilisation rates in drying paddy grain from 23–24% initial moisture content to 18–20% m.c.

Heating unit	Rice hull furnace	Kerosene burner	Rice hull furnace	Kerosene burner
Annual utilisation rate, days[a]	60	60	120	120
Annual capacity, cavans[b]	10,560	10,560	21,120	21,120
Total investment cost, pesos	110,000	85,000	110,000	85,000
Dryer unit	65,000	65,000	65,000	65,000
Engine, 5 h.p. gasoline	10,000	10,000	10,000	10,000
Dryer shed	10,000	10,000	10,000	10,000
Rice hull furnace	25,000	–	25,000	–
Total fixed cost, pesos/year	27,280	21,080	27,280	21,080
Depreciation[c]	9,900	7,650	9,900	7,650
Interest on average capital invested[d]	9,680	7,480	9,680	7,480
Repair and maintenance[e]	5,500	4,250	5,500	4,250
Taxes and insurance[f]	2,200	1,700	2,200	1,700
Total variable cost, pesos/year	44,576	83,016	89,153	166,032
Labour[g]	26,400	26,400	52,800	52,800
Rice hull[h]	1,080	38,400	2,160	76,800
Gasoline[i]	14,400	14,400	28,800	28,800
Miscellaneous[j]	1,256	2,376	2,512	4,752
Oil and grease[k]	1,440	1,440	2,880	2,880
Total drying cost, pesos/year	71,856	104,096	116,433	187,112
Drying cost, pesos/cavan ($[l]/cavan)	6.80 (0.26)	9.86 (0.38)	5.51 (0.21)	8.86 (0.34)
Drying fee, pesos/cavan ($/cavan)	12.00 (0.46)	12.00 (0.46)	12.00 (0.46)	12.00 (0.46)
Total net income, pesos	54,863.60	22,598.40	137,007.20	66,316.80
Return on investment, %	49.88	26.59	124.55	78.02
Payback period, years	2.00	3.76	0.80	1.28

[a] Based on 16 hours/day operation
[b] 50 kg/cav at 11 cavan/hour capacity from 23–24% initial m.c. to 18–20% final m.c.
[c] Straightline method, 10% salvage value, 10 years life span
[d] 16% interest rate per year
[e] 5% of investment cost
[f] 2% of investment cost
[g] 3 persons at 2.50 pesos/cavan input
[h] 20 kg/hour at 0.025 pesos/kg
[i] 1.5 litres at 10 pesos/litre at 16 hours/day
[j] 3% of labour and fuel costs (for towing and other incidental expenses due to variation of days of utilisation
[k] 10% of gasoline cost
[l] The conversion rate used was 25 pesos to US$1.

Table 3. Comparison of costs of various drying options during wet season harvest.

Drying option	Final m.c.[a] %	Selling cost pesos/kg ($/kg)	Weight when sold[b] kg	Gross income pesos/cavan[c] ($/cavan)	Drying cost pesos/cavan ($/cavan)	Net income pesos/cavan ($/cavan)
1. Sell wet	24	4.0 (0.15)	50.0	200.0 (7.69)	0	200.0 (7.69)
2. Sell dry but damaged	14	5.0 (0.19)	44.2	221.0 (8.50)	10 (0.38)	211.0 (8.12)
3. Flash dry and sun dry	14	6.0 (0.23)	44.2	265.2 (10.20)	16 (0.62)	249.2 (9.58)
4. Flash dry to 18%	18	5.5 (0.21)	46.3	254.9 (9.80)	12 (0.46)	242.9 (9.34)
5. Flash dry to 14% m.c.	14	6.0 (0.23)	44.2	265.2 (10.20)	25 (0.96)	240.2 (9.24)

[a] From initial moisture content of 24%.

[b] From initial weight of 50 kg.

[c] One cavan = 50 kg.

Commercialisation

Credit assistance

The Land Bank of the Philippines (LBP) forged an agreement with NAPHIRE in 1991 for a credit assistance program to farmer cooperatives that wish to purchase NAPHIRE-designed improved postharvest technologies. LBP provides the financial resources while NAPHIRE gives the technical assistance to these cooperatives.

Accredited manufacturers

Recognising that cooperative development of machinery by both the research institution and the manufacturers is a highly effective method for successful technology development and transfer, NAPHIRE enlisted the participation of eligible machinery manufacturers in building the dryer. From among the 35 manufacturers who have signified their intention to build MFDs, NAPHIRE has selected and accredited 12 manufacturers (Table 4). Accreditation of manufacturers is a continuing activity of the Training and Extension Department of NAPHIRE.

Commercialized units

As of December 1994, 385 units of flash dryers have been sold. The units marketed have been adopted by cooperatives throughout the Philippines as beneficiaries of the Grains Production Enhancement Program (GPEP) of the government.

Aside from GPEP, the mobile flash dryer has been selected by cooperating government agencies of the GPEP Postharvest Component including local government units to be the type of dryer disseminated to eligible cooperatives.

Table 4. List of fully accredited manufacturers of flash dryers in the Philippines.

1.	**CMC Metal Craft**	Bayugan, Agusan del Sur, Philippines.
2.	**Emerald Machinery Sales, Inc.**	Diamond Motor Service Bldg., 41-B Serrano Ave. Quezon City.
3.	**Gregorio Danganan Welding & Repair Shop**	3438 Liboro St., Pag-asa, San Jose, Occidental Mindoro.
4.	**Josian International Machines**	Maahas, Los Banos, Laguna.
5.	**KATO Machineries**	Manila.
6.	**Los Banos Agricultural Machineries**	Maahas, Los Banos, Laguna.
7.	**Mateo Tayag Metal Craft**	Juan Luna St., San Jose, Occidental, Mindoro.
8.	**Morallo Iron Works**	661 Highway 1, San Miguel, Iriga City.
9.	**MTP Metal Craft**	Turayong, Cauayan, Isabela.
10.	**Prime Index Philippines**	1651 Oroquieta St., Sta. Cruz, Manila.
11.	**R & B Metal Craft c/- Equity Enterprises**	Cauayan, Isabela.
12.	**ROPALI Trading Corporation**	Cauayan, Isabela.
13.	**Tropics Agro-Industries, Inc.**	25 Panganiban St., Naga City, Camarines Sur.

References

Bulaong, M.C., Paz, R.R., Anchiboy, T.F., and Rodriguez, A.C. 1992. Development and pilot testing of the NAPHIRE mobile flash dryer. Muñoz, Nueva Ecija 3120, Philippines, NAPHIRE, Technical Bulletin No. 14.

Tumambing, J.A. and Bulaong, M.C. 1988. Drying in bulk storage of high moisture grains in tropical climate. Muñoz, Nueva Ecija 3120, Philippines, NAPHIRE, Project Terminal Report.

Grain Condition Monitoring and Aeration Control Systems

Cao Guanzhi*

THE Grain Condition Detection, Analysis, and Ventilation Control System (GCDAVCS) can monitor remotely the temperature and humidity of a grain mass. The computer controls detection of grain conditions and determines the requirements for aeration, temperature change, and moisture adjustment. Depending on the conditions provided by the host computer (control unit), the substations then provide dynamic real time and closed-loop control through the software of the aeration model.

Operational Procedure

The GCDAVCS transmits the field signals to the host computer, through the sensors, substations (data collectors), and double twist wires in a predetermined sequence. The host computer then computes the aeration necessary based on the information provided. To improve the calculation, the analysis of the grain mass is done by a mathematically-based model. Figure 1 shows the components and arrangement of the GCDAVCS.

Main Functions

Timing of the data collection

If the time for reading of the sensors in the detection circuit is set, the GCDAVCS units will operate automatically at that time every day. The host computer will store data for three days and it can be saved and printed.

Real time data recovery

Operators can read the sensors at any time when the detection circuit is not operating (including grain and air temperatures and humidities).

Grain condition dynamic intelligent analysis

Compared with the use, collection and analysis of temperature information by hand, GCDAVCS has been an important breakthrough. With its analysis based on artificial intelligence and fuzzy logic, GCDAVCS can analyse the grain temperature range present and detect signs of heating using the special mathematical model for changing patterns of conditions in grain. The model induces automatically the local temperature change patterns and modifies the temperature curves to forecast the limit of the temperature trend and its pattern of change. Three dimensional pictures are used to provide easily seen illustrations of the temperature change.

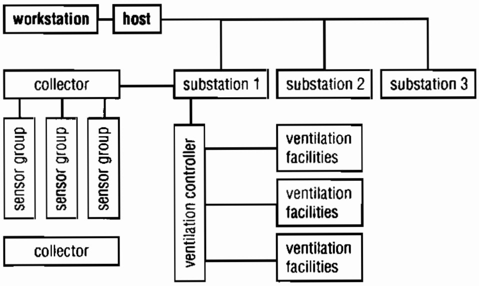

Figure 1. Diagram of the Grain Condition Detection, Analysis, and Ventilation Control System (GCDAVCS).

Intellgent automatic aeration control

Because of the equations and data provided by the 'Mechanical Ventilation of Provision Reserve Technical Rules,' the GCDAVCS does not require operators to calculate the equilibrium humidity and temperature difference for aeration air to establish the required temperature and humidity differences in the grain mass. Thus, mechanical ventilation (aeration) can be controlled automatically by the GCDAVCS if the storage identification number, grain present, its

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moisture content and the purpose of the aeration (lowering temperature, reducing moisture contact, or adjusting) are put into the computer. In this way, condensation is prevented during aeration.

Practical Application

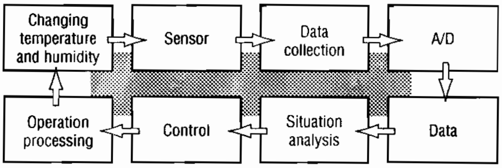
The field signals by the collector substations of temperature, humidity, A/D converter and data can be computed into the control substations independently. Each substation may cut short the reading of the circuit of sensors. They also send out on/off signals to the aeration controllers according to the aeration conditions required by the central host computer. Store keepers can thus program sensor monitoring and aeration control off line from the network. When grain temperature is being reduced and aeration is carried out according to the 'Mechanical Ventilation of Provision Reserve Technical Rules', the allowable temperature conditions are: at the beginning, $T_2 - T_1 \geq 8°C$ (subtropical zone $T_2 - T_1 \geq 6°C$); during the course $T_2 - T_1 \geq 4°C$ (subtropical zone $T_2 - T_1 \geq 3°C$); where T_2 is the average temperature in the grain mass (°C); and T_1 is the air temperature (°C) outside the granary.

The allowable humidity conditions for temperature reduction with aeration are: below the interstitial grain temperature, the equilibrium absolute grain humidity, PS_2, is higher than the interstitial absolute air humidity PS_1, that is, $PS_2 > PS_1$. To end the temperature reduction with aeration, the condition is $T_2 - T_1 \leq 4°C$ (subtropical zone, $T_2 - T_1 \leq 3°C$); the temperature gradient of the grain mass ≤ 1°C/m grain layer thickness: the grain mass moisture gradient ≤ 0.3%/m grain layer thickness. The conditions for moisture reduction and aeration vary among grains. During moisture reduction with aeration of wheat of moisture content below 16%, late rice below 18%, maize below 20%, beans below 18%, and rapeseed below 12%, the allowable humidity conditions for moisture reduction and aeration are: grain moisture reduces 1%; grain temperature = grain average temperature T_2 > air dew-point temperature T_{11}, that is, $T_2 > T_{11}$.

The allowable temperature conditions for moisture reduction with aeration are: grain moisture reduces 1% and grain temperature = air temperature T_1; equilibrium absolute grain humidity PS_{21} > interstitial absolute air humidity PS_1, that is $PS_{21} > PS_1$. When the aeration air is introduced to the bottom layer of the grain the drying front moves through to the top grain layers. When the aeration air is sucked from the bottom layer, the drying front moves to the bottom of the mass and when the grain temperature gradient ≤1°C/m grain layer thickness, the aeration should be stopped.

Temperature and moisture adjustment with aeration must be done before grain processing. The allowable conditions for adjusting temperature with aeration are: the average grain temperature T_2 > air dew-point temperature T_{11}, that is, $T_2 > T_{11}$. After aeration, the upper grain mass temperature should not exceed the safe storage temperature after the moisture content of the grain mass has increased. The allowable humidity conditions for adjusting moisture content with aeration are: the grain moisture increasing 2.5% and the grain temperature = air temperature T_1; the equilibrium absolute humidity PS_{22} < the interstitial absolute air humidity PS_1, that is, $PS_{22} < PS_1$. When the moisture content of the grain mass reaches the required level, it should be below the safe reserve moisture level, with the grain mass moisture gradient ≤ 0.5/m grain layer thickness; and the grain mass temperature gradient ≤ 1°C/m grain layer thickness. At this point the aeration should be stopped.

Using the above-mentioned principles, the intelligent automatic aeration control system can operate on many automatic aerated storages at the same time. When the storage identification number, grain present, its moisture content, and the purpose of the aeration are put into the computer, the GCDAVCS uses this information to provide dynamic real time control for monitoring of conditions and automatic operation of the aeration. The working diagram (see below) is a control circle.



Data collection is done once every two minutes monitoring the temperature changes. After the control information is programmed into the computer, the substations collect temperature and humidity of the ambient air and the temperature of the grain to enable calculation of the relative equilibrium humidity, the absolute humidity and the grain mass dew point. Aeration is then done according to the following:

Aeration Purpose	Allowable conditions for aeration	
Temperature reduction	The first temperature difference and the operating tempering difference $PS_1 < PS_2$	
Moisture reduction and adjustment	$PS_1 < PS_3$ $PS_1 > PS_5$	$T_2 > T_4$ $T_2 > T_4$

T_1 Air temperature; T_2 Grain mass temperature; PS_1 Air absolute temperature; PS_2 Below the interstitial grain temperature, the equilibrium absolute grain humidity; PS_3 When the grain temperature is close to the air temperature, the grain moisture w%–1% to the equilibrium absolute humidity; T_4 Air dew-point; PS_5 When the grain temperature is close to the air temperature, the grain moisture w% + 2.5% to the equilibrium humidity.

Summary

Advanced mathematical models are used to manage grain conditions and provide dynamic real time control of aeration. This automatic control replaces the experienced technicians in analysis, collection of data, and decision making. Because of the large quantities of data involved, the mathematical model for grain monitoring and analysis of grain conditions is installed in the computer. The model for aeration control can be installed in the substations. Because of the differences in grains involved, their moisture and the purpose of the aeration, the substations work independently. If the central host computer is out of order, the substations can still operate. The system is now widely distributed, being installed in about 100 state grain reserve depots. The results have all been good.

Bibliography

Department of Provision Management, State Grain Provision Reserve Bureau n.d. The Chinese Grain Reserve Encyclopedia.

Use of Rice Husk Gasification in Grain Drying

Chen Zhishun*

JIANGSU is one of the important agricultural provinces of China producing on average 32 Mt of grain. Some 8 Mt of this is held in storage. Jiangsu is located on the east coast of Asia and is seasonally very hot and humid.

A recent estimate located nearly 750 grain dryers of diverse type in the province. This accounts for about 30% of the total number of dryers in China. Of these, there are 580 fluidised-bed dryers with the balance being rotary dryers, steel tower dryers, flat dryers, vibrating fluidised-bed dryers, and infrared dryers. These units handle on average, 1 Mt of wet grain annually. Performance data for the three main types of dryer are given in Table 1.

Jiangsu has a large amount of storage with varied facilities using appropriate methodology for handling the wet grain in an area which, as indicated above, is seasonally very hot and humid. It is typical of China.

Rice Husk Gasification for Grain Drying

The yearly average of 1 Mt of wet grain being dried by the 750 dryers consumes 24 000 t of fuel. It is thus very important and urgent to exploit renewable resources to replace the fuel oil and coal which are in short supply and expensive. Grain dryers are commonly located near rice mills which produce large quantities of husk residues. This rice husk may be regarded as an appropriate and cheap source of heat energy for drying grain.

Jiangsu province consumes approximately 18 500 t of rice husk each year for drying grain. This accounts for 77% of the total fuel consumption in the province for grain drying and 90% of national use of rice husk for this purpose.

Four types of rice husk furnace were designed to match the growth of the grain drying in the rice industry:

(i) Manually operated furnace constructed of brick
(ii) Manually operated furnace fabricated from metal
(iii) Down-draft rice husk gas producer
(iv) Up-draft rice husk gas producer.

The following is a brief introduction to the operation of these types of furnace.

Manually operated furnaces

This type is commonly installed in primary grain depots. The facilities have low construction costs, are convenient in operation, and have a higher calorific efficiency. They have a brick or metal casing with the furnace body comprising a burning chamber and a mixing chamber

Rice husk gasification units

A unit consists of a rice-husk gas producer, a conditioning drum, and a burning chamber. The unit supplies steady heat to the grain dryer and its main advantage is that it does not pollute the dried grain. In a random sampling test, the BaP content of the grain is nearly constant at 0.72 ppb before and after drying whereas with hard coal and rice husk tunnel gas the BaP content increases to 1.28 ppb and 2.05 ppb respectively.

The gasification process

Rice husk is fed from the top of the furnace into the reaction chamber and the producer gas led to the conditioning drum for storage and thence to the burning chamber. The producer gas is mixed with air and burnt in the 'heat exchanger' to produce high temperature flue gas which is then mixed with twice the volume of air and then used as the heat source for drying the grain.

The reaction in the gas producing furnace is divided from top to bottom according to temperature into a drying layer, a distillation layer, and an active gasification layer. The reaction formulae are as follows:

$$\begin{aligned} C + O_2 &= CO_2 + 97{,}650\ \text{kcal} \\ C + 1/2O_2 &= CO + 29{,}430\ \text{kcal} \\ C + CO_2 &= 2CO - 38{,}790\ \text{kcal} \\ C + H_2O &= CO + H_2 - 28{,}800\ \text{kcal} \\ CO + H_2O &= CO_2 + H_2 + 9{,}849\ \text{kcal} \end{aligned}$$

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Table 1. Test data of the three main types of dryer

Types	HH32x320 Fluidised-bed dryer	HY125x10 Rotary dryer	HLZ-30 Netted Column dryer
Capacity (t/h)	7.80	15.08	11.64
Moisture removal (%)	2.07 (15.92–13.85)	3.33 (18.03–14.70)	2.20 (16.2–14.00)
Fuel	Rice husks	Coal	Coal
Fuel consumption (kg/h)	85.2	122	58.8
Energy consumption in water removal (kcal/kg water)	1321	1079	1023
Breakage rate (%)	+1	+2.5	+0.5

Table 2. Analysis of rice husk

Components	Content (%)
Water	11.66
Volatiles	55.62
Fixed carbon	16.33
Ash	18.32
Calorific value	2960 kcal/kg

There are two types of gas producer: the down-draft and the up-draft system.

The down-draft rice husk gas producer

The body of the producer is the gasification chamber. The top is open for feeding in the rice husk and air. There is a gas outlet in the jacket of the furnace to remove the producer gas and the bottom of the chamber is sealed with water to prevent explosions.

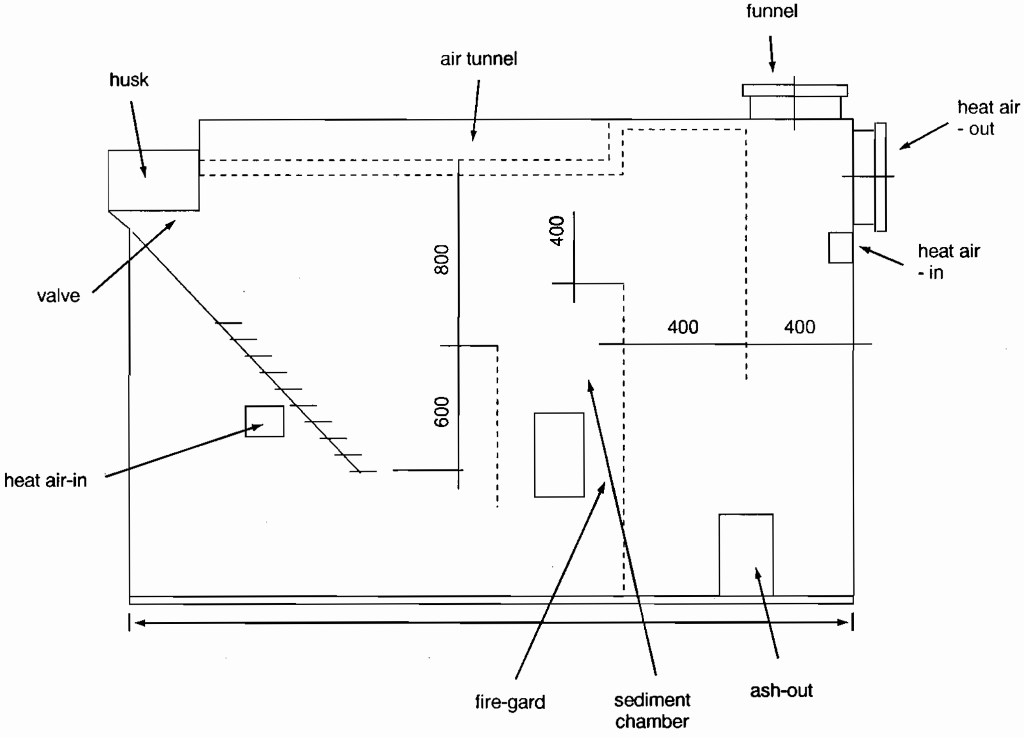

Figure 1. Manually operated furnaces for rice husk.

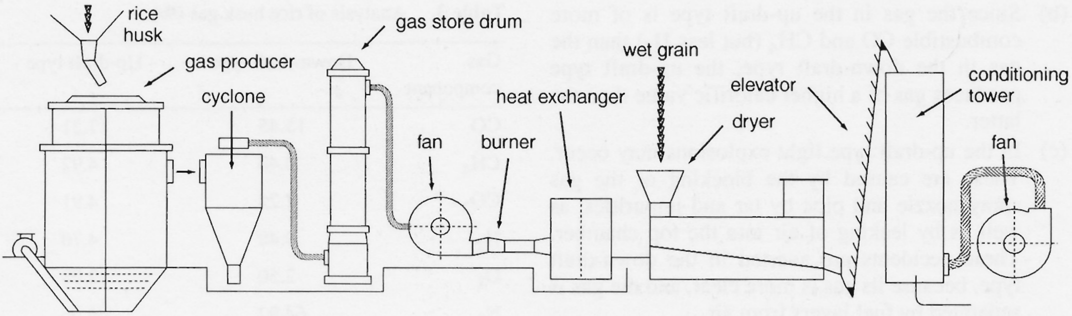

Figure 2. Integration of rice-husk gasification into grain drying

Ash falls into the water through the grate at the bottom of the chamber and is removed by a screen conveyor. The body of the furnace is filled with a water-jacket for heat insulation. A fan assists starting the combustion process and moving the gas when the unit is operating.

The up-draft rice husk gas producer

This is another application of the gasification system for indirectly drying grain. The air-flow is in the reverse direction to that of the previous gas producer and construction is different. The furnace cover is sealed and is blown by a fan from the bottom of the chamber. After the several reactions as in the down-draft process, the gas is drawn off from the empty space in the top of the reaction chamber and passed to the conditioning drum and then burnt to dry the grain.

A comparison between the down-draft and up-draft gas producers

(a) Gasification strengths are respectively 132 kg/m^2h for the down-draft type and 149 kg/m^2h for the up-draft type. This indicates that the dimensions of the second type may be reduced by 10% to reduce costs. In such modification of design, however, attention should be paid to the attenuation of calorific efficiency in that type of gas producer.

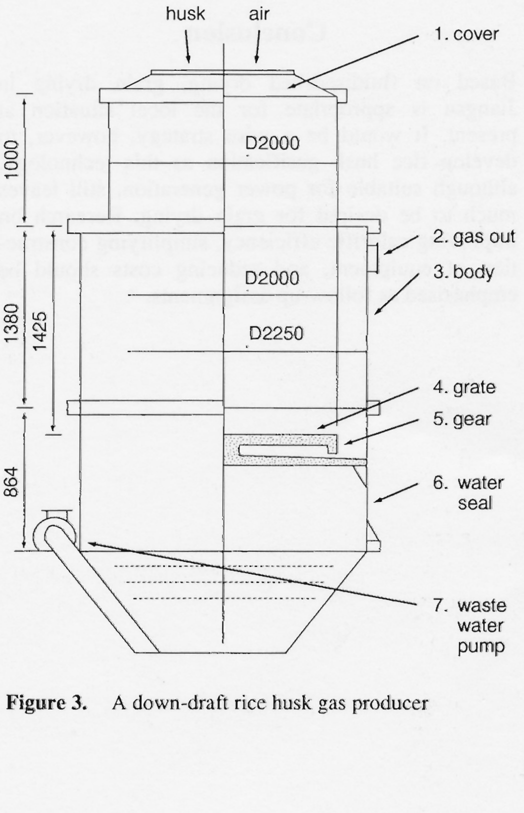

Figure 3. A down-draft rice husk gas producer

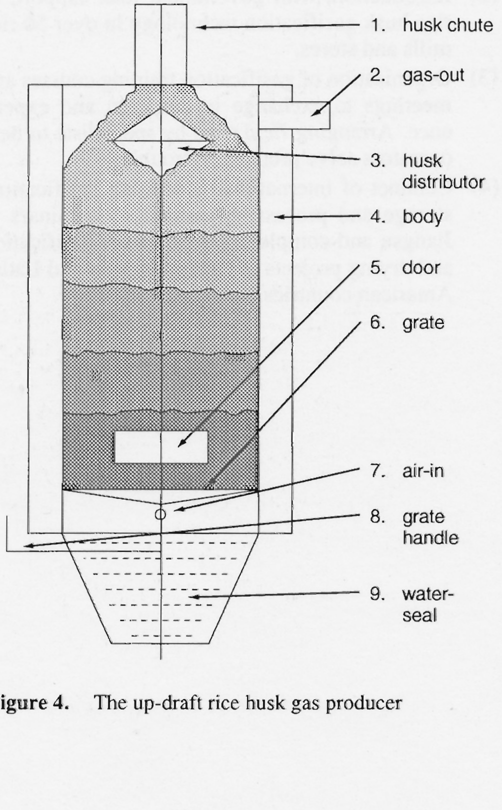

Figure 4. The up-draft rice husk gas producer

(b) Since the gas in the up-draft type is of more combustible CO and CH_4 (but less H_2) than the gas in the down-draft type, the up-draft type produces gas of a higher calorific value than the latter.

(c) In the up-draft type light explosions may occur. These are caused by the blocking of the gas spray nozzle and pipe by tar and impurities, as well as by leaking of air into the top chamber. These accidents are averted in the down-draft type, because its gas is more clear, and the gas is separated by fuel layers from air.

(d) The down-draft drying system may be operated in parallel with the gas generating system. Thus the combined system can supply a rice mill with heat for drying and electric power for mill operation.

Diffusion of Rice Husk Gasification Technology

On behalf of the Jiangsu Provincial Grain Bureau, the Jiangsu Grains Oils and Foods International Corporation has promoted rice husk gasification technology, and accomplished programs as follows.

(1) Research on rice husk gasification and successful design of Models 6250 and 6160 rice husk gasification units.

(2) Introduction, with government loan support, of rice husk gasification technology in over 50 rice mills and stores.

(3) Organisation of gasification training courses and meetings to exchange information and experience. Arranging field trips by specialists to help operators solve production troubles.

(4) Conduct of international rice husk gasification, storage and processing technology seminars in Jiangsu and completing 9 rice husk gasification and drying projects in Asian, African and Latin-American countries.

Table 3. Analysis of rice husk gas (%).

Gas component	Down-draft type	Up-draft type
CO	15.45	17.21
CH_4	0.40	4.92
CO_2	7.25	4.91
H_2	9.48	4.70
O_2	2.50	2.98
N_2	64.92	64.96
C_nH_m	–	0.32

Table 4. Technical data on gas producers.

Item	Down-draft type	Up-draft type
Diameter of container	2 m	1 m
Gasification strength	132 kg/m^2h	149 kg/m^2h
Gasification effect	4.5 m^3/kg	2.3 m^3/kg
Calorific efficiency	73%	63.7%
Calorific value	750 $kcal/m^3$	1 100 $kcal/m^3$
Husk consumption	400 kg/h	138 kg/h

Conclusion

Based on fluidised-bed drying, grain drying in Jiangsu is appropriate for the local situation at present. It would be a wise strategy, however, to develop rice husk gasification as this technology, although suitable for power generation, still leaves much to be desired for grain drying. Research on improving calorific efficiency, simplifying construction of equipment, and reducing costs should be emphasised as follow-up assignments.

The Effects of Drying and Shelling on *Fusarium* spp. Infection and *Fusarium* Toxins Production in Maize

O.S. Dharmaputra*, H.K. Purwadaria†, H. Susilo§, and S. Ambarwati§

TOXIGENIC *Fusarium* species can grow on some of the staple foods of both humans and animals, among them maize. According to Miller (1994) deoxynivalenol was produced by both *F. graminearum* and *F. culmorum*, while nivalenol was produced only by *F. graminearum*. Deoxynivalenol could cause some diseases, among others necrosis of the skin (Ueno 1977), while nivalenol caused vomiting in ducks and dermal toxicity in rabbits (Betina 1989).

According to Dharmaputra et al. (1994), a survey conducted by a BIOTROP team in 1992 revealed that:

- the highest percentage of maize kernels infected by *F. moniliforme* and *F. semitectum* was in freshly harvested maize cobs (77.4%), while the lowest was on dry shelled maize stored at trader level (30.8%);
- the highest nivalenol content was on shelled maize (12.5 ppm), while the lowest was on dry maize cobs (5.8 ppm);
- during the dry season the highest deoxynivalenol content was on dry maize cobs (2.8 ppm), while the lowest was on dry shelled maize (1.2 ppm);
- during the wet season the highest content was on freshly harvested maize cobs (3.8 ppm), while the lowest was on dry shelled maize stored at trader level (1.9 ppm).

Postharvest handling (including drying and shelling) can affect fungal infection. In general, the moisture content of freshly harvested maize is still high, and it is therefore a good substrate for fungal growth. Shelling can cause mechanical damage, and fungal spores can infect the kernel through the damage. Consequently, the kernels should be shelled using a proper tool and at an appropriate moisture content to reduce the damage.

The objective of this study was to obtain information on the effects of some methods of drying and shelling on *Fusarium* spp. infection and *Fusarium* toxins production in maize stored under laboratory conditions. Also sought was information on the effect of drying and shelling on the integrity of kernels, and the effect of storage duration on changes in moisture content.

Materials and Methods

Maize variety

Two maize varieties (Arjuna and CPI-2) were used in this study. They were grown at the experimental plot of the Research Institute for Food Crop Biotechnology, Bogor, harvested at 90 and 97 days after planting, respectively, and husked immediately after harvest.

Drying and shelling

Cobs of maize were divided into four lots. The 1st and the 2nd lots were sun dried to 20% moisture content (m.c.), then shelled and further dried after shelling to 17 and 14% m.c., respectively. The 3rd lot was sun dried to 17% m.c. then shelled but was not dried further. The 4th lot was sun dried to 17% m.c., then shelled and further dried after shelling to 14% m.c. All maize samples were sun dried by spreading the cobs or kernels on a paved floor.

Nail-down wood and a mechanical sheller type Yanmar TF 55-di with a cylinder rotation of 500-700 rpm were used for shelling the maize.

Storing of maize and method of sampling

After drying and shelling, 500 g of maize from each treatment was placed in a 3.3 L jar covered with muslin cloth, and stored for 1, 2, and 3 months under laboratory conditions. Two replicates were used for each treatment. The ambient temperature and relative humidity of the storage were recorded using a Wilh. Lambrecht thermohygrograph type 252.

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An initial sample was obtained from each replicate (jar) at the beginning of storage, and further samples at 1, 2, and 3 months of storage. Each sample was divided twice using a sample divider to obtain working samples for moisture content, damaged kernels, population of *Fusarium* spp., and *Fusarium* toxins content analyses.

Moisture content, damaged kernels, population of *Fusarium* spp., and *Fusarium* toxins content analyses

Moisture content (wet basis) was determined using the oven method at 130°C for 2 hours (BSI 1980). The damaged kernels analyses were carried out at the beginning of storage to obtain the percentage of damaged kernels caused by shelling.

Fusarium spp. was isolated using dilution method on Dichloran Chloramphenicol Peptone Agar (DCPA) (Pitt and Hocking 1985). *Fusarium* toxins content was determined using high performance liquid chromatography (HPLC) methods (Blaney et al. 1986).

Experimental design

The data were analysed using a completely randomised factorial design with 4 factors. The 1st, 2nd, 3rd, and 4th factors were maize variety, method of drying, method of shelling, and duration of storage, respectively.

Results and Discussion

The effect of maize variety, methods of drying and shelling, and storage duration on moisture content and incidence of damaged kernels

Based on statistical analysis, the effects of drying, duration of storage, and their interaction caused significant differences to moisture content, while variation in variety and method of shelling was not significant (Table 1).

At the beginning of storage, the moisture contents of the grain subjected to drying methods I, II, III, and IV were 16.84, 14.10, 17.11, and 14.35%, respectively. Following 1 month of storage moisture contents had fallen (13.98, 13.51, 14.05 and 13.75%, respectively), and then remained almost constant for 2 and 3 months of storage (Table 2). It was assumed that the moisture content of maize at 2 and 3 months of storage would approach an equilibrium with the relative humidity of the storage. According to Hall (1957) and Henderson and Perry (1976), this equilibrium moisture content is reached when the grains cease to either absorb or release vapour. Brooker et al. (1974) reported that the equilibrium moisture content is affected by temperature, humidity, variety, and maturity of grains. The ranges of temperature and relative humidity of the storage were 21.75–29.25°C and 47.88–88.25%, respectively (Table 3).

Maize variety, drying, and shelling each had a significant effect on occurrence of damaged kernels, but their interaction was not significant (Table 4).

The percentage of damaged kernels of maize var. CPI-2 (5.0%) was higher than that of var. Arjuna (3.6%) (Table 5). It was presumed that the kernels of var. CPI-2 were larger and less solid than var. Arjuna, and therefore could be more easily cracked or broken during shelling.

Table 1. Analysis of variance on the effects of variety, drying, shelling, duration of storage and their interaction on moisture content of maize.

Source of variance	df	SS	MS	F Value
A	1	0.0200000	0.0200000	0.22
B	3	22.2191000	7.4063667	81.58**
A×B	3	0.1580750	0.0526917	0.58
C	1	0.1682000	0.1682000	1.85
A×C	1	0.0288000	0.0288000	0.32
B×C	3	0.7585250	0.2528417	2.78*
A×B×C	3	0.2064250	0.0688083	0.76
D	3	137.6364812	45.8788271	505.32**
A×D	3	0.2039063	0.0679688	0.75
B×D	9	40.7079438	4.5231049	49.82**
A×B×D	9	0.6937437	0.0770826	0.85
C×D	3	0.2252688	0.0750896	0.83
A×C×D	3	0.1070437	0.0356812	0.39
B×C×D	9	1.3455312	0.1495035	1.65
A×B×C×D	9	0.4364063	0.0484896	0.53
Error	63	5.7198875	0.0907919	

A	Variety
B	Drying
A×B	Interaction between variety and drying
C	Shelling
A×C	Interaction between variety and shelling
B×C	Interaction between drying and shelling
A×B×C	Interaction among variety, drying and shelling
D	Duration of storage
A×D	Interaction between variety and duration of storage
B×D	Interaction between drying and duration of storage
A×B×D	Interaction among variety, drying and duration of storage
C×D	Interaction between shelling and duration of storage
A×C×D	Interaction among variety, shelling and duration of storage
B×C×D	Interaction among drying, shelling and duration of storage
A×B×C×D	Interaction among variety, drying, shelling and duration of storage
*	Significantly different at 95% confidence level
**	Significantly different at 99% confidence level

The percentage of damaged kernels of maize shelled at 20% m.c. (drying methods I and II) (4.7 and 5.4%, respectively) was higher than for maize shelled at 17% m.c. (drying methods III and IV) (3.7 and 3.2%, respectively). According to SFCDP (1990), low quality maize generally contains more than 3% damaged kernels, and the percentage increases if the grain is shelled at greater than 18% m.c..

The percentage of damaged kernels (5.7%) in maize shelled by mechanical sheller was higher for maize shelled by nail-down wood (2.9%). It was assumed that shelling of each cob of maize using a nail-down wood did not result in friction between cobs, in contrast to shelling using a mechanical sheller. Moreover, manual shelling using a nail-down wood can be controlled to reduce friction between the sheller and the maize. According to Suprayitno (1980) the percentage of damaged kernels of maize shelled using a mechanical sheller is higher because of friction between intact kernels and between intact kernels and the cylinder of the mechanical sheller.

Table 2. Moisture content of maize treated with different methods of drying during storage.

Drying method[a]	Moisture content (%)			
	Duration of storage (months)			
	0	1	2	3
I	16.84 a	13.98 cd	13.18 g	13.08 g
II	14.10 bc	13.51 ef	13.04 g	13.02 g
III	17.11 a	14.05 bcd	12.95 g	13.21 g
IV	14.35 b	13.75 de	12.99 g	13.01 g

Numbers followed by the same letter do not differ significantly according to Duncan's Multiple Range Test at 95% confidence level

[a] I Cobs of maize were sun dried to 20% moisture content, then shelled and re-dried after shelling to 17% moisture content.
II Cobs of maize were sun dried to 20% moisture content, then shelled and re-dried after shelling to 14% moisture content.
III Cobs of maize were sun dried to 17% moisture content, then shelled and were not re-dried.
IV Cobs of maize were sun dried to 17% moisture content, then shelled and re-dried after shelling to 14% moisture content.

Table 3. Range of temperature and relative humidity in the storage room.

Duration of storage (month)	Temperature (°C)	Relative humidity (%)
1	21.8–28.4	61.0–88.3
2	21.8–28.4	61.0–88.3
3	21.8–29.3	47.9–88.3

Table 4. Analysis of variance on the effects of variety, drying, shelling and their interaction on damaged kernels of maize at the beginning of storage.

Source of variance	df	SS	MS	F Value
A	1	15.52637813	15.52637813	16.33**
B	3	22.82528438	7.60842813	8.00**
AxB	3	3.33008437	1.11002812	1.17
C	1	63.59100313	63.59100313	66.89**
AxC	1	0.05695312	0.05695312	0.06
BxC	3	1.97750938	0.65916979	0.69
AxBxC	3	2.94960937	0.98320312	1.03
Error	15	14.2605719	0.9507048	

A	Variety
B	Drying
A×B	Interaction between variety and drying
C	Shelling
A×C	Interaction between variety and shelling
B×C	Interaction between drying and shelling
A×B×C	Interaction among variety, drying and shelling
**	Significantly different at 99% confidence level

Table 5. The effect of maize variety, methods of drying and shelling on damaged kernels at the beginning of storage.[a]

Effect	Damaged kernels (%)
Maize variety	
Arjuna	3.6 a
CPI-2	5.0 b
Method of drying[b]	
I	4.7 cd
II	5.4 c
III	3.7 de
IV	3.2 e
Method of shelling	
Nail-down wood	2.9 f
Mechanical sheller	5.7 g

Numbers followed by the same letter do not differ significantly according to Duncan's Multiple Range Test at 95% confidence level

[a] Damaged kernels analysis was carried out only at the beginning of storage

[b] I Cobs of maize were sun dried to 20% moisture content, then shelled and re-dried after shelling to 17% moisture content.
II Cobs of maize were sun dried to 20% moisture content, then shelled and re-dried after shelling to 14% moisture content.
III Cobs of maize were sun dried to 17% moisture content, then shelled and were not re-dried.
IV Cobs of maize were sun dried to 17% moisture content, then shelled and re-dried after shelling to 14% moisture content.

The effect of maize variety, methods of drying and shelling, and storage duration on population of *Fusarium* spp.

Two species of *Fusarium* were isolated: *F. moniliforme* and *F. nygamai. F. moniliforme* can produce moniliformin (Martin 1976) and fumonisin (Gelderblom et al. 1988). According to Dharmaputra et al. (1993), *F. moniliforme* and *F. nygamai* can produce deoxynivalenol.

Based on statistical analysis, maize variety had a very significant effect on the population of *Fusarium* spp. duration of storage gave significant differences, while drying, shelling, and interaction among maize varieties, and drying, shelling and duration of storage did not give significant differences (Table 6).

The population of *Fusarium* spp. on maize var. Arjuna (8892 colonies/g) was higher than that on var. CPI-2 (3282 colonies/g) (Table 7). It was assumed that maize var. Arjuna was more susceptible to *Fusarium* spp. than var. CPI-2.

Fusarium spp. population on maize shelled at 20% m.c. (drying methods I and II) (9715 and 8846 colonies/g) was higher than that on maize shelled at 17% m.c. (drying methods III and IV) (2283 and 2953 colonies/g), but the difference was not significant (Table 7). It was assumed that *Fusarium* grew well on substrate with a high moisture. According to Christensen and Kaufmann (1974), *Fusarium* needs substrate with high moisture content (22–23%) for its growth.

The population of *Fusarium* spp. on maize shelled by mechanical sheller (7129 colonies/g) was higher than on that shelled by nail-down wood (5044 colonies/g), but the difference was not significant (Table 7). It was assumed that the proportion of damaged kernels in maize shelled by mechanical sheller was higher than in maize shelled by nail-down wood, and consequently that maize shelled by mechanical sheller could be more easily infected by *Fusarium*.

Fusarium spp. population increased at 1 and 3 months of storage, from 2537 colonies/g to 9385 and 9096 colonies/g, respectively, but it decreased at 2 months of storage. It was assumed that there were fungi antagonistic to *Fusarium* spp., because one kernel could be infected by more than one fungal species.

The effect of maize variety, methods of drying and shelling, and storage duration on *Fusarium* toxin content

Two *Fusarium* toxins were obtained: nivalenol (NIV) and deoxynivalenol (DON). Tamm and Tori (1984) and Dharmaputra et al. (1993) reported that *F. moniliforme* and *F. nygamai* produced DON.

The effects of maize variety, shelling, duration of storage, and interaction among varieties, drying, shelling, and duration of storage gave very significant differences to NIV content, while drying did not give significant differences (Table 8).

The effects of maize variety, drying, and duration of storage resulted in very significant differences to DON content, shelling gave significant differences, while interaction among maize varieties, drying, shelling, and duration of storage did not give significant differences (Table 8).

Table 6. Analysis of variance on the effects of variety, drying, shelling, duration of storage and their interaction on population of *Fusarium* spp. (transformed into log. population of *Fusarium* spp. + 1) of maize.

Source of variance	df	SS	MS	F Value
A	1	34.48470925	34.48470925	7.32**
B	3	1.76225659	0.58741886	0.12
A×B	3	9.53619213	3.1783071	0.67
C	1	5.05448890	5.05448890	1.07
A×C	1	8.04765365	8.04765365	1.71
B×C	3	15.37478516	5.12492839	1.09
A×B×C	3	10.55589127	3.51863042	0.75
D	3	40.04969385	13.34989795	2.83*
A×D	3	2.86088526	0.95362842	0.20
B×D	9	54.59030187	6.06558910	1.29
A×B×D	9	60.03023921	6.67002658	1.49
C×D	3	5.31038397	1.77012799	0.38
A×C×D	3	10.02239775	3.34079925	0.71
B×C×D	9	32.61029761	3.62336640	0.77
A×B×C×D	9	29.27228927	3.25247659	0.69
Error	63	296.6930382	4.7094133	

A	Variety
B	Drying
A×B	Interaction between variety and drying
C	Shelling
A×C	Interaction between variety and shelling
B×C	Interaction between drying and shelling
A×B×C	Interaction among variety, drying and shelling
D	Duration of storage
A×D	Interaction between variety and duration of storage
B×D	Interaction between drying and duration of storage
A×B×D	Interaction among variety, drying and duration of storage
C×D	Interaction between shelling and duration of storage
A×C×D	Interaction among variety, shelling and duration of storage
B×C×D	Interaction among drying, shelling and duration of storage
A×B×C×D	Interaction among variety, drying, shelling and duration of storage
*	Significantly different at 95% confidence level
**	Significantly different at 99% confidence level

NIV and DON contents of maize var. CPI-2 (1.86 and 0.28 ppm) were higher than those of var. Arjuna (1.80 and 0.25 ppm) (Table 9).

NIV contents of maize dried using the four methods were not significantly different from each other (1.81–1.85 ppm). The DON content of maize dried using the 1st and 3rd methods (0.24 ppm) was lower than in the 2nd and 4th methods (0.31 and 0.26 ppm, respectively) (Table 9).

Table 7. The effect of maize variety, methods of drying and shelling, and duration of storage on population of *Fusarium* spp.

Effect	Population of *Fusarium* spp. (colonies/g)	
	Not transformed	Transformed into log *Fusarium* spp.+ 1
Maize variety		
Arjuna	8892	6.739 a
CPI-2	3282	5.701 b
Method of drying[a]		
I	9715	6.351 c
II	8846	6.321 c
III	2833	6.132 c
IV	2953	6.078 c
Method of shelling		
Nail-down wood	5044	6.022 d
Mechanical sheller	7129	6.419 d
Duration of storage (months)		
0	2537	5.522 e
1	9385	6.784 f
2	3329	5.820 ef
3	9096	6.755 f

Numbers followed by the same letter do not differ significantly according to Duncan's Multiple Range Test at 95% confidence level

[a] I Cobs of maize were sun dried to 20% moisture content, then shelled and re-dried after shelling to 17% moisture content.

II Cobs of maize were sun dried to 20% moisture content, then shelled and re-dried after shelling to 14% moisture content.

III Cobs of maize were sun dried to 17% moisture content, then shelled and were not re-dried.

IV Cobs of maize were sun dried to 17% moisture content, then shelled and re-dried after shelling to 14% moisture content.

NIV content of maize shelled by mechanical sheller (1.87 ppm) was higher than that shelled by nail-down wood (1.78 ppm), while for DON content it was the opposite (0.25 and 0.27 ppm, respectively).

NIV and DON contents increased with increasing storage duration, but they were still lower than the lethal doses for mice. Their contents at the beginning of storage, and at 1, 2, and 3 months of storage, were 1.22 and 0.08 ppm, 1.99 and 0.30 ppm, 2.02 and 0.32 ppm, and 2.08 and 0.34 ppm, respectively (Table 9). According to Betina (1989) the lethal dose of NIV for mice is 4.1 ppm, while Miller (1994) reported that animal feed should contain not more than 1 ppm of DON in the diet. According to Betina (1989), the LD_{50} of DON for male and female mice are 70.0 and 76.7 ppm, respectively.

Conclusions

1. Moisture contents of maize decreased at 1 month of storage, and remained almost constant at 2 and 3 months of storage.
2. Maize var. CPI-2 was more resistant than var. Arjuna to *F. moniliforme* and *F. nygamai* infections, although the percentage of damaged kernels of maize var. CPI-2 was higher than in var. Arjuna.

Table 8. Analysis of variance on the effects of variety, drying, shelling, duration of storage and their interaction on *Fusarium* toxins contents of maize.

a. Nivalenol

Source of variance	df	SS	MS	F Value
A	1	0.10927812	0.10927812	24.12**
B	3	0.03221094	0.01073698	2.37
A×B	3	0.03534581	0.01178194	2.60
C	1	0.22411513	0.22411513	49.47**
A×C	1	0.02880000	0.02880000	6.36**
B×C	3	0.01106856	0.00368952	0.81
A×B×C	3	0.20265469	0.06755156	14.91**
D	3	15.74015056	5.24671685	1158.17**
A×D	3	0.01365519	0.00455173	1.00
B×D	9	0.05657450	0.00628606	1.39
A×B×D	9	0.09951387	0.01105710	2.44*
C×D	3	0.03161769	0.01053923	2.33
A×C×D	3	0.08266656	0.02755552	6.08**
B×C×D	9	0.11851963	0.01316885	2.91**
A×B×C×D	9	0.11831575	0.01314619	2.90**
Error	63	0.28540047	0.00453017	

Table 8. Cont'd.

b. Deoxynivalenol

Source of variance	df	SS	MS	F Value
A	1	0.03455163	0.03455163	16.74**
B	3	0.10848777	0.03616259	17.53**
A×B	3	0.03191734	0.01063911	5.16**
C	1	0.01254132	0.01254132	6.08*
A×C	1	0.04832163	0.04832163	23.42**
B×C	3	0.03306677	0.01102226	5.34**
A×B×C	3	0.00005109	0.00001703	0.01
D	3	1.38876634	0.46292211	224.34**
A×D	3	0.01499727	0.00499909	2.42
B×D	9	0.03933220	0.00437024	2.12*
A×B×D	9	0.01657438	0.00184160	0.89
C×D	3	0.01547184	0.00515728	2.50
A×C×D	3	0.02377527	0.00792509	3.84*
B×C×D	9	0.02272820	0.00252536	1.22
A×B×C×D	9	0.00119113	0.00013235	0.06
Error	63	0.12999862	0.00206347	

A	Variety
B	Drying
A×B	Interaction between variety and drying
C	Shelling
A×C	Interaction between variety and shelling
B×C	Interaction between drying and shelling
A×B×C	Interaction among variety, drying and shelling
D	Duration of storage
A×D	Interaction between variety and duration of storage
B×D	Interaction between drying and duration of storage
A×B×D	Interaction among variety, drying and duration of storage
C×D	Interaction between shelling and duration of storage
A×C×D	Interaction among variety, shelling and duration of storage
B×C×D	Interaction among drying, shelling and duration of storage
A×B×C×D	Interaction among variety, drying, shelling and duration of storage
*	Significantly different at 95% confidence level
**	Significantly different at 99% confidence level

3. In general, the best drying method was to sun dry maize cobs to 17% m.c., then shell them and further dry to 14% m.c.
4. *Fusarium* spp. population of maize shelled by mechanical sheller was not significantly different from that in maize shelled by nail-down wood, though the percentage of damaged kernels in maize shelled by mechanical sheller was higher.
5. Populations of *Fusarium* spp. increased at 1 and 3 months of storage, but decreased at 2 months of storage.
6. Nivalenol and deoxynivalenol contents increased with increasing length of storage.

Table 9. The effect of maize variety, methods of drying and shelling, and duration of storage on *Fusarium* toxins contents.

Effect	*Fusarium* toxins contents (ppm)	
	NIV	DON
Maize variety		
Arjuna	1.80 a	0.25 j
CPI-2	1.86 b	0.28 k
Method of drying		
I	1.84 c	0.24 l
II	1.85 c	0.31 m
III	1.81 c	0.24 l
IV	1.81 c	0.26 l
Method of shelling		
Nail-down wood	1.78 d	0.27 n
Mechanical sheller	1.87 e	0.25 o
Duration of storage (months)		
0	1.22 f	0.08 p
1	1.99 g	0.30 q
2	2.02 h	0.32 r
3	2.08 i	0.34 r

Numbers followed by the same letter do not differ significantly according to Duncan's Multiple Range Test at 95% confidence level

I	Cobs of maize were sun dried to 20% moisture content, then shelled and re-dried after shelling to 17% moisture content.
II	Cobs of maize were sun dried to 20% moisture content, then shelled and re-dried after shelling to 14% moisture content.
III	Cobs of maize were sun dried to 17% moisture content, then shelled and were not re-dried.
IV	Cobs of maize were sun dried to 17% moisture content, then shelled and re-dried after shelling to 14% moisture content.

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References

Betina, V. 1989. Mycotoxins: chemical, biological and environmental aspects. Bioactive Molecules Volume 9. Amsterdam, Elsevier Science Publisher B.V., 438 p.

Blaney, B.J., Ramsey, M.D., and Tyler, A.L. 1986. Mycotoxins and toxigenic fungi in insect-damaged maize harvested during 1983 in far north Queensland. Australian Journal of Agricultural Research, 37, 235–244.

Brooker, D.B., Bakker-Arkema, F.W., and Hall, C.W. 1974. Drying cereal grains. Westport, Connecticut, USA, Avi Publishing Company, 265 p.

BSI (British Standards Institution) 1980. Methods of test for cereals and pulses. Part 3. Determination of moisture content of cereals and cereal products (routine method). London, British Standards Institution.

Christensen, C.M. and Kaufmann, H.H. 1974. Microflora. In: Christensen, C.M., ed., Storage of cereal grains and their products. St Paul, Minnesota, USA, American Association of Cereal Chemists, 158–191.

Dharmaputra, O.S., Susilo, H., and Ambarwati, S. 1993. *Fusarium* associated with some economical crops in some locations of West Java, Indonesia, and their mycotoxin productions on maize kernels. In: Proceedings of the XII National Congress and Scientific Seminar, Indonesian Phytopathology Society, Yogyakarta, Indonesia, 6–8 September 1993, 550-559. (In Indonesian)

Dharmaputra, O.S., Retnowati I., Purwadaria, H.K., Susilo, H., Sidik, M., and Sunjaya. 1994. The effect of postharvest handling on grain intactness, fungal infection and mycotoxin production of maize. I. Surveys on postharvest handling, damaged kernels, fungal infection and mycotoxin contamination on maize collected from farmers and traders. Grant Competition Research Report II/1. SEAMEO BIOTROP. 50 p.

Gelderblom, W.C.A., Jaskiewicz, K., Marasas, W.F.O., Thiel, P.G., Horak, R.M., Vleggaar, R., and Kriek, N.P.J. 1988. Fumonisins—novel mycotoxins with cancer-promoting activity produced by *Fusarium moniliforme*. Applied Environmental Microbiology, 54, 1806–1811.

Hall, C.W. 1957. Processing equipment for agricultural products. Michigan, Edward Brothers, Inc..

Henderson, S.M. and Perry, R.L. 1976. Agricultural process engineering. New York, John Wiley and Sons Inc.

Martin, P.M.D. 1976. A consideration of the mycotoxin hypothesis with special references to the mycoflora of maize, sorghum, wheat and groundnuts. Tropical Products Institute, London. 111 p.

Miller, J.D. 1994. Epidemiology of *Fusarium* ear diseases of cereals. In: Miller, J.D., and Trenholm, H.L., ed., Mycotoxins in grain; compounds other than aflatoxin. St. Paul, Minnesota, USA, Eagan Press, 19–36.

Pitt, J.I. and Hocking, A.D. 1985. Fungi and food spoilage. Sydney, Academic Press, 413 p.

SFCDP 1990. Studies on postharvest handling on corn, soybean and cassava in Lampung, East Java and South Sulawesi. Indonesia, MOA–AID.

Suprayitno 1980. Mempelajari Beberapa Alat Pemipil Jagung (Study on some mechanical sheller of maize). Faculty of Agriculture Mechanization and Technology, Bogor Agricultural University, Bogor, Indonesia. Internal Report (In Indonesian).

Tamm, Ch. and Tori, M. 1984. Trichothecenes. In: Betina V., ed., Mycotoxins; production, isolation, separation, and purification. Amsterdam, Elsevier Science Publishers B.V., 131–182.

Ueno, Y. 1977. Trichothecenes: overview address. In: Rodricks, J., Hesseltine C.W., and Mehlman, M.A., ed., Mycotoxins in human and animal health. Illinois, USA, Pathotox Publishers, Inc., 189–207.

Drying Simulation: a PC–based, User-orientated Decision Support System for In-store Drying and Aeration of Grains

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SIMULATION of grain drying in deep beds, also known as in-store drying, has been extensively used in agricultural engineering research to acquire a better understanding of the drying processes and related systems. The old mainframe versions of the simulation models developed for predicting the changes in the air and grain conditions are not easily accessible or user-interactive for direct applications. Also, many users are discouraged from utilising the computer simulation techniques because of their complexity.

Drying Simulation is an easy-to-use, PC–based decision support system which offers a user-interactive environment for computer simulation of in-store drying of paddy, maize, and soybeans. The software package developed can be used for designing and performance evaluation of in-store drying and aeration of selected grains. It has a menu-driven user-interface and can display results graphically for quick interpretation and analysis. *Drying Simulation* should prove to be a practical and useful means to find out what would happen under different available options for in-store drying and aeration of grains, and for subsequent decision making.

Drying Simulation Features

The program relies on the modified Thompson et al. (1968) and the Thompson (1972) near-equilibrium models to simulate grain drying and rewetting in deep beds. *Drying Simulation*, developed and compiled in Microsoft BASIC 7.0 (also known as BASIC PDS), provides a user-interactive environment which allows users to easily perform drying simulations based on these models and their combined form.

Drying Simulation offers the following features:

- *Drying Simulation* is a stand-alone software package with menu-driven user-interface and graphics capability. There is on-line HELP available for the explanation of various items in each menu. In addition, general information on important aspects of in-store grain drying/aeration simulation and the software package itself is included in a README file.
- Built-in choices for different grain selection include paddy, maize, and soybeans. The program supports the Plot, View, Print, and Save options for both simulation and plot data when pausing intermittently during a simulation run and at the end.
- Selection of three different simulation approaches along with related model equations can be made for general comparison.
- An easy-to-use interface facilitates input of the simulation conditions. A data window showing the input data and selected models can be displayed and closed instantly before and after a particular simulation run.
- Uniform and non-uniform initial grain and inlet air conditions can be handled. Users can select a stopping criterion (e.g. average final moisture content, drying duration, etc.) to end a simulation run. Several fan and heater control strategies can be examined.
- In simulation runs with non-uniform input air conditions and/or initial grain bed conditions, the corresponding air and grain data files can be created and/or edited directly in the program.
- When the simulation program is running, the changes in condition of the grain bed as drying progresses are continuously displayed and updated on screen. Current drying time, and fan and heater operating times, are also displayed. The heater and fan energy requirements, moisture removal, and dry matter loss are computed and displayed continuously on the screen during a simulation run based on 1 m^2 cross-sectional area of the grain bed.
- Simulation results can be plotted on screen. Users can plot various simulation profiles of the moisture content, temperature, relative humidity, and dry matter loss against drying time or depth of grain bed.

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- Simulation results can be saved on a file and imported into other software packages for further analysis. *Drying Simulation* does not offer direct support for printing of the simulation plots. However, the simulation data and other graphics information can be saved on a file and imported into a spreadsheet package (e.g. Lotus 1-2-3) for plotting and printing.

System Requirements

Drying Simulation will run on an IBM® PC or compatible machine with at least 640 kb of available memory. The software requires a CGA, EGA, or VGA display for the graphics routines. When using a monochrome monitor with Hercules driver, the file MSHERC.COM available from MS DOS 5.0 must be loaded to support the plotting of graphs by *Drying Simulation.*

The software can be run from a floppy disk system with a minimum of 720 kb disk drive capacity (e.g. two 360 kb drives, or one 1.2 Mb or higher capacity drive). A hard disk is recommended for best performance.

Drying Simulation would run under DOS 3.3 or higher. A spreadsheet package like LOTUS 1-2-3 is required for printing the simulation plots. Alternatively, the graphics screen capture utilities, such as GRAB available from WordPerfect Corporation, may be used. Further details on the printing of simulation plots are provided in a README file.

Availability

Copies of *Drying Simulation* are available for US$50 from Dr V.K. Jindal, AIT, GPO Box 2754, Bangkok, Thailand; fax: 66 2 524 6200 or 66 2 516 2126; email: < jindal@ait.ac.th >.

References

Thompson, T.T. 1972. Temporary storage of high-moisture shelled corn using continuous aeration. Transactions of the American Society of Agricultural Engineers, 15, 333–337.

Thompson, T.L., Peart, R.M., and Foster, G.H. 1968. Mathematical simulation of corn drying—a new model. Transactions of the American Society of Agricultural Engineers, 11, 582–586.

The Current Situation and Prospects for Grain Drying in Northeastern China

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THE Songliao Plain of northeastern China is a major grain-producing region. In the provinces of Heilongjiang, Jilin, and Liaoning, the total output of grains is 60 Mt. In the north of Heilongjiang, wheat and soybean are the principal crops, in Jilin, Liaoning and the south of Heilongjiang maize predominates, whilst in the east of the three provinces close to the mountains, rice is produced. All the area is influenced by the climate of Siberia, that is cold in winter and warm in summer. In spring and early summer, from March to June and in autumn from September to October, the climate is dry with little rain. The frost-free period is about 140–160 days each year, and the grain moistures are high. The meteorological conditions and moisture contents of grains are shown in Tables 1 and 2.

An average of 50% of grain produced in the three provinces passes through commercial channels. Local government agencies in three provinces purchase a total of 26–28 Mt of which 21.25 Mt need drying. This is equal to 70% of grain dried throughout the whole country. The amount of high moisture grain that needs drying is shown in Table 3 for the three provinces.

Current Grain-drying Technology in Northeastern China

Grain drying is a key measure for long-term safe storage of grain. Because of different grain varieties, grain moisture contents, and meteorological conditions, drying methods and equipment are different. The major methods are high temperature drying, sun drying, and aeration (Table 4).

The technique of grain drying

In north-east China, grain drying machines appeared first in the 1940s. From the 1950s, the Kuaibas grain drying unit was introduced from the former USSR and a steam drying unit, the Berico crossflow grain drying unit, was obtained from the Behlein Co., USA (Fig. 1). Further developments were the concurrent drying unit from the Weslaken company, Canada and the crossflow drying technique (Figs 2–3). Large amounts of capital and manpower were thrown into the development of grain dryers and the series connection mixed flow grain drying unit was developed in Canada (Fig. 4). Various mixed flow units were developed in China including one based on cyclic high temperature water and other equipment generally suited to drying high moisture grain (Fig. 5).

Table 2. Moisture content of grain in three provinces of North East China (%).

Province	Maize	Rice	Soybean	Wheat	Other Grains
Liaoning	22–30	15–17	13–15	–	16–19
Jilin	24–30	15–17	14–15	–	15–17
Heilongjiang	25–33	15–17	14–17	14.5–15.5	15–17

Table 3. Amount of high moisture grain that needs drying in three provinces of North East China ('000t).

Province	Total grains	Maize	Rice	Soybean	Wheat	Other grains
Liaoning	6050	4000	1250	50	–	750
Jilin	9350	7500	500	–	–	550
Heilongjiang	4850	3000	750	500	500	100
Total	20250	14500	2500	550	500	1400

To meet the needs for drying paddy and rapeseed on a small scale in central and southern China, the vibration dryers, fluidised-bed dryers, and rotating dryers were developed rapidly.

After 50 years of development of techniques for grain drying, there are now about 1200 drying units of various types in use in northeastern China. Most of the large units which can process 150 t of wet grain per

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day are kept by state granaries, grain processing factories, state farms, and feed-processing plants, totalling about 858 units. Most small, tower type drying units are kept by rural stores or collectives. Units developed after the introduction in 1992 of the policy of reducing state purchases are, in major part, concurrent drying units. Such units make up about 15% of the total drying capacity.

The grain drying equipment which is now in use and has been so for the past 6 years, consists of series connected mixed flow tower type drying units and steam drying units. The number, processing capacity, regional distribution, and main technical functions are given in Table 5.

The mixed-flow, multiple series drying units of brick construction (Fig. 6) have advantages such as even drying, use of local materials, ease of construction, and long service life. The disadvantages are the high capital cost, lengthy construction times, and high breakage rate of grain during drying. The strong points of the steam drying units are the high quality of dried grain and the low consumption of energy. Most are series connected and a high breakage rate of grain is very common. Their cost of manufacture is 25% higher than that of the mixed-flow brick drying units.

The emergence and development of drying units constructed of steel

Since the early 1980s, and because of the disadvantages listed above, steel grain drying units have been introduced and manufactured. A sample unit of the Bekley type of dryer was introduced by Hongqi State Farm in 1981. A multiple-ring mixed flow drying unit manufactured in 1987 in China was put into use in the Mudanjiang granary (Fig. 5).

Work in this period proved that steel construction for drying units had the advantages of low cost, suitability for large-scale production, and ease of introduction of advanced technology and process control.

Currently, there are three types of steel tower drying units in China—mixed flow, crossflow, and concurrent. In winter and spring, the target for energy use (kcal/kg H_2O) differs between northern and southern areas. Mixed flow direct grain drying units target 2000–2300, indirect units 2200–2500, crossflow units 2000–2300, and concurrent units 1900–2200 kcal/kg H_20.

Equipment for supplying heat for grain drying

Grain dryers consist of the drying unit and the heat supply equipment. The heat supply technique is vital to the function of drying machines. It affects the investment costs, the choice of fuel, the quality of the dried grain, pollution, and the service life of the equipment.

Table 1. Meteorological data for three provinces of North East China.

Province	Average annual temperature (°C)	Average annual relative humidity (%)	Average temperature from March to June (°C)	Average relative humidity from March to June (%)	Average annual moisture evaporation (mm)	Average moisture evaporation from March to June (mm)	Average annual wind velocity (m/sec)	Average wind velocity from March to June (m/sec)	Average annual precipitation (mm)	Average precipitation from March to June (mm)
Liaoning (ShenYang)	8.1	63	12.4	57	1445	731	3.0	3.6	680	200
Jilin (ChangChun)	4.9	65	9.6	56	1719	929	4.3	5.1	594	164
Heilongjiang (Harbin)	3.7	68	8.4	59	1099	584	3.8	4.4	582	146

Table 4. Amount of grain dried by different methods in three provinces of North East China (x1000t).

Province	Total grain				Maize				Rice				Soybean				Wheat		Others
	Sun drying	Heat drying	Aeration	Wind drying	Sun drying	Heat drying	Aeration drying	Wind drying	Sun drying	Heat drying	Aeration drying	Wind drying	Sun drying	Heat drying	Aeration drying	Wind drying	Sun drying	Aeration drying	Sun drying
Jilin	2450	5000	–	30	2000	5000	–	–	450	–	–	30	–	–	–	–	–	–	–
Liaoning	1615	2300	80	–	600	2300	–	–	600	–	80	–	270	–	–	–	–	–	145
Heilongjiang	1500	2250	400	350	650	2000	–	50	150	250	300	50	150	–	100	250	500	–	100
Total	5565	9550	480	380	3250	9300	–	50	1200	250	380	80	420	–	100	250	500	–	245

Table 5. Types of drying equipment in North East China.

Province	Technology						Type of machine									
	Mixed flow		Cross–flow		Concurrent		Anthracite direct		Soft coal indirect		Steam & high temperature water		Mechanical		Manual	
	No of units	Capacity (×1000t)	No of units	Capacity (×1000t)	No of units	Capacity (×1000t)	No of units	Capacity (×1000t)	No of units	Capacity (×1000t)	No of units	Capacity (×1000t)	No of units	Capacity (×1000t)	No of units	Capacity (×1000t)
Liaoning	82	4000	20	400	150	2000	–	–	170	2400	82	4000	102	4400	150	2000
Jilin	348	5400	40	600	–	–	–	–	260	3000	128	4000	180	4920	208	2080
Heilongjiang	205	2610	10	300	3	90	135	1650	78	1200	5	150	38	1000	180	200
Total	635	12010	70	1300	153	2090	135	1650	508	6600	215	8150	320	10320	538	6080

Because gas, oil, and electricity are prohibited for heat generation in China, the heat supply for most early stage grain drying is from anthracite and steam stoves. During the last 20 years, because of the high costs and pollution, studies on new equipment and technology for soft coal, indirect heating, and hot-air drying which began in 1978 were examined and approved in 1982, thus making such technical equipment available in the 1980s.

Research work in the past 10 years has led to a new stage in the development of grain-drying technology. The features of the main unit and the indirect heating supply are low costs, suitability for use with a range of fuels, high quality, large-scale production, and short construction period. These are the solid foundations for the rapid development of steel dryers using soft coal in heated air stoves in China in the 1990s. It is also a basis for the formulation of policy and development plans for grain drying technology throughout China.

Sun drying

Sun drying involves spreading the grain on a flat surface to a depth of 6–9 cm when there is abundant sunshine and little rain. The grain is turned with a wooden spade until the moisture content has fallen to the level for safe storage—windy conditions assist drying. In the three provinces a total 5–6 Mt is sun dried, approximately 35% of the total quantity involved (Tables 3 and 4). To prevent cracking and heating of high moisture grain, soybean is normally dried in the sun first and then the wheat and other grains. In the province of Heilongjiang, soybean is sun dried as it cannot be stored at high moisture content after 10 April when ambient temperatures are rising. The advantages of sun drying are the larger quantities that can be done compared with high-temperature drying, and the drying cost is one third to one half that of heated drying. The disadvantages are that it is dependent on weather conditions, only small drying pavements are often available, more labourers are used and the work is heavier, and minerals may contaminate the grain requiring that the site be prepared by consolidation and sweeping as well as spreading mats and using cover.

Use of natural air and heated air for drying

Grain may be dried by ventilation with natural air when conditions are warm and dry, or by air which has been heated using medium- or low-pressure blowers. The storehouse must be appropriately constructed for such aeration. Various materials may be used, e.g. iron sheet-storehouses, bamboo grain barns, and so on. Such storehouses can reduce grain moisture to safe levels and so enable grain to be stored for years without mould growth. The three provinces of northeastern China have a continental climate as can be seen from Table 1. From March to June the temperature is high during the day, with little rain, a low relative humidity and thus high evaporation and so is suitable for drying. The larger grains give grain masses that are more porous and so easier to ventilate. As long as the most suitable aeration method is chosen, the shape of the grain mass is adequate, the correct times for ventilation are chosen, and management is good, the desired results will be achieved. This method is suitable for drying soybean, rice, and wheat where the moisture is a little high, or maize when sun dried or dried by heated air and the moisture again is a little high.

An advantage of the method is that it uses the latent heat of evaporation using little or no fuel and so saving energy. The amount of grain that can be dried is large and the grain is not subject to cracking or pollution from decomposition products of the fuel. Aeration is simple and convenient in operation with low costs that can be spread across normal operational costs. The cost of drying is one third of the cost of drying with heat and 30% of the cost of sun drying. As a result the method is accepted in the rice-producing areas such as Wa Chang, Yan Shou, and Tailai county of Heilongjiang. In this area aeration drying has almost replaced drying with heat and sun drying. Wuchang county dries 50000 t of rice each year and the technology has been in use since 1990. Currently 500000 t are dried by aeration of which 400000 t are in Heilongjiang.

The major types of aeration are as follows:

Radial flow ventilation

Studies on this type of aeration drying began in 1980 and were finalised in 1983. Originally bamboo-clappers were used but were replaced by perforated steel. A unit had four or more grain houses with a central bucket elevator and the complex later was enclosed in a weatherproof shed. This type of equipment found application in Heilongjiang in the middle of the 1980s and following preparation of model specification, there are now 30 such units in this province and in Jilin (Fig. 9).

The radial-flow dryer is a low-temperature aeration type dryer which strips moisture from the grain by using the dynamic equilibrium between grain moisture and ambient air when dry air is forced through the grain by a fan. The dryer has a central porous air cell from which the air passes radially through the grain and out through porous walls. The air passing through the grain may be heated to assist drying. The heated air has two functions: to provide the energy for drying and to remove the evaporated water from the grain mass. Thus safe moisture levels which prevent mould growth can be achieved gradually.

The specifications for drying units are given in Table 6. The temperatures of different grains during the drying process are given in Table 7 and the least input air ratios of various wet grains in Table 8. According to the data for the J30/60 Model drying barn, a 4-72-116A pneumatic conveyer was used.

The dryer was operated at temperatures of 15–30°C and relative humidities of 30–50%. Table 9 gives the drying time per barn, and Table 10 throughput rates. The energy dissipation index data are as follows.

Host machine power wasting:

maize	0.06 kg water
rice, soybean	0.09 kg water

Unit heat consumption (heating with bituminous coal hot-blast stove, temperature rises 15°C:

maize	200–700 kcal/kg H_2O
rice, soybean	1000 kcal/kg H_2O.

At 15°C and a suitable relative humidity, it is possible to use ambient air and not need supplementary heating, so there is no heat waste.

Aeration and drying with ducting for air distribution

Currently, there are 276 silos which use below-floor ventilation, and 514 silos which use above-ground ducting. With horizontal storages, 78 stores use below-floor ventilation and 252 use above-ground ducting. The design of all these storages conforms to the regulations issued by the Ministry of Agriculture. In the arrangement, consideration is given to lower temperatures, rain and ventilation, and the processing quantity is less than 1.4.

According to Ministry of Agriculture regulations, unit ventilation quantities are as follows:

- the moisture content of grain 14, 16, 18, 20%
- the lowest unit ventilation quantity is 25, 30, 60, 80 m^3/h.t.

The height of the grain in silos in Heilongjiang province is 12 m, and in horizontal storages and squat round storages is 3–7 m. The unit ventilation quantity is usually lower than 5–16 m^3/h.t. Above 15°C and under 60% r.h., 40–200 hours of ventilation are required to reduce the moisture content of rice from below 18% and maize from below 20% to maximum safe moisture contents.

Radial ventilation drying in a bamboo screen grain bin

In the bamboo screen grain bin, the bamboo screen forms a circle of 6 m diameter. There is a central air cell duct of 500–700 mm diameter and the unit may load 60–70 t of rice. The air blower is 4-72-11 6 A type, made in China. The unit ventilation quantity is 70–80 m^3/h.t. Above 15°C and under 60% r.h. between 20–120 hours of mechanical ventilation will reduce the moisture content of paddy and soybean to a safe level of 15–17%.

The merits of this method are the fixed investment costs and the ease with which it can be popularised. This method has been generally adopted for grain drying in part of the counties of Heilongjiang province, replacing sun-drying and stoving.

Natural air-drying in stacks

The warm, dry, and windy weather of early summer (February–June) may be used to dry soybean, rice, and maize in open stacks if the moisture content is less than 18%. The bags are stacked in single or double layers in a copper coin hole form. The moisture content will reach safe levels in 15-40 days. This method may be used where there is insufficient power and will lower the drying expenses as there is no need for further investment and equipment. In Xhaozhou county of Heilongjiang province, there are 30000–40000 t of maize and soybean dried with this method. The method may be used when the moisture content is below 18%. Attention must be paid to the orientation of the stack, to guarding against moisture and rain, and to generally maintaining the site.

Table 6. The specification and capacity of the drying granary.

Specification	Diameter of granary (m)	Height of granary (m)	Area (m^2)	Diameter of air cell (m)	Capacity (m^3)	Weight of grain per batch (t)
J25/60	2.5	6.0	4.9	1.0	25.0	maize 20.0 rice 13.6
J30/60	3.0	6.0	7.1	1.0	37.9	maize 31.3 rice 20.0

Table 7. The temperature of various grains in the aeration–drying process.

Grain	Lowest temperature (°C)		Wind temperature (°C)	Relative humidity	
	Grain in air	Heating air		Air	Heating air
Maize	15	–5	15–40	<60	Not considered
Rice	15	0	15–30	<60	Not considered
Soybean	10	–5	10–30	<60	Not considered
Wheat	15	0	15–40	<60	Not considered

Table 8. The least input air ratio of various wet grains in aeration drying.

Moisture content of wet grain (%)	Least input air ratio (m^3 air/ m^3 grain.h)
Below 16	80
16–20	140
20–24	200
Above 24	260

Prospects for Grain Drying in the Northeastern Provinces

Importance of grain drying technology

Grain drying is one of the most important measures in storage of grain. The variety, moisture content, and temperature features of grain must be taken into account in grain drying to preserve the quality and conserve energy, lowering the costs of drying and preventing pollution. Rice, soybean, and wheat at low moisture contents should be dried with ambient or heated air. With maize, with its high moisture content, larger quantities to be handled, and limited drying period, it is necessary to adopt high-temperature drying (stoving) or combine the stoving, aeration, and natural air drying methods. We may divide the drying process into steps by first making most use of drying pavements for sun drying and, in the western plains area, making most use of the natural conditions which are dry and windy and suitable for aeration and natural air-drying in stacks.

Low-temperature drying

The various methods of low-temperature drying should be studied to develop the equipment, facilities, and ventilation systems necessary to raise the efficiency of the drying and lower the moisture contents achievable.

High-temperature drying equipment

This method involves advanced technology, relatively simple structures, and ease of operation. The cost also is low. With this method, we may lower the moisture content to a safe level for long term storage. Grain quality is good, energy is conserved, and costs are low. It is thus appropriate to develop the mixed flow, cross flow, and concurrent drying machines. The silo type cross flow dryers will be used and developed in the south part of Harbin and Mudanjiang—the 45° latitude area.

Table 10. The processing quantity (t) per storage in radial aeration drying.

Type of store	Maize	Rice, wheat	Soybean
J 25/60	0.6	0.7–1.4	–
J30/60	0.8	1.0–2.0	1.0–2.0

Large-scale dryers

The development of dryers designed in series and produced on a large scale mostly from steel.

Computer control

The inclusion of computer-based monitoring and controlling systems including for measurement of moisture content.

Alternative energy sources

Soft coal and rice husks should be used as the sources of heat energy, combined with indirect drying methods using heated air from heat exchangers. These should replace all anthracite direct drying machines lowering energy consumption to 20–30% of the original level.

Technical improvements

Improvement of the furnace and drying machine, to extend their service life to more than 5 years and 15 years, respectively.

Matching dryer capacities to drying needs

The state granaries should adopt mainly the large and medium type drying machine, supplementing them with the small types. In smaller enterprises, lower capacity units would be appropriate.

Improving grain quality

Improve the grain handling to reduce breakage of grain.

Table 9. Drying time per barn.

Grain	Moisture content (%)	Ventilation quantity (m^3/h)	Ventilation quantity ratio (m^3/m^3 grain.h)	Time to safe moisture level in drying
Maize	26	10500	277	35–60
Rice	16.5	9876	261	15–30
Wheat	15.5	7740	204	20–20
Soybean	16.0	11000	280	10–20

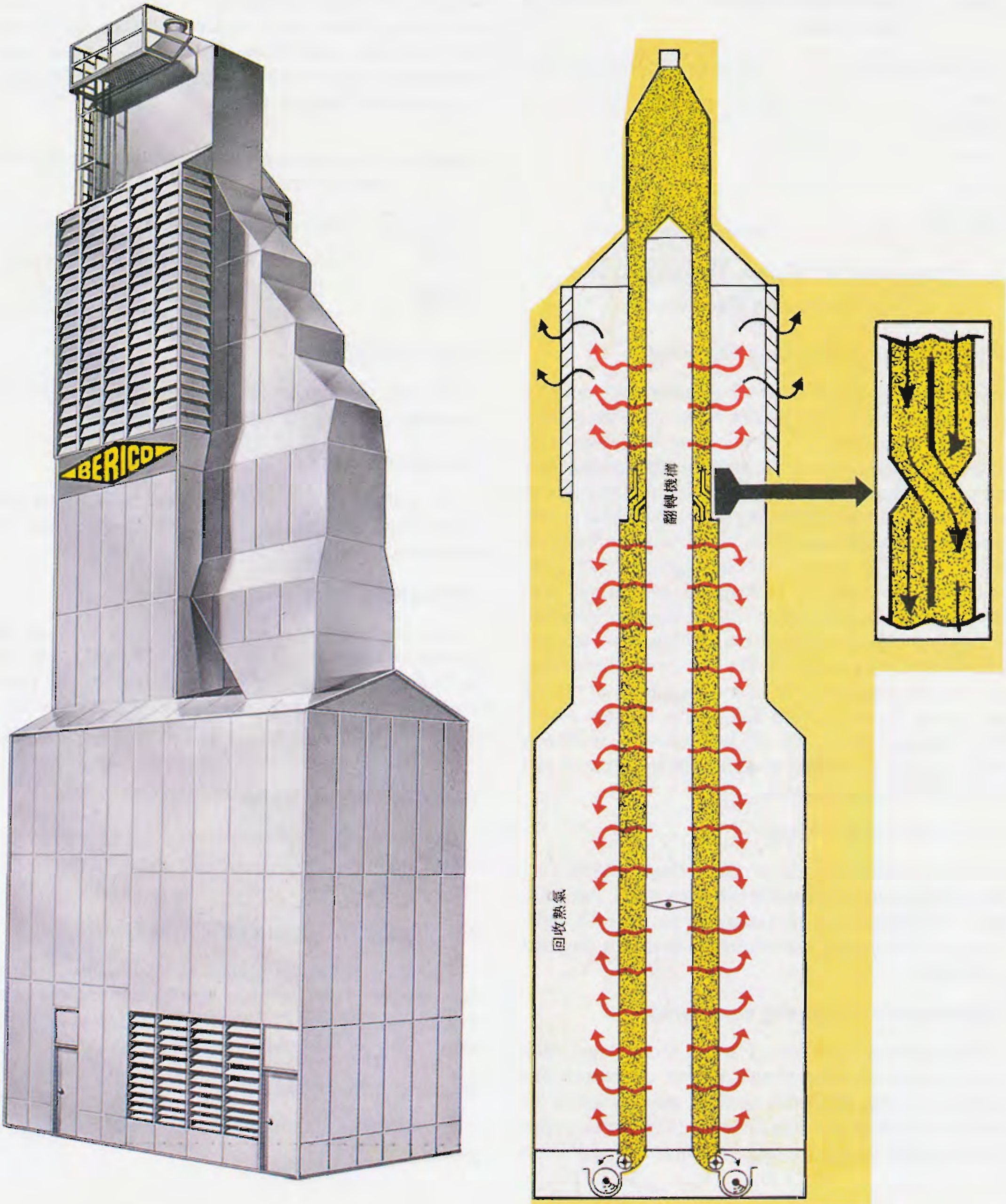

Figure 1. Crossflow grain drying machine.

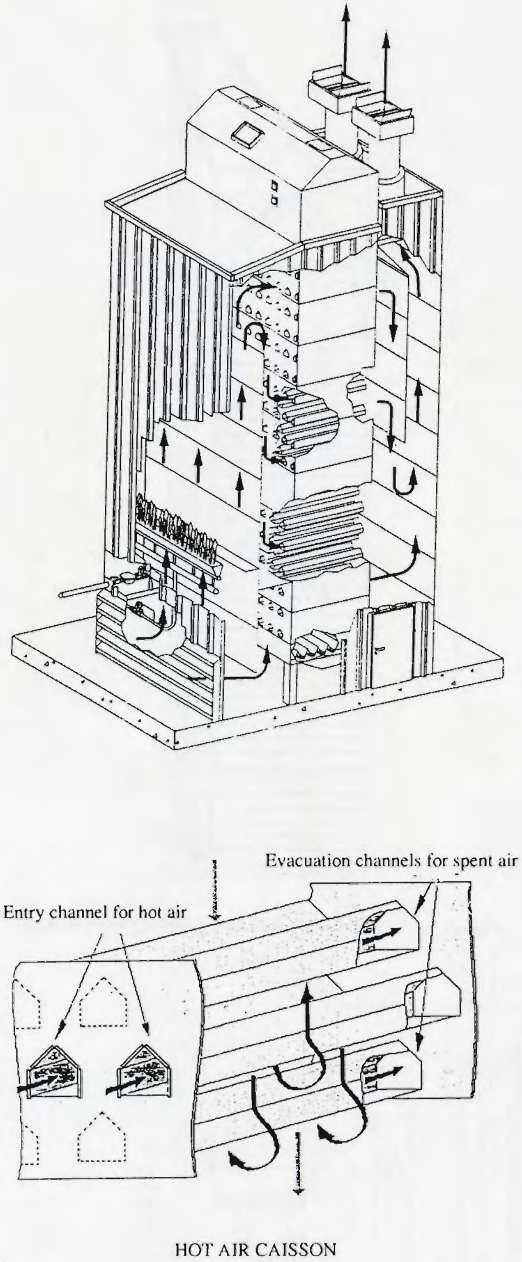

Figure 2. Mixed flow grain drying machine.

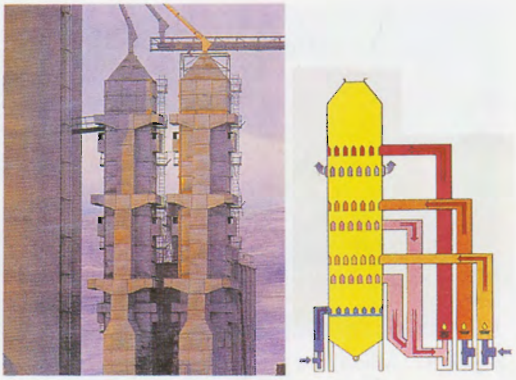

Figure 3. Counter-current grain drying machine.

Figure 4. Multi-pass mixed flow grain drying machine.

Figure 5. Mixed flow grain drying machine.

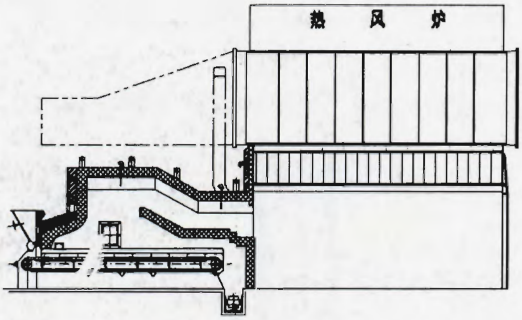

Figure 8. A new type of coal-fired hot-air stove.

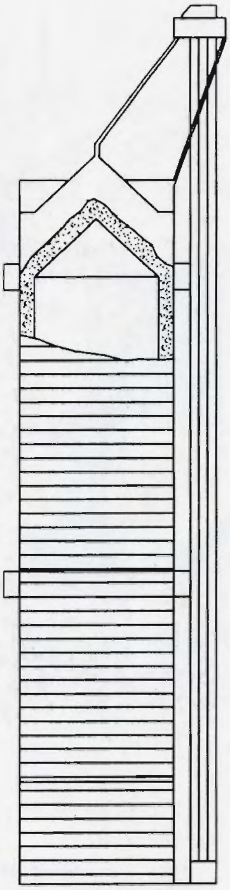

Figure 6. Cylindrical crossflow grain drying machine.

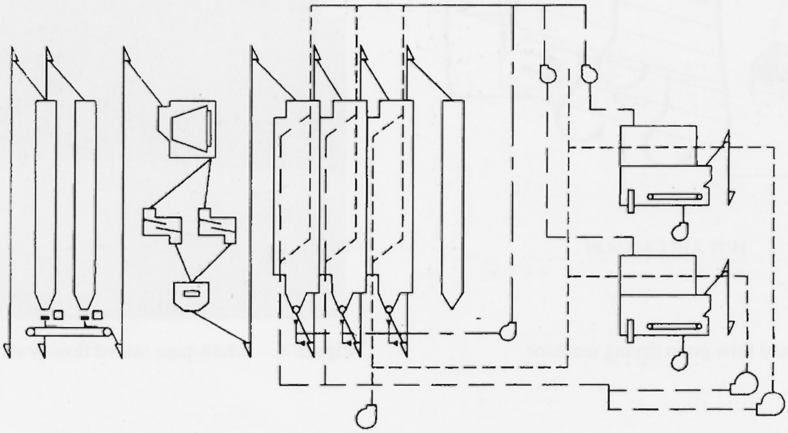

Figure 7. Process diagram for grain drying machine.

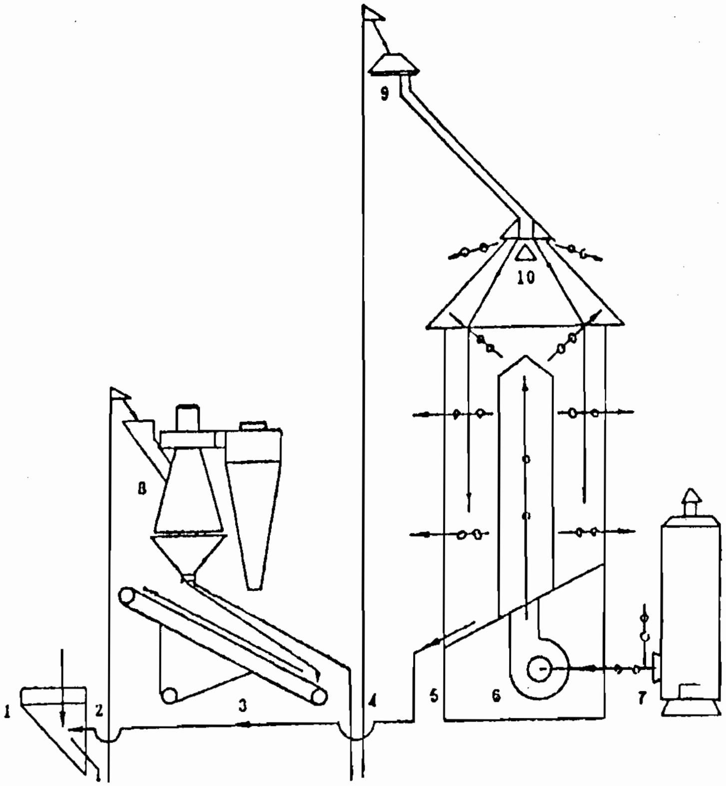

Figure 9. Radial type mechanical ventilation drying granary.

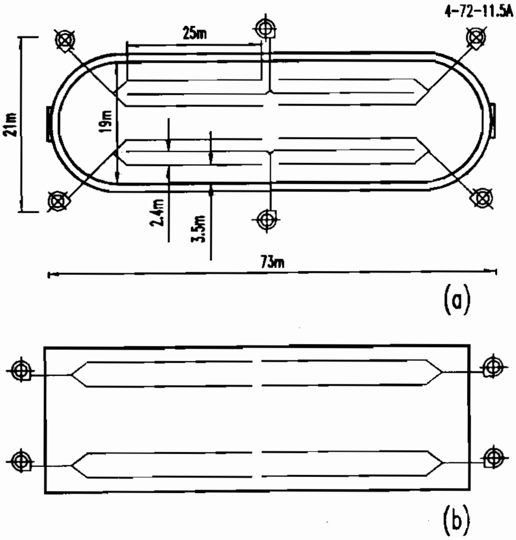

Figure 10. Plan view of ventilation ducting for (a) arch grain house, and (b) storehouse.

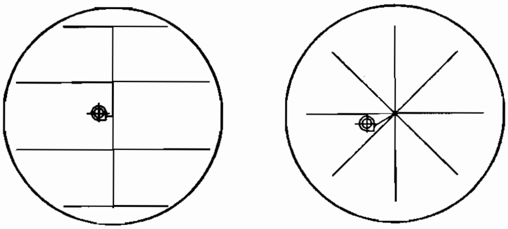

Figure 11. Plan view of ventilation ducting for cylindrical grain stores.

Grain Drying in India — Problems and Prospects

Sone Lal* and C.P. Ramam†

It is an accepted fact that drying of the grain is essential for its safe storage. A better storability of the grain can be ensured if the moisture content is within safe limits. As a rule of thumb, a 1% decrease in the moisture content or a 10°F (5.5°C) reduction in temperature of the grain doubles the storage life. Lower moisture level or temperature moderates the behaviour of the grain in storage.

Storage and handling of high moisture grain have posed serious problems in India, particularly at farm level, where mechanical dryers are not considered feasible due to heavy investment and maintenance costs. Traditional methods of sun drying are widely practised, but have certain disadvantages such as (i) unreliability; (ii) uncontrolled heating of grains; (iii) thermal stresses leading to grain fissures and breakage during milling, thus reducing its value; (iv) vulnerability to infestation (due to fissures and by lying out in the open); and (v) losses due to birds, rodents, etc. The problems are further aggravated by rains, floods, and cyclones, to which farmers in the vast Indian coastal belt are most prone. Here, even under normal conditions, high humidity is a serious factor impeding proper drying and storage of grains. The problem assumes even greater seriousness when crops are harvested early, and high humidity coupled with rains at harvesting time delay sun drying (Shankar et al. 1989).

The drying problem is more serious for paddy than for wheat in India, because most paddy-growing areas are in the coastal part of the country where unseasonal rains and sudden cyclonic rains are not uncommon during harvesting months. In the last decade, the northern part of India, particularly Punjab, Haryana, and Terai regions of U.P., have become major paddy producing areas and about 25% of the total paddy production of the country now comes from these three states. These states are major contributors of rice to the Central Pool as about 56% of the total annual national procurement of rice comes from these states (Table 1). As a result of the use of combine harvestors for paddy harvesting in these three states, high moisture paddy (in the range 16–28%; Doharey et al. 1993) is harvested and farmers bring the produce directly to market for sale, which is posing problems in government procurement of paddy. The real challenge is in proper drying of the paddy and adoption of appropriate technologies available in the country.

Problems

Though low moisture level of the grain is a long-term insurance against deterioration in storage, farmers are usually reluctant to incur extra expense on mechanical drying. The existence of favourable atmospheric conditions virtually rules out mechanical drying, a costly alternative. However, severe problems are observed during cyclonic storms when the fields are inundated and the grain is saturated. Even water dripping from harvested panicles and continuous inclement weather conditions do not stimulate introduction of mechanical drying as these are seasonal problems and mechanical drying is costly.

A study commissioned by the ASEAN Food Handling Bureau in 1985 in West and Central Java, Indonesia, indicated that the farmers dry only that paddy which they intend to keep for consumption, and sun drying is the only method used. A similar situation prevails in India, with seed grain also sun dried.

In the northern states of India, particularly in Punjab, Haryana, and Tarai regions of U.P., which have emerged as major paddy producing areas over the last decade, harvesting time coincides with the rainy season and the peak time for wheat sowing. The farmers try to sow early-maturing varieties of paddy or even harvest the paddy when it is slightly immature, so that the main wheat crop sowing is not delayed. In these states harvesting of paddy by combine harvestors is also widespread. Paddy having high moisture contents up to 28% is brought directly from harvesting to marketing yards (mandies) for sale to the government. This is posing a serious problem for the government. Though the government has installed mechanical grain dryers in certain marketing yards, farmers do not want to use the facilities.

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Table 1. Production and procurement of rice ('000 t) in Punjab, Haryana, and Uttar Pradesh during marketing years 1992–93 and 1993–94 with reference to national production and procurement.

State	Production and year		% of production on national basis		Procurement and year		% of procurement on national basis	
	1992–93	1993–94	1992–93	1993–94	1992–93	1993–94	1992–93	1993–94
Haryana	1869	2057	2.56	2.60	909	1248	6.96	8.75
Punjab	7002	7624	9.61	9.65	4905	5486	37.58	38.47
Uttar Pradesh	9709	10115	13.32	12.81	1186	1295	9.08	9.08
Total	18580	19796	25.49	25.06	7000	8029	53.62	56.30

All India figures of production and procurement ('000 t) during marketing year 1992–93 and 1993–94

Production and year		Procurement and procurement % of total production	
1992–93	1993–94	1992–93	1993–94
72867	78972	13053 (17.91)	14260 (18.06)

Though early harvest and subsequent mechanical drying reduces shattering losses and increases head yield, the farmers in India, because of transportation problems and the high cost, are not adopting these practices. The majority of the fields do not have proper approach roads, slushy conditions prevail in the fields in some areas, and labour costs are high.

In southern, northeastern, and eastern states, where there is no pressure to harvest so another crop can be sown, farmers do not harvest their produce at an early stage with high moisture content even if favourable weather conditions exist. Another problem faced by farmers is the lack of proper threshing devices for crops harvested at high moisture content. Harvesting at high moisture also poses the problem of preservation of straw for cattle feed as the straw spoils if kept at high moisture content for long periods (C.P. Ramam, unpublished data).

Sutherland (1989) pointed out that a major reason for the slow introduction of mechanical drying techniques in the ASEAN region is lack of financial incentives for farmers to dry their paddy. This is true also in the Indian case. Moreover, farmers believe that even if the moisture content is marginally more in the harvested grain it will be removed during processing (rice milling). If it is meant for parboiling, the high moisture level of the grain is of no consequence, as these grains invariably pass through a dryer.

Present Status of Grain Drying in India

Grain drying is not at present a priority area at farm level. Like fire services the need is felt in emergency situations such as unseasonal rains, or cyclonic storms at the time of harvest. Heavy demand is generated for quick drying under these adverse situations and then easily forgotten immediately the crisis passes. Now, after introduction of combine harvesters in Punjab and Haryana, a need is also felt in these states for introducing mechanical paddy drying facilities at farm/market levels. In India, drying facilities are available in rice mills which produce parboiled rice, in seed-processing units and, to a limited level, in marketing yards of Punjab state. These drying facilities are not open to farmers, while those at seed-processing units are available only to those farmers who contribute the grain for seed purpose to that particular corporation or company. So it can be safely assumed that farm-level grain drying facilities are totally absent in India. The main reason for this constraint is lack of incentives for dried grain and the consequential huge initial costs involved for limited seasonal use.

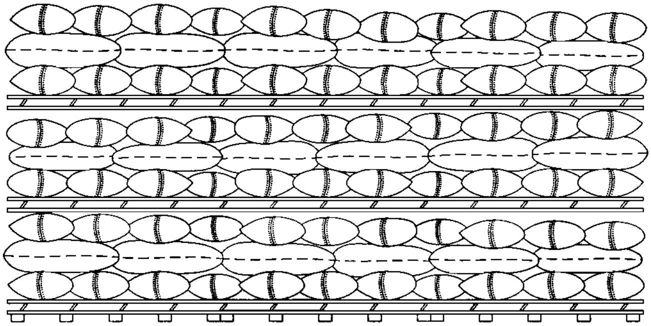
Case Study

In a study conducted in 1978 (C.P. Ramam, unpublished data) a block of villages with an assumed minimum of 50 t of paddy per day to be dried in 8 hours operation was considered. The basis for this assumption is that a common drying facility can serve a block of villages having an area of 1250 ha approximately. If such facility were available, villages adjoining that block would be tempted to use the facility also, so that there will be overlapping of areas. So it is reasonable to assume the drying facility, if established, would serve an area of 2000 ha. As per present production level, if 30% of grain produced reaches the drying centre then it is expected that a total quantity of 2500 t will be dried. The grain will be at various moisture levels, so if an average of 50 t per day of drying capacity is taken, the whole area can be serviced in 50 days, which is a very acceptable duration. In the case of unexpected rains, operation of the facility could be extended for 10–15 days. So drying capacity of 50 t per day is needed for 2000 ha. Marginal adjustments in the capacity of drying unit could be made, depending on the demand.

High Moisture Storage Problem at Commercial Level

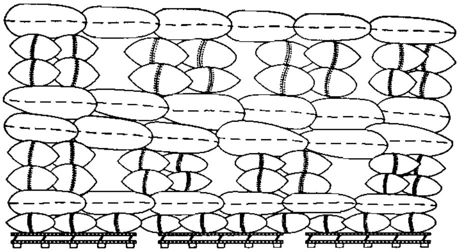
Private companies in India also have the problem of storage of high moisture grain. In the far south of the country, one corporation which handles and stores bulk of high moisture grain adopts various stacking techniques (Fig. 1): 'sandwich' stacking; 'window' stacking; and block stacking. The idea is to allow the free movement of air around the stack and through the stack so that the free moisture from grains can be transferred to the atmosphere when the humidity is low.

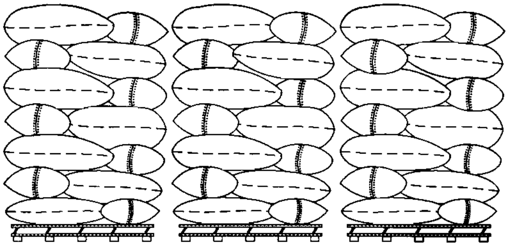
The Indian Grain Storage Institute is experimenting with low-cost, locally fabricated dehumidifiers using silica gel as a medium of absorption (Fig. 2). Exhaust fans are already installed in the godowns to pump out the high humidity air from inside them. Some success has already been achieved in this respect. A 10% reduction of relative humidity in a godown after 12 hours was observed during preliminary trials. This experiment established that even a crude dehumidifier (commercially available dehumidifiers are very expensive) can reduce the relative humidity of the air in storage godowns. An optimisation exercise remains to be carried out to determine the numbers, location, capacity, etc. Suitable modifications of the godowns, especially in the design of doors and ventilators, can enable protection of high humidity grains for a limited period, while simultaneously assisting in moisture reduction.



(a) sandwich stacking

(b) window stacking





(c) block stacking

Figure 1. Method of stacking bagged grain: (a) sandwich stacking; (b) window stacking; (c) block stacking.

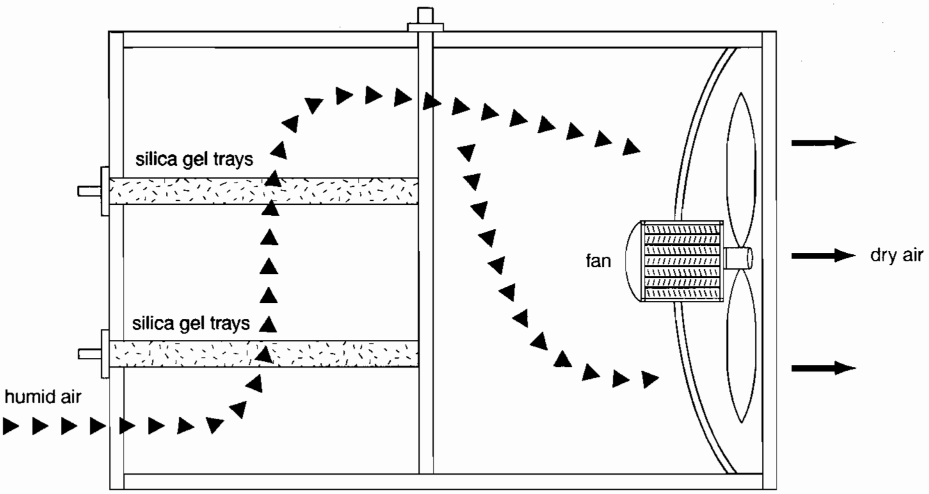


Figure 2. Dehumidifier.

Preservation of High Moisture Paddy at Farm Level

The Indian Grain Storage Institute has also developed a high moisture grain storage system which can help to reduce grain moisture gradually and store the grain safely. The system uses natural draught drying techniques for reduction of moisture in the grain. Natural airflow and convection currents of air help dry the stored grain if a vortex wind machine, as designed by the International Rice Research Institute (IRRI), Manila, Philippines, and the Central Institute of Agricultural Engineering (CIAE), Bhopal, India, is installed in the structure. Alternatively, a blower which can be driven either by a small diesel engine, electrical power, or otherwise, will accelerate the process of reduction of moisture.

The system consists of two concentric shells, cylindrical in shape. The inner shell and its base are perforated and the outer shell is plain protective sheet. The annular space (0.25 m radial) provides an ideal cushion to the variation of ambient parameters. The flow of air is further enhanced by static pressure (convection) as well as by air movement from areas of high relative humidity to these lower values (diffusion) (Fig. 3).

The paddy harvested in the first week of December 1983, during rain and having a moisture content of 22%, was loaded into the bin. The paddy was stored in the bin for 85 days. Periodic inspections of paddy, sample analysis, and recording of ambient and intergranular parameters were undertaken. The final moisture content during unloading was 14.5%. The physical analysis of the grain showed that discoloration was arrested. Organoleptic tests proved that the grains were palatable and as acceptable as any other grain stored safely. No bad odour or taste was found. The chemical analyses carried out on the grain indicated that all parameters were within acceptable limits. The samples were also studied for fungi and mycotoxins. The sample was found to have a mycotoxin contamination level of 20 ppb, 30 ppb being the tolerance limit prescribed by FAO for India. The viability dropped from 85 to 60% in 4 months, but the grain was not meant for seed purposes.

This design has also been adopted by Indonesia where five such bins have been erected. We would like to hear more from our Indonesian colleagues about the performance of these bins in their country.

The second-generation bin, of 3 t capacity has two concentric metal (G.P. sheet, 24 gauge) cylindrical shells with a larger annular space (42 cm) between them. It is an outdoor structure erected on a masonry pillar foundation. The bin has an outer diameter of 3 m and a height of 3 m. Optimising the design, it has a covered, inclined (15°) outer base to provide for drainage of water, discharge of grains in the base, to receive solar radiation from solar reflector, and to help movement of cold air from drainage port to the upper regions of the bin by convection. The base of the inner shell is perforated and suspended above the outer base at the same 15° angle. The suspension is achieved by means of M.S angle 50 × 50 × 6 truss design. An inner perforated diagonal pipe is provided within the perforated inner bin to help aerate the core of the bin (as diameter is large), as well as to help discharge wet air into the annular space (at top) of the bin and thence into the annular space atmosphere through vent holes at the top below the roof overhang.

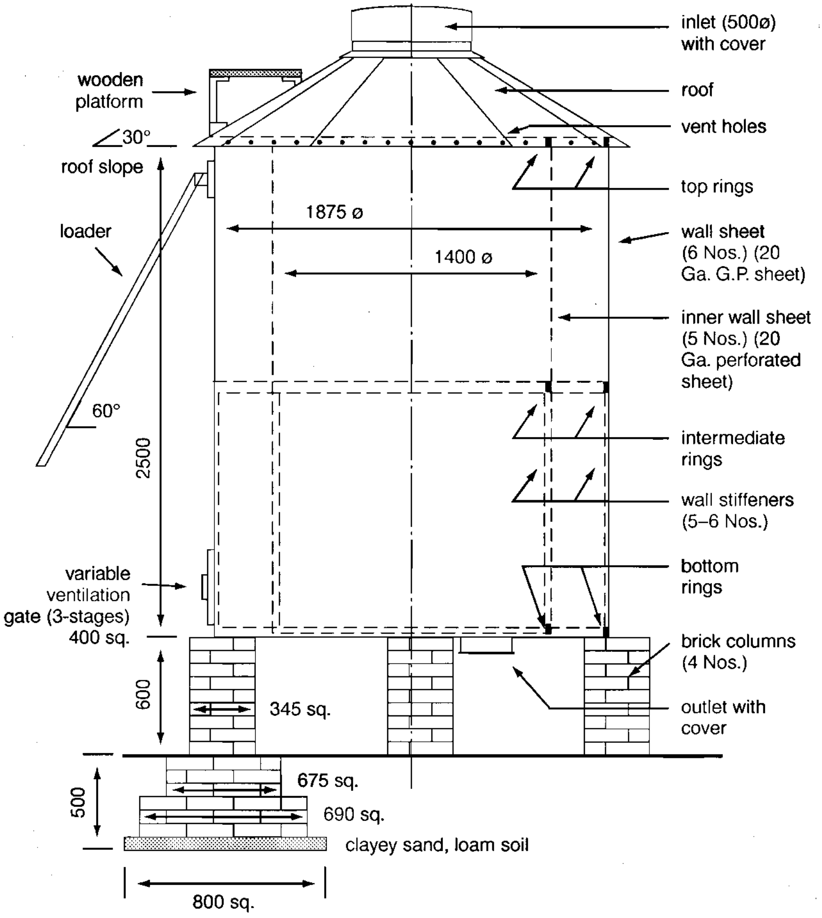


Figure 3. High moisture paddy bin.

A belt is provided to open or close the vent holes at the top (as required for airtightness) during fumigation. Ventilation flaps (four, equispaced around bin) are provided at the bottom of the side walls to facilitate natural airflow into the annular space for effective cooling and scavenging. An inspection door enables inspection within annular space and cleaning, and facilitates erection of the bin. Manual loading through ladders and an inlet cover at the top is provided. Two tubular discharge outlets enable quicker discharge by gravity flow. The bin is placed in such a way that the incline of the base faces N–S. A solar dish reflector (with angle adjustments) is kept at the upper side of the base to reflect solar radiation always into the projected base of the bin. This will heat up the air in the base of the annular space of the bin just sufficiently to augment the convection mode of natural air drying. The reflector is lined with 0.075 mm thick aluminium foil to improve its reflectivity.

Results of the experiments conducted for high moisture paddy stored in this structure are summarised below.

During the first trial, moisture content was reduced from 16.2 to 14% in two days (stored for 11 days), while it fell from 21 to 17% in two days, followed by a reduction to 13.8% in eight days and was unloaded at 12% (after more than two months). The solar reflector provided for airflow convection by raising the annual air temperature by 2–5°C (depending on sun conditions). The moisture was reduced to 15% in one week and fell even further to 14% on the 24th day. The ambient relative humidity varied between 63 and 89% while the inter-granular relative humidity was 80–90%. Ambient temperature ranged between 25 and 34°C. The grains were cool, and there was no damage due to moisture, no condensation, no moulds, and no hot spots observed. Using the solar reflectors enhanced the performance.

Based on the same principles, the Institute also developed a non-metallic high moisture paddy bin suitable for the northeastern region of the country. The results of a trial with this were very satisfactory: moisture content was reduced from 17.7 to 13.3% in a three-month period without any loss of quality.

The Institute does not claim that this is a solution for all high moisture paddy problems in India. It is only meant to supplement the drying activity in the country and also to implant the concept of scientific 'drying' in farmers' minds. It is interesting to note that some of the traditional systems have merits of inbuilt ventilation leading to some aeration and natural drying. The need for natural aeration has been understood and provided for down the ages. So it is probably unnecessary to further emphasise the significance of well ventilated conventional as well as modern systems in grain storage. India has tremendous export potential for agricultural commodities, especially rice. If this potential is to be properly explored, greater realisation of the importance of grain drying will be necessary.

Development of Mechanical Dryers for Farm-level Use

Various national institutions in India have evolved many designs of mechanical dryers using solar energy and agricultural waste. The Indian Grain Storage Institute had developed some designs which are applicable at the farm level. One such design is a fuel operated dryer in which conduction material in the form of stones is used. No electrical energy is required and the construction is very simple. It can be done by the village artisans. A drying bin with a perforated base is constructed from bricks and mud mortar. An oil drum is used as an indirect heat exchanger which is heated by agricultural waste. The heat exchanger is covered with stone pieces which absorb heat from the exchanger and retain the energy for a long time, so that it is available for drying the grain. The heated air enters the dryer by natural draught and no forced circulation is employed thus eliminating the need for electrical power (Fig. 4).

The Institute also developed an electrically operated blower with an agricultural-waste-fired furnace (EBAWFF) 1 t capacity batch dryer. The dryer has three, equidistantly spaced vertical stacks as its drying chamber. The drying chamber is linked to the furnace with flexible rubber pipes so that the drying chamber as a whole can be tilted backwards for easy discharge of dried grains. The furnace, which uses agricultural waste as fuel, is provided with three pipes which can be connected directly to each of the plenum chambers through an axial blower. A 50 mm air pipe is connected to an air duct–blower system to ensure better combusion by fluidisation of the fuel (Fig. 5).

Hence, adequate technology is available in India to meet fully the drying requirement at farm level. The question is one of cost, skill, and incentive to produce stable dry grains of high marketable value.

Designs for solar batch dryers have also been developed and tested for their performances in coastal areas and northeastern parts of the country where high prevailing relative humidity limits the storability and drying of food grains. These dryers of 650 kg batch capacities incorporate solar cabinet collectors (single and double pass types) as well as parabolic reflectors (horizontal and inclined) which can be adopted with the same holding chamber blower regime (1.5 h.p. electric blower). These provide elevated, but controlled, temperatures to air for drying, varying from 5 to 15°C, and can produce high quality dry grain when compared with traditional sun drying. Hence, these dryers could be very useful where sufficient insolation is available.

Future Plan of Action

Minister Jesus Tanchanco rightfully mentioned in his opening remarks at the FAO Workshop on Rice Postharvest Technology held in the Philippines in July 1984 that commercial aspects of research of grain drying should not be forgotten. It is not only biology or physics of the grains and dryers which are important but also the socioeconomic considerations, communication problems, and designing or re-designing the technology to suit the needs of developing societies (Khan 1984). These observations are as relevant to present Indian conditions as to any developing country. Hence, suitable modifications of available technology may be essential for its adoption at field level. Intensive popularisation and extension efforts are necessary to convince the farmers to adopt drying techniques.

The Ministry of Food in the Government of India has taken the responsibility of postharvest technology research and extension activities through the Indian Grain Storage Institute and Save Grain Campaign activities covering the length and breadth of the country.

A cooperative effort is needed at farm level for establishing multipurpose postharvest technology centres in which drying units could be an important component. In addition, cleaning, milling, and storage facilities could also be installed. Management of such units should be done through cooperatives, either farmers or marketing federations. The technical help in the initial stages could be provided by organisations like the Indian Grain Storage Institute and the Save Grain Campaign until the cooperatives acquire full technical competency. Manilay et al. (1984) made a similar observation that organisation of farmers into cooperatives or associations could solve the problems of volume and capital needed to provide drying facilities at farm level.

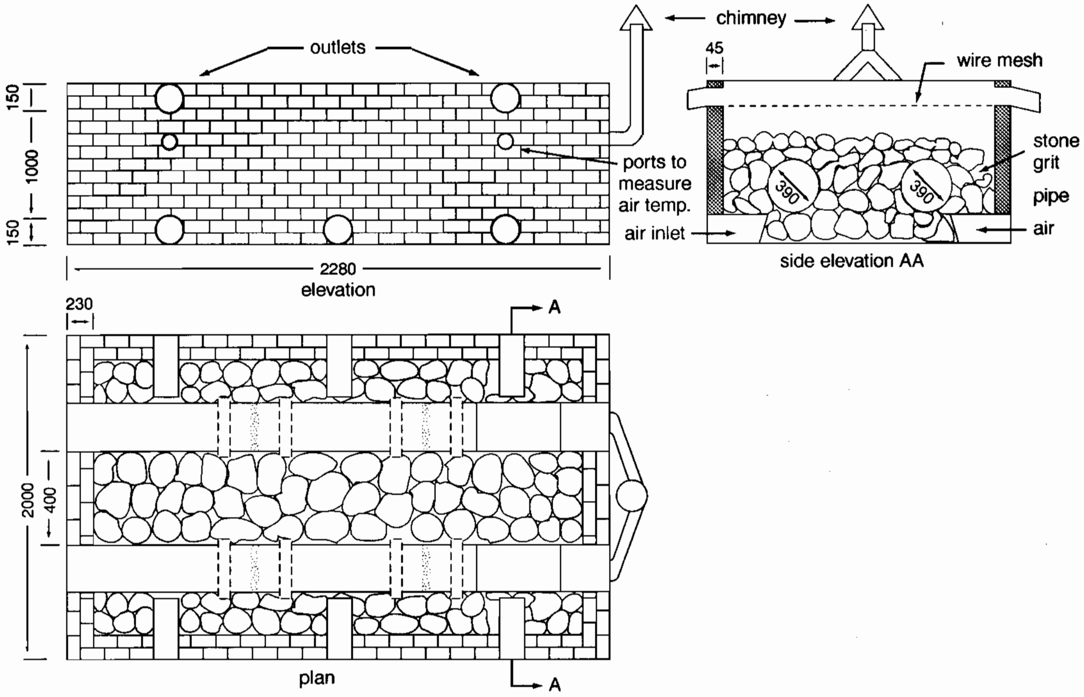


Figure 4. Fuel-operated dryer.

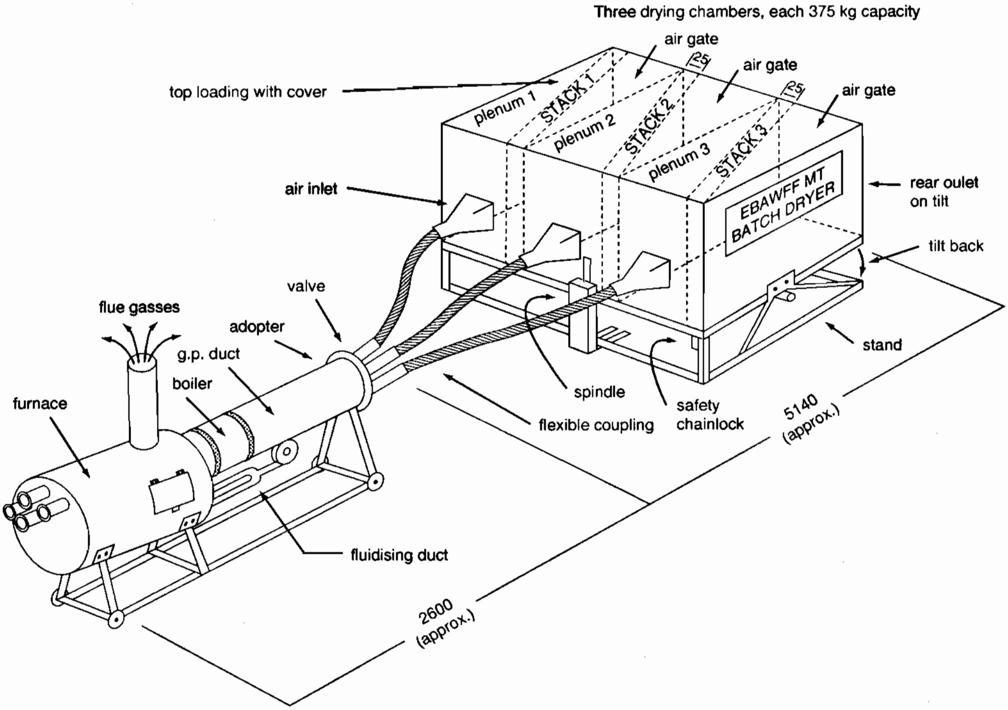


Figure 5. Electrically operated blower with agricultural-waste-fired furnace.

Introduction of incentive schemes for marketing and preserving grain will also make quality grain available to the consumer. Hence, an integrated approach to technologies and extension strategies should be evolved so that grain drying at farm level becomes a reality.

References

Doharey, R.B., Pal, R., Singh, R.P., Chander, R., Aggarwal, J.P., Singh, B.M., and Lal, S. 1993. Studies on the impact of combine harvesting and threshing machines on the breakage and milling of common, fine and superfine varieties of paddy in comparison with manual harvesting and threshing. Document no. 31(3)–165–170.

Khan, F.H. 1984. Paddy procurement and drying: certain constraints. Paper presented at FAO Workshop on Rice Postharvest Technology, Manila, Philippines, 1984.

Manilay, A.A., Jose, J.L., and Divinagracia, L. 1984. A feasibility study of a thresher–dryer mill operation at farm association level. Paper presented at FAO Workshop on Rice Postharvest Technology, Manila, Philippines, 1984.

Shankar, G., Kumar, S.R., Sirka, H.C., and Ramam, C.P. 1989. Storage system for high moisture paddy grain — a natural draught technique. Journal of the Institute of Engineers (India), 69, 77–86.

Sutherland, J.W. 1989. The potential for grain aeration and drying in the ASEAN region. In: de Mesa, B.M., ed., Grain postharvest systems. Proceedings of the 10th ASEAN Technical Seminar on Grain Postharvest Technology, Bangkok, 19–21 August 1987. ASEAN Grains Postharvest Programme, 52–58.

Revisiting Sun Drying of Grain: Widely Adopted but Technologically Neglected

Reynaldo M. Lantin, Bernabe L. Paita and Herbert T. Manaligod*

THE drying of paddy using the sun is as old as the rice culture itself. It is a basic form of postharvest processing and, although primitive, it is still the popular method of drying in developing countries. It fits into the cultural, technological, and economic situation of present users, namely small-scale farmers, and medium-scale paddy traders and rice millers.

Although widely used, sun drying has been taken for granted. Modern mechanical dryers have been claimed as technologically superior to sun drying, overshadowing the latter's biggest single advantage: it is a free and clean energy source. Sun drying has not received technological attention to remove its defects or deficiencies. Rather, the tendency has been to replace sun drying with mechanical drying.

FAO (1995) has forecast Asia's output for paddy in 1995 as 494 Mt, about 4 Mt up from 1994. If, through technology intervention, 90% of the paddy were to be dried mechanically, and if 70.8 kg CO_2 were produced per tonne of rice in large-scale drying facility (Oida et al. 1995), the total amount of CO_2 emitted per year for drying rice would be about 25.3 Mt. Thus, from a global warming point of view, it would be fortunate if sun drying remained as the dominant method of drying.

In Japan, sun drying of paddy (in the field by hanging rice sheaves on wooden frames and in the yard by spreading grain on straw mats) was the sole practice until 1930, falling to about 30% by 1972 (Yamashita and Ikeda 1985). Greenhouse sun drying began to be adopted in 1980 and has been gradually adopted since then, along with mechanical drying.

In the Philippines, rice millers who are forced by competition to procure wet and freshly harvested paddy, use the sun drying method as a standard for deciding on investing in mechanical dryers. They look for comparable simplicity or ease of operation, low operating expenses, and low capital costs in prospective mechanical dryers.

The fact that still more than 90% of paddy locally produced and processed in Laguna, Philippines is sun dried, attests to the recognised advantages of and preference for sun drying (Paita and Lantin 1995). The rising labour cost in sun drying and the increasing demand for quality rice could be compelling reasons for a switch to mechanical drying if the sun drying method is not improved.

Previous Research on Sun Drying

Research on the technological aspects of sun drying has dealt with the following topics: design of a wheeled rake (Kumaresan et al. 1995); modelling of the sun drying principle (Suhargo et al. 1994; Elepaño 1991); determining optimum grain thickness and sun drying weather probabilities, and mechanising grain stirring (Gayanilo 1988); grain losses, quality deterioration, and paddy stack temperature rise in field crop drying (Bockhop 1984); and effectiveness of drying surface materials (Khan 1973).

In the Philippines, comparative cost studies of sun drying versus mechanical drying for dry and wet seasons (Bonifacio et al. 1990) showed the superiority of mechanical drying when direct and indirect costs (quality and quantity losses) were considered in the computations. In a case study, Phan Hieu Hien (1991) reported that direct costs of sun drying were lower than those of the mechanical flat-bed dryer. Tolentino et al. (1990) proposed alternatives to highway sun drying.

Problems of Sun Drying and Local Improvements Made

The major problems in sun drying involve weather risks, losses, and high labour costs. Some details and improvements made are described below.

1. *Ineffective sun drying during rainy weather.* Protection against rain must not only be in place, but also drying of the grain must proceed to avoid spoilage. Water must be drained quickly and

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completely. Some of the indigenous methods farmers and rice-mill operators employ to protect the paddy from rain are canvas or plastic sheet covers on grain piles or bunds, large-capacity scoops and solid board rakes for quick paddy retrieval, and a tractor-powered payloader or bulldozer for mechanising grain collection. Crowned, corrugated, and peripherally drained pavements have been designed to shed and drain rain water easily.

2. *Lack of control in drying process resulting in grain overdrying and fissuring.* Sun drying is difficult to control in terms of temperature and exposure time of the grain at high temperatures. Some of the local techniques for attaining uniform grain drying are periodic raking of paddy ridge and pavement furrow or corrugated thin grain layer, progressive paddy layer thinning, and using a corrugated pavement.
3. *Limited capacity.* The recommended 4 cm thickness of the grain bed to effect fast and uniform sun drying of paddy limits the amount of paddy to be dried on a given pavement size. Some small- to medium-scale rice mills solve the limited space problem by contracting drying to groups of labourers who have access to paved areas, like streets of housing areas and even highways. This solution brings forth secondary problems and is to be considered as a stop-gap measure.
4. *Labour-intensive and low-productivity nature of sun drying.* Few local improvements have been made to increase labour productivity except in large rice mills where grain retrieval is mechanised.
5. *Sun drying on roads and highways.* This practice is hazardous and is normally prohibited. The National Post Harvest Institute for Research and Extension (NAPHIRE) in the Philippines is supporting farmers' cooperatives by providing technical and financial assistance for two-stage drying and multi-purpose sun drying pavements as alternatives to highway sun drying.
6. *Limited drying floor space.* Paddy drying at the farming household level has never been improved. Plastic nets or bamboo or woven palm leaf mats are used as underlays for sun drying small quantities of paddy on the yard or street shoulder.
7. *Hygiene problems.* Stones, dirt, other seeds, debris, fowl and animal excreta, perspiration by workers, feet with skin diseases or wounds, and even toxic chemicals may contaminate the paddy grains while they are being dried. The degree of hygiene observance in sun drying depends upon the attitudes of the labourers and of the trader or rice-mill operators contracting them. This aspect of sun drying has received insufficient attention.

Engineering Innovations for Improving Sun Drying—Applications

So far, engineered innovations to improve sun drying or to correct its inherent defects are few and far between. The following machines are intended to increase labour productivity and to cope with the need for quick grain retrieval when rain is imminent.

(a) *Pavement grain collector* (Fig. 1). Designed by IRRI (Manaligod and Quick 1989), the machine was tested and modified by the Central Luzon State University (Santiago 1991) and is being pilot tested in rice mills by the Philippine Rice Research Institute (PhilRice).

Figure 1. The pavement grain collector designed by IRRI.

(b) *Grain suction-blower.* The pneumatic principle embodied in a commercial unit meant for various grains may be adapted to rapidly collect and spread paddy. The high power requirement, initial cost of the machine, and the rapid wear of grain-contacting parts may hinder its adoption by the intended users.

(c) *Multi-purpose yard drying implement* (Kumaresan et al. 1995). This wheeled rake with different attachments is pushed by two workers over the grain bed to stir the grain.

Engineering Innovations for Improving Sun Drying—Concepts to Pursue

The following concepts to solve the major problems in sun drying may be the subject of future research in sun drying of paddy:

(a) *Protection from rain.* A movable roof or canopy may be made of clear plastic to reduce material costs and at the same time to trap solar radiation. It may be telescoping, collapsible, or retractable, wheeled so as to move readily on rails or pavement, and with separable sections to protect paddy collected and piled at selected spots on the pavement (Fig. 2).

(b) *Attainment of uniform drying, prevention of overheating and overdrying, and coping with overcast periods and rainy weather.* Evenly dried paddy may be achieved by mechanised stirring. In a more sophisticated design, stirring may be automated using microprocessors. Conceptually, the sun-drying pavement itself is like a mechanical dryer in which the bin is horizontally expanded. The configuration, however, requires a different scheme whereby supplemental heat from a rice-hull gasifier is introduced only during overcast periods. For all-weather operation and all-time drying, a clear plastic canopy, which can be rolled or folded, will protect the grain from rain. The principles of low-temperature on-pavement drying and storage system will be applied. The following schemes integrate the provision of supplemental heat with the sun-drying operation:

  (i) Flame drying using a rice hull gasifier. An engine- or motor-powered mobile device consisting of a gas-fired burner, a blower, and a set of grain stirrers, will initially run rapidly across the grain bed surface to skin-dry and sterilise the paddy. Afterwards, only heated air is blown through the stirred paddy. This concept is shown in Figure 3.

  (ii) Partially perforated floor for heated air. A thick bed of moist paddy is spread on rows of perforated plastic pipes embedded in the pavement or on rows of perforated metal sheets over built-in channels. Heated air from a burner fuelled from a rice-hull gasifier is blown through the pipe or channel to dry the grain. This concept is shown in Figure 4.

  (iii) Condensed moisture absorption. Wheels lined with absorbent material are attached to the rake or grain turning device. After the ridge is turned over and shoved to the dried pavement furrow the wheels are rolled over the wet pavement to absorb the moisture condensed underneath the paddy ridge. The absorbed water will be squeezed out at the end of the run or on-the-go. This technique may be studied or modelled.

  (iv) Circular drying pavement with weather chamber. This concept takes advantage of the higher efficiencies and easier automation involved in circular travel of the devices for paddy spreading, stirring, aerating, collecting and supplemental heat application, and the sensing instruments, compared with back-and-forth travel over rectangular-shaped pavements. A variant is to use only a portion of the existing rectangular drying pavement to reduce costs. The system could be made portable for field use. Studies of the design parameters and models of the circular pavement concept may be undertaken. The hybrid design concept is illustrated in Figure 5.

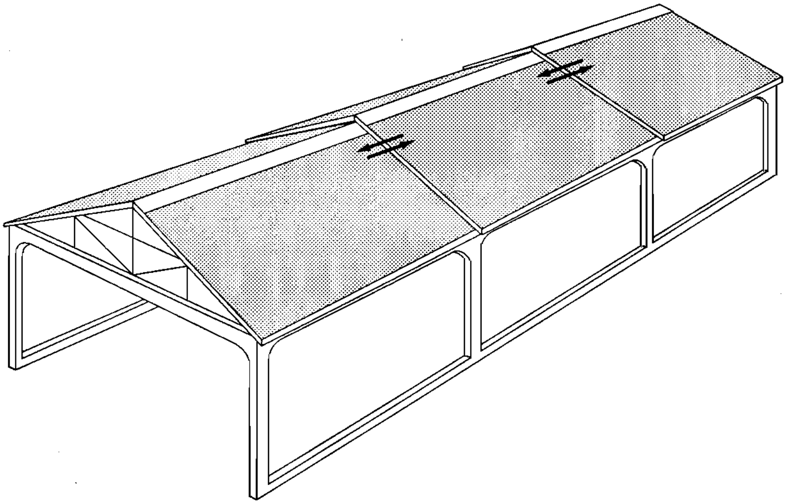

Figure 2. Movable roof on stationary framework.

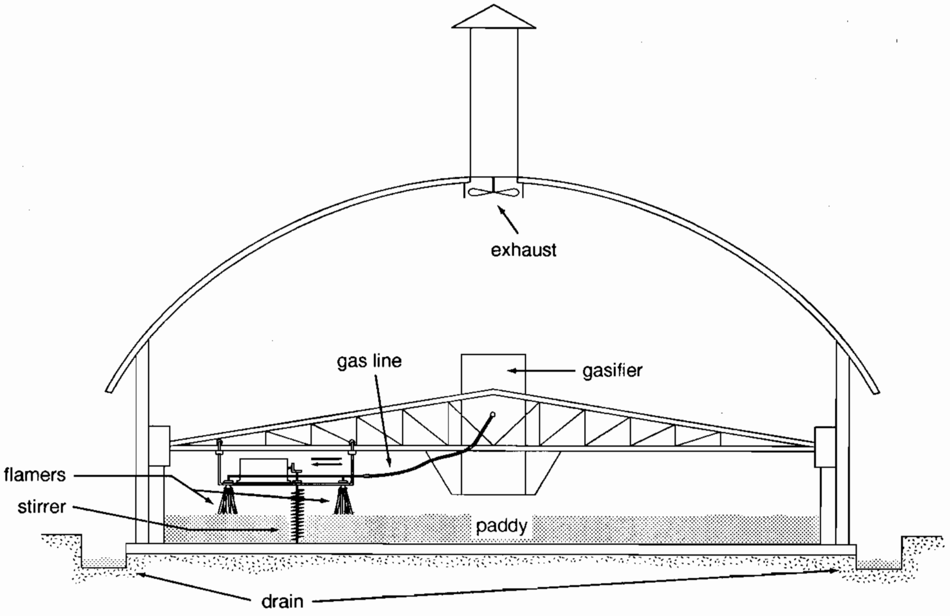

Figure 3. Flash drying of wet grain during rainy or cloudy weather.

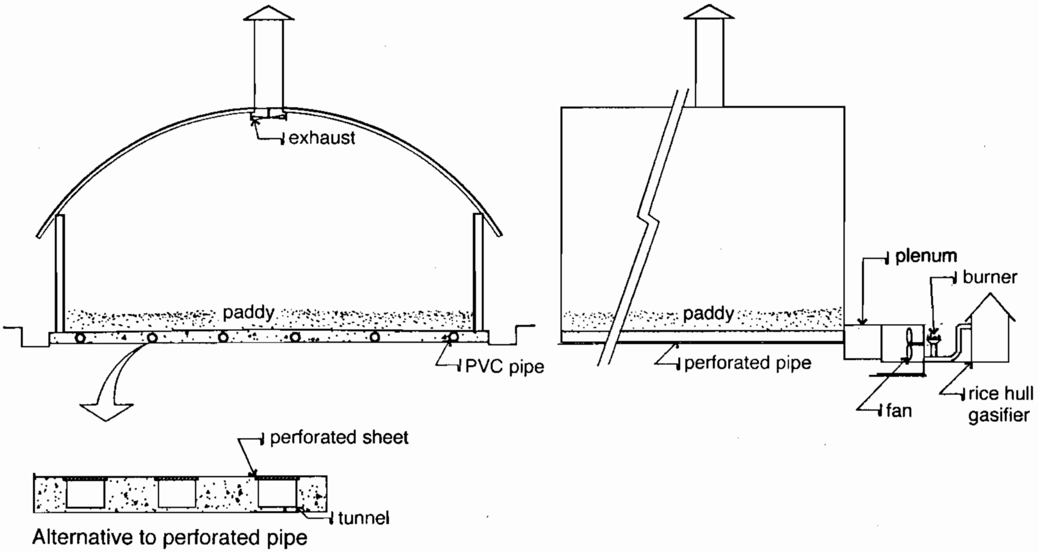

Figure 4. Supplemental heat for rain-protected sun drying pavement.

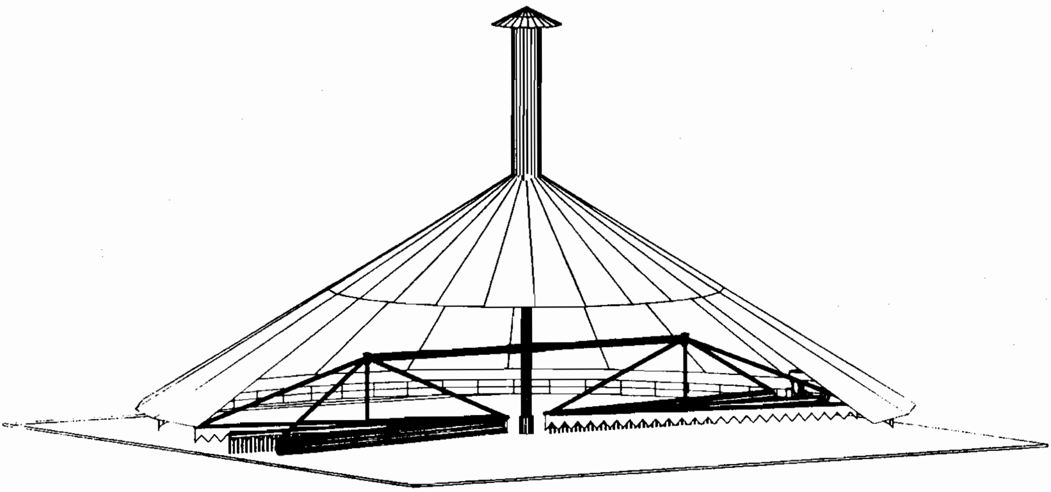

Figure 5. Circular drying platform with weather chamber.

Other Sun Drying Concepts for Adaptation

(a) *Tunnel drying*. Developed by the University of Hohenheim, Germany, this sun drying technique for high-valued crops is considered too expensive for rice. Certain features, however, may be studied for adaptation.

(b) *Fully automated sun drying*. This concept by Sato (1993) emphasises the reduced carbon dioxide emission from a solar drying facility. A 10 cm thick layer of paddy with 24% initial moisture content is sun dried on a 5 × 50 m concrete floor covered with vinyl sheet. Paddy is stirred and conveyed by electric motor-driven devices. The system is calculated to emit only one-tenth as much carbon dioxide per tonne of rice as in a rice centre or large-scale drying facility where 53.3 kg CO_2/t of rice comes from burning kerosene and 17.5 kg CO_2/t of rice comes from using electricity which is generated using fossil fuels. The concept is shown in Figure 6.

Farm-level Drying

There is debate as to whether drying technology should be in the hands of only traders and millers who can achieve economies of scale. This would put the farmers in a situation where they cannot add value to their paddy before marketing it, and some schemes to reverse this situation, like cooperative drying and contract drying, have been formulated and promoted.

The lack of sun-drying pavement or space should no longer be a constraint to sun drying by farmers. They can use their harvested dry fields for technologically improved sun drying by using bamboo mats or fine plastic nets on straw underlay. A bonus is that weeds will be controlled.

If the problems of labour-intensiveness, rain, and lack of supplemental drying means are solved by adaptation of the concepts described above, the solutions could in turn be adapted at the farm level through farmers' associations or cooperatives. These are challenges for engineers, social scientists and economists working together to develop innovative systems so that farmers' incomes can be improved through achieving an increased share of the return from their marketed rice product. Using sun drying as the base system, the solutions will no doubt be also environmentally benign.

Future Steps

The IRRI Engineering Division seeks to collaborate with the postharvest institutes or engineering units/centres of the National Agricultural Research Systems (NARS) in the developing countries, and with the advanced engineering laboratories in developed countries regarding research and technology development related to sun drying.

IRRI and NARS can work together as partners in formulating research and development proposals to donors. Existing networks, such as the Crop and Resource Management Network (CREMNET) of IRRI and the Regional Network for Agricultural Machinery of UN/ESCAP, may be utilised under suitable arrangements.

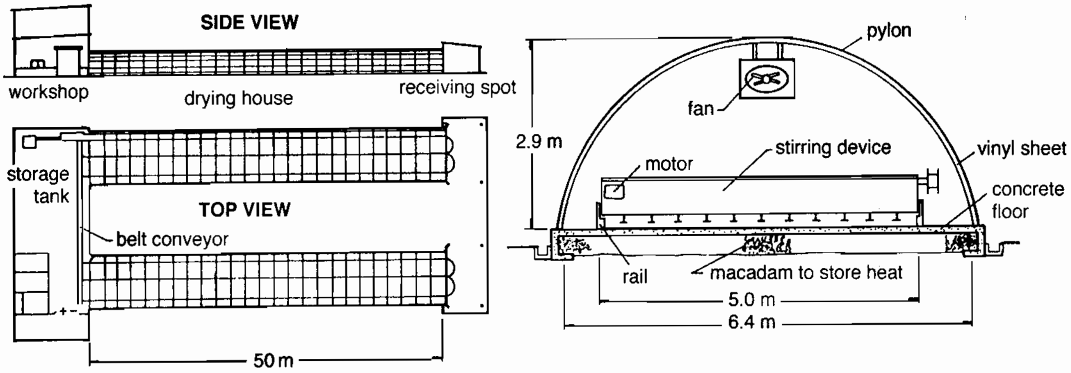

Figure 6. Rice drying facility using solar heat.

References

Bockhop, C.W. 1984. Deterioration of paddy grains in field handling and drying under humid environment. Proceedings of the International Conference on Paddy Deterioration in the Humid Tropics, Bangkok, Thailand, 1984, 32–33.

Bonifacio, E., Quick, G.R., and Pingali, P.L. 1990. Deriving design specifications for mobile dryers: an end-user perspective. International Rice Research Institute Paper, 1990.

Elepaño, A.R. 1991. Mathematical modelling of selected agricultural crop dryers for the humid tropics. PhD thesis, Queen's University, Kingston, Ontario, Canada.

FAO (Food and Agriculture Organization) 1995. Food outlook, No. 8/9 (August/September 1995). Rome, FAO.

Gayanilo, V.G. 1988. Paddy sun drying studies. In: Naewbanij, J.O., ed., Advances in grain postharvest technology. Proceedings of the 11th ASEAN Technical Seminar on Grain Postharvest Technology, Kuala Lumpur, Malaysia, 23–26 August 1988, 21–44.

Khan, A.U. 1973. Alternative solar drying methods. International Rice Research Institute Agricultural Engineering Department Semi-annual Report No. 17, 1973.

Kumaresan, K., Kumaravel, S., and Dakshinamurthy, A. 1995. Multipurpose yard-drying implement for rice. International Rice Research Notes, 20(4), 22.

Manaligod, H.T. and Quick, G.R. 1989. Pavement grain collector. Patent application. International Rice Research Institute, Los Baños, Philippines.

Oida, A., Hoki, M., and Salohke, V.M. 1995. Development of environment-symbiotic agricultural machinery. Proceedings of the 1994 Mie International Forum and Symposium on Global Environment and Friendly Energy Technology, 22–25 March 1995, Tsu, Mie, Japan.

Paita, B. and Lantin, R.M. 1995. Characterization of rice postharvest technology practices. Progress Report to International Rice Research Institute.

Phan Hieu Hien 1991. Unpublished report of trip to Pangasinan Province, Philippines (18–20 September 1991). Los Baños, Philippines, International Rice Research Institute.

Santiago, E.P. 1991. Testing, evaluation and modification of the IRRI prototype grain collecting machine. MS thesis, Institute of Graduate Studies, Central Luzon State University, Muñoz, Philippines.

Sato, J. 1993. Drying and adjusting facilities (in Japanese). Report on agricultural production technology for environmental conservation. Japan Society of Agricultural Machinery, 1993. [Cited by Oida et al. 1995]

Suhargo, Widayat, H.P., and Bakker-Arkema, F.W. 1994. Sun-drying of grain. Proceedings of the International Commission of Agricultural Engineering, XII World Congress on Agricultural Engineering, 29 August–1 September 1994, Milan, Italy, Volume 2.

Tolentino, H.A., Rodriguez, A., Regpala, A.R., and Dingle, A.J.P. 1990. Study on the alternatives to highway paddy drying in Central Luzon, Philippines. Muñoz, Nueva Ecija, Philippines, National Postharvest Institute for Research and Extension, Technical Bulletin No. 15.

Yamashita, R. and Ikeda, Y. 1985. Evolution of paddy drying in Japan. Proceedings of the International Conference on Small Farm Equipment for Developing Countries. International Rice Research Institute, Los Baños, Philippines, 2–6 September 1985.

A Low-cost In-store Grain Dryer for Small Farmers

Le Van Ban, Bui Ngoc Hung, and Phan Hieu Hien*

DRYING paddy harvested during the wet-season in Vietnam is an urgent problem that must be solved if losses due to grain deterioration are to be reduced. Current dryers used in Vietnam are of medium size and suitable only for areas with fairly large production. Smallest among these is the popular flat-bed dryer, with about 600 units currently in use in the Mekong delta; these dryers are used under a contractor's system for farmers having 1–2 ha of land. For the majority of small farmers cultivating less than 0.5 ha (as in Ho-Chi-Minh City suburbs, Tien-Giang and Ben-Tre provinces of the Mekong delta, southeastern provinces, central coast, and northern provinces), dryers so far have not been been cheap enough to be accepted.

In recent years, rural electrification in Vietnam has been accelerated. Major new hydropower plants amply supplied with water during the rainy season are providing more energy to the agricultural sector. For example, in Thai Binh, a major rice-producing province in the Red River delta in the north, power lines have reached all villages.

A 'very low-cost dryer', called SRR-1, has been developed at University of Agriculture and Forestry (UAF), Ho-Chi-Minh City, to meet the needs of small farmers with scarce finance, who live in areas where electricity is available.

Materials and Method

Design of SRR-1 dryer

The design of the SRR-1 dryer is based on the principle of low-temperature in-store drying. This technology has long been applied in temperate climate countries, and was introduced into Asian countries some years ago (Kim et al. 1989). Tests at the International Rice Research Institute showed that paddy at high moisture content (26% wet basis) could be dried in one stage to 14% without adversely affecting grain quality (Muhlbauer et al. 1992; Gummert 1994).

The dryer (Fig. 1) has three components: a two-stage axial fan; an electric heater; and a bamboo-mat drying bin.

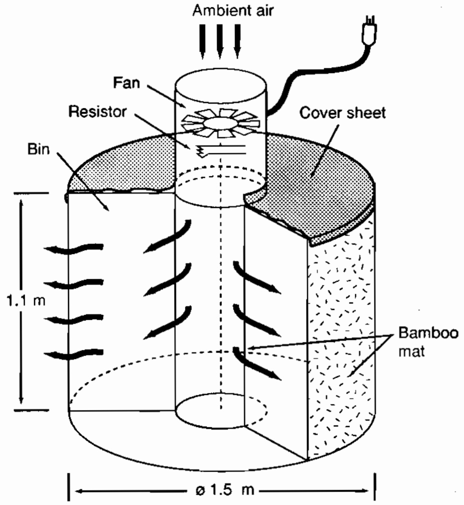

Figure 1. Construction of SRR-1 dryer.

The *drying bin* consists of two concentric bamboo-mat cylinders 0.4 and 1.5 m diameter, both 1.1 m high. The inner cylinder is supported by a frame made of 6 mm steel wire. The bin can hold 1 t of paddy.

The *fan* is driven by a 0.37 kW (0.5 h.p.), single-phase, 2800 rpm electric motor. Two 350 mm-diameter, 7-blade rotors are mounted on both ends of the motor shaft and inside a steel casing. The plastic rotors are locally made, and readily available in the market as a spare part for car radiators. The fan is positioned on top of the inner bamboo-mat cylinder. The fan performance curve from testing is shown in Figure 2. At 400 Pa static pressure, the airflow is 0.3 m^3/s.

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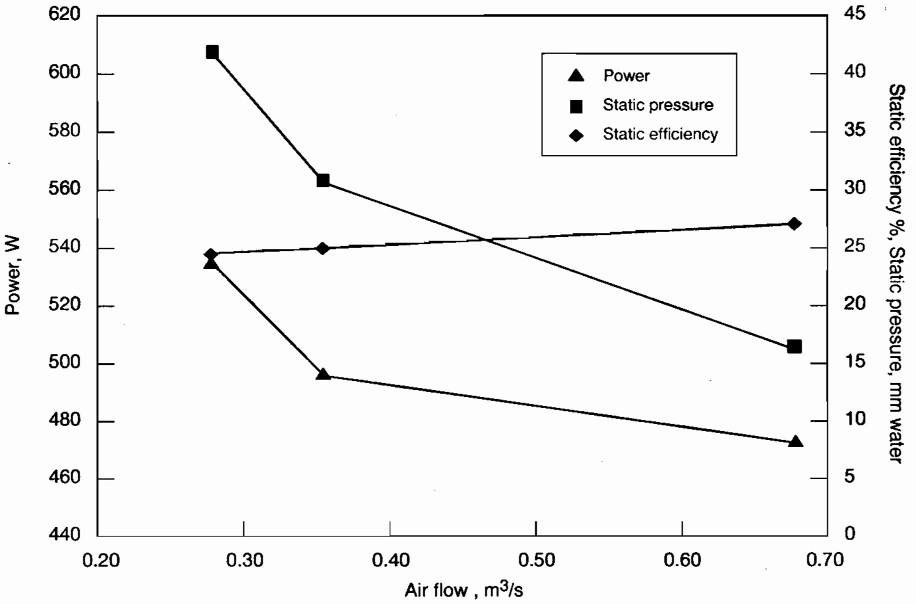

Figure 2. SRR-1 fan performance curves.

The *heater* is a 1000 W resistor from an electric stove; it is mounted beneath the lower rotor. Supplemental heat from the resistor is used selectively at night or during continuous rain.

Experimental

Operation

The SRR-1 dryer was installed at Bay Tu rice mill in Long An Province and was tested on four batches of paddy during the 1995 wet-season harvest. Between 10 August and 10 September 1995, 15 units of the SRR-1 were installed for paddy drying in Ho-Chi-Minh City and Long An, Tien Giang, Dong Nai, and Hue provinces. On the basis of local weather data, and to reduce energy consumption, the dryer was operated as follows:

- Day time (from 8 a.m. to 6 p.m.). The fan is turned ON, and the resistor (heater) is OFF.
- First night. With fan ON, the heater can be optionally ON or OFF. If the heater is used, the drying time is reduced, but energy consumption is higher.
- Second night. Both fan and resistor are ON, because without supplemental heat, paddy near the inner cylinder might be low enough to be rewetted by ambient air, which has relative humidity of 95% or more.
- Third, fourth night. Both fan and resistor are turned OFF. Paddy moisture content has been reduced to a level low enough to permit delaying further drying until the next day time, when the heat content of the air can be used.

Test procedures

The following measurements were made at Bay-Tu Rice Mill: drying time, energy consumption of the fan and heater, and moisture content of the grain at six locations in the dryer (Fig. 3) at set intervals. Instrument used were a balance, a watt-hour meter, a timer, and a Kett moisture meter.

A Fluke datalogger was used for monitoring temperature variation at various points in the grain mass, and in the plenum chamber. Ambient dry and wet-bulb temperatures were recorded. A total of 11 channels was used.

Head rice recovery was analysed in the Postharvest Laboratory of UAF with standard equipment.

Results and Discussion

Results from the drying of four batches of paddy at Bay-Tu Rice Mill are summarised in Table 1.

Moisture reduction

The course of moisture reduction in the paddy is plotted in Figures 4, 5, and 6. P1, P2, P3 are the sampling points in the paddy in the circular drying bin; L1 and L2 are the inner and outer layers of the paddy (see Fig. 3).

Table 1. Results from testing the SRR-1 dryer at Bay-Tu Rice mill, 20 July–30 August 1995.

	First batch	Second batch	Third batch	Fourth batch
Loading date	20 July	28 July	18 August	25 August
Unloading date	24 July	2 August	24 August	30 August
Initial weight of paddy, kg	963	1006	1004	
Final weight of paddy, kg	867	845	835	835
Water removed, kg	96	161	169	169
Average moisture content				
Initial, % wet basis	20.0	26.0	29.0	28.6
Final, % wet basis	13.6	14.5	14.5	14.5
Drying time, hours	60	84	98	84
Energy consumption				
Fan, kWh	35.8	56.0	63.6	50.4
Heater, kWh	66.3	12.0	26.5	68.5
Diesel fuel, L[a]	3	1.5		
Specific energy requirement, kWh/kg H_2O	1.06	0.42	0.53	0.70

[a] For running back-up generator during power interruption (for testing only).

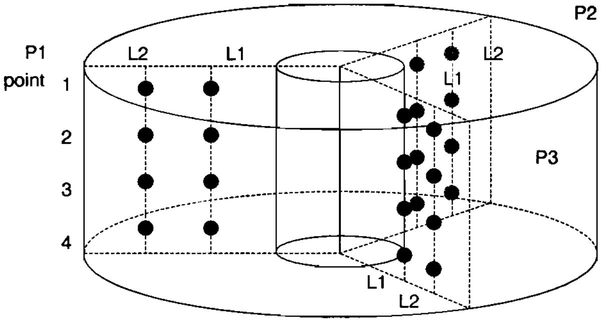

Figure 3. Locations for sampling.

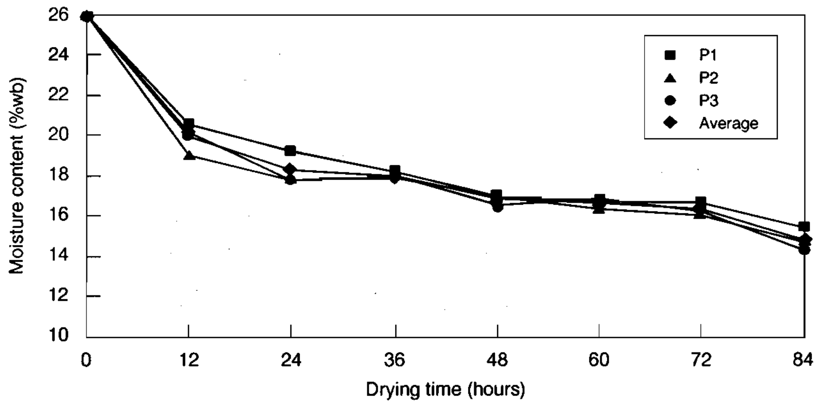

Figure 4. Moisture reduction of paddy by SRR-1 dryer: second batch, 28 July–2 August 1995.

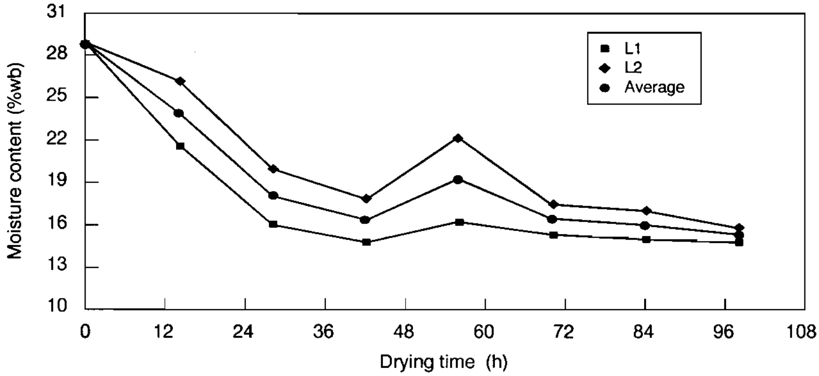

Figure 5. Moisture reduction of paddy by SRR1 dryer: third batch, 18–24 August 1995.

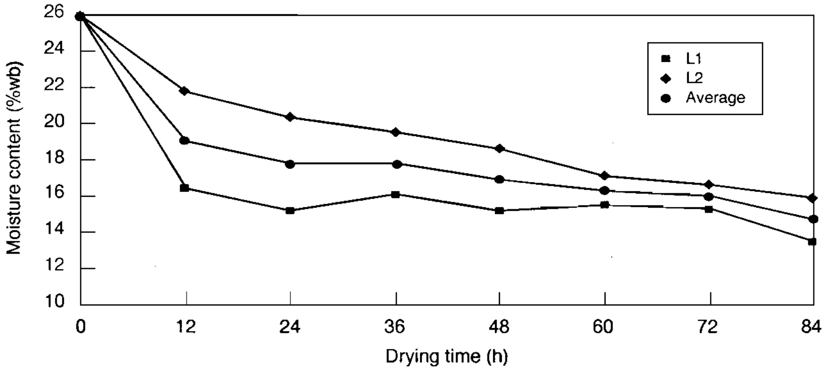

Figure 6. Moisture reduction of paddy by SRR1 dryer: fourth batch, 25–30 August 1995.

From the plots, it can be seen that high-moisture paddy (> 26%) can be dried to 14–15% within 4 days. The moisture differential between various points in the grain mass was within 1.5%.

Temperature variation

Figure 7 shows typical variation in temperature during drying of a batch of paddy. It can be seen that:

- peak temperatures corresponded to near and after midday; and
- the average difference between plenum and ambient temperature was about 2°C.

Head rice recovery

Figures 8 and 9 show the milling recovery percentage of two batches (18–24 August and 25–30 August). Head rice recovery was comparable to shade drying. The difference in head rice recovery between the two batches was due to the varieties and quality of the input grain. With good, freshly harvested paddy (Fig. 8), there was an increase in head rice of about 2%.

Investment and drying costs

Table 2 gives an estimate of the SRR-1 investment cost, using prices in October 1995 at Ho-Chi-Minh City.

A dryer worth US$55 holds the record for the lowest-cost mechanical dryer in Vietnam (SRR stands for 'very cheap dryer' in Vietnamese).

The drying cost was calculated with data and assumptions listed in Table 3.

The calculated drying cost of 65600 VND/t (US$6.00/t) is acceptable to farmers in places where the dryers have been installed.

The benefits of using the SSR-1 dryer can be summarised as follows: a higher selling price of US$2.50/t due to increased head rice; a labour saving of $2.50/t (either as labour rent, or opportunity cost of the owner); no investment needed in sun drying yard costing $150/t; and an insurance of not losing paddy at $10–20/t due to quality deterioration.

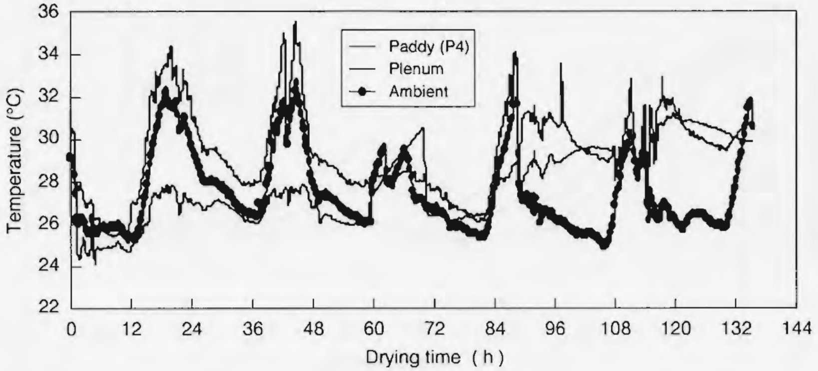

Figure 7. Temperature variation in the plenum and paddy in SRR-1 dryer, and ambient temperature.

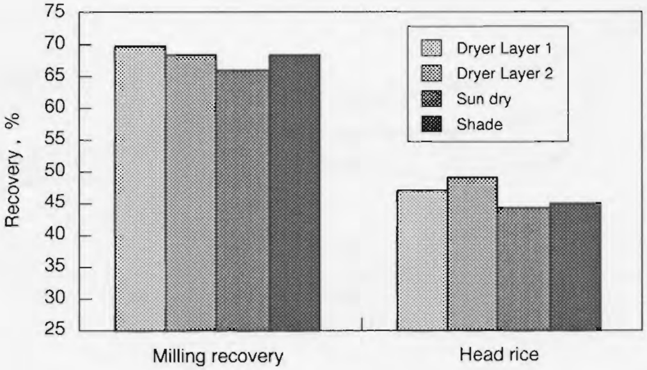

Figure 8. Milling quality of paddy dried using the SRR-1 dryer (18–24 August 1995) compared with sun and shade-dried paddy.

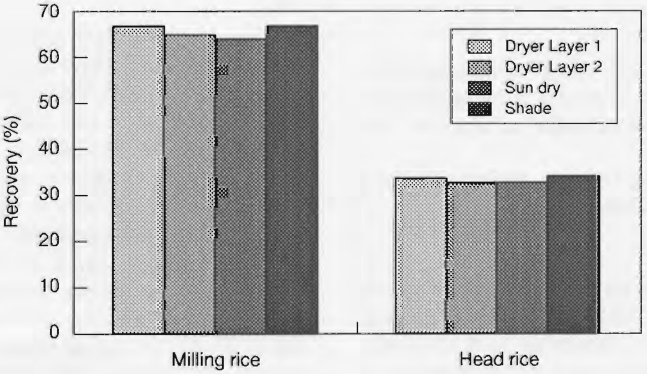

Figure 9. Milling quality of paddy dried using the SRR-1 dryer (25–30 August 1995) compared with sun and shade-dried paddy.

Table 2. Estimated investment cost of SRR-1 dryer.

Item	VND[a]	US$ equivalent
Electric motor	300000	27
Fan and heater assembly	150000	14
Bamboo-mat and accessories	150000	14
Total	600000	55

[a] During October 1995, ca 11000 Vietnam dong (VND) = US$1.

Table 3. Data and calculation of drying cost.

Data	
Capacity	1 t/(80-h batch) (28% m.c. (wet basis) to 14%)
Investment	600000 VND
Life	3600 hours (= 5 years × 30 days/year × 24 h/day)
Interest rate	23%/year
Electric power consumption (total)	80 kWh/batch
Electric power price (for household use)	550 VND/kWh
Cost component	**VND[a]**
(Cost/batch = cost/tonne)	
Depreciation and repairs	14000
Interest	7600
Electric power	44000
Total	65600 VND/t = **US$6.00/t**

[a] During October 1995, ca 11000 Vietnam dong (VND) = US$1.

Conclusion

The testing and actual use of the SRR-1 dryer showed that it has met the needs of small, cash-starved farmers for a dryer with adequate capacity, high quality of dried grain, and reasonable drying cost. From enthusiastic responses, comments, and inquiries by hundreds of farmers throughout central and southern Vietnam in six weeks since the design was released, we anticipate that in coming years, thousands of SRR-1 dryers will be in the service of these small farmers.

Acknowledgments

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References

Gummert, M. 1994. Low-temperature in-bin and storage systems testing manual. Material book presented at the information exchange workshop on low-temperature in-bin and storage systems, International Rice Research Institute, Los Baños, Philippines, 11–13 April 1994.

Kim, K.S., Slim, M.G., Kim, B.C., Rhim, J.H., Cheigh, H.S., Muhlbauer, W., and Kwon, T.W. 1989. An ambient-air in-storage paddy drying system for Korean farms. AMA Journal, 20(2), 23–29.

Muhlbauer, W., Maier, G., Berggotz, T., Esper, A., Quick, G.R., and Mazaredo, A.M. 1992. Low-temperature drying of paddy under humid tropical conditions. In: Proceedings of the International Agricultural Engineering Conference, Asian Institute of Technology, Bangkok, 7–10 November 1992.

The Present Situation and Directions for Development of Grain Drying in China

Li Huojin*

CHINA'S grain production is large, approximating 450 Mt per year. Most types of grain and oil seeds are grown, including rice, wheat, maize, and soybeans. The major grains are maize in the north, wheat in the central zone, and rice in the south. When harvested, grain may have high moisture content. In the northeast, early frost results in moisture contents (m.c.) at harvest that can reach 20–40%. In the south, rain results in grain moisture levels of 17–20%. In order to store the grain safely and avoid fermentation and loss, it is necessary to reduce the moisture content to a safe level.

In China, grain drying is classified as natural and artificial. Natural drying is of greatest importance and makes use of sunlight and wind. Man-made drying accounts for only 10% and makes use of dryers and mechanical ventilation.

Current Drying Technology and Equipment

Infrastructure for training and research

The Chinese Government pays considerable attention to training and research on the technology of drying grain. There are special agencies engaged in this teaching and research. In the Department of Storage and Transportation in the Zhengzhou Grain College some professors specialise in teaching and studying the discipline. The office of grain drying in the Zhengzhou Grain Scientific Research and Design Institute specialises in the technology of drying grain. A special fund is available for study of the technology in China. During the fifteen years covering the sixth to the eighth five-year-plans, such studies have been designated a key task for science and technology at the national level. These activities are well funded.

Equipment for drying grain

Grain drying machines in China are classified into three types according to the system used — (1) drying; (2) aeration and condensation; and (3) grain cooling. The aeration and condensation system is used in southern China. For grain at 40% m.c., mechanical aeration and condensation is used.

Depending on the air flow direction, the equipment may be located beneath the storage, in the space above the grain, or in cross-flow configurations.

Forced air drying using heated air has been developed also in the south of China. Computer models can be used particularly with the aeration and condensation system to increase the efficiency of drying and so conserve energy resources. This is being promoted in the grain industry nationally. Forced air drying with refrigerated air is under development. As a result of all these developments, grain drying in Heilongjiang, Fujian, and other places is more efficient and uses less energy.

The important types of equipment are as follows:

Tower dryers

Tower dryers are the most common and have widest distribution throughout China. They represent 32% of the total dryers available. They are used for drying high moisture maize and soybean in the north of the country. They usually consist of three heating towers in series connected with one cooler tower.

Steam dryers

These dryers are used for high moisture maize and soybean. They include four heater towers in series connected with three cooler towers and necessarily are large. The heat energy for drying is supplied by steam and transmitted to the grain by conduction.

Multi-pass dryers

These dryers are used to dry maize and soybean, as well as wheat and cereal.

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Rotary sleeve dryers

These dryers are used principally for cereals. The capacity is 15 tons/hour. The grain being dried is uniform and quality of grain and heating efficiency are assured.

Concurrent dryers

These dryers are suitable for high moisture grain where the moisture content is over 20%. The rate of drying is great. They are used efficiently in Huabei (central) and Dongbei (north–east) zone of China.

Fluidised bed dryers

These dryers are present in large numbers and widely distributed in China. They represent 33% of all dryers. They are used to dry wheat, maize, soybean, as well as other grains, rapeseeds, etc. They are also used for preheating maize.

Stationary bed dryers

These dryers are classified as stacked deck dryers, two–way vaporisation dryers, multi–deck dryers, and cross–flow dryers. Other types exist.

Technology of drying grain

The major fuel used in dryers in China is coal and cereal shells. Liquid fuels and steam conduction heating cannot be used as in developed countries. Much of the technology is local, with little imported from overseas. This has resulted from the availability of coal as the energy source and the dependence of imported equipment on liquid fuel or steam. Modification of the drying equipment is under consideration to overcome these constraints.

Technologies for drying grain have not received priority China in recent years, but developments are accelerating. Nowadays, the typical technologies are as follows:

(i) Single machine technologies — loading, drying as with rotary dryer, and cooling by aeration in silos or by use of cooling towers. These are used mainly for cereals.

(ii) Drying with flow-through preheating — loading, predrying (fluidised bed dryer), drying (multi-pass dryer), and cooling (cooling tower). This is used for high moisture maize.

(iii) Drying with three stages connected in series — loading, drying (concurrent dryer), drying (multi-pass dryer), and cooling (cooling tower). These dryers are used for high moisture maize. Experiments have shown that moisture of maize may be reduced to 14.5% from 30% by using this technology.

Factors Affecting Artificial Grain Drying in China

Very little grain is artificially dried in China. Factors influencing use of dryers are as follows:

(a) Resources and personnel available at present dictate that natural drying can save energy and costs.

(b) The management skills of workers and small farmers is low. Natural drying and drying in the sun can resolve most of their problems satisfactorily.

(c) Specialised drying equipment is required for large scale handling and storage of grain but the requirements of efficiency, quality of product, selection of energy resources, and costs of drying are not met so adoption is limited.

Directions for Further Development of Grain Drying in China

There is sufficient equipment for drying grain in the north of China, but it needs to be renewed and modernised. There is little equipment for drying in the south. Because cereals prices have increased recently, and drying the grain is now cost effective, there is an increasing requirement for grain drying equipment. As yields of grain increase, technology improves, and the social economy develops, artificial drying of grain will increase in China at the expense of natural drying. The government is paying attention to the theory of artificial drying, including the technology and equipment involved and modelling of drying systems. It attaches great importance to development of this technology and equipment. As a consequence, there is considerable market potential for the technology of artificial drying of grain and associated equipment in China's grain industry.

The requirements of equipment for drying grain are as follows:

(a) Equipment for aeration that is economical in terms of energy resources and suitable for automatic control.

(b) Coal should be the energy resource of the dryers. It saves other energy resources and is very efficient.

(c) The grain must be dried evenly, breakage must be minimal, and costs low.

(d) In the southern cereal-producing zone in China, the dryers must be suited to local conditions. They must prevent breakage from heating and be adaptable to different kinds of fuel including husks. Currently their price must match the industries' needs and the equipment must be small and mobile.

(e) The cost of the equipment must be low and it must be economical in operation.

The Development of Artificial Drying of Paddy in Malaysia

Loo Kau Fa*

DURING the period in the late sixties and seventies, rice production in Malaysia had undergone rapid expansion mainly due to various government inputs such as irrigation and drainage facilities, the introduction of modern high yielding varieties of paddy, and the adoption of double-cropping practices. As a result of these concerted efforts, the country which once used to import some 45% of its rice requirements, was able to achieve a self sufficiency level of about 85% at one stage. Since then the rice production has consolidated with government efforts concentrated on the eight granary schemes involving estimated planted area of 639,000 hectares with paddy (rough rice) production recorded at 1.78 Mt in 1993.

Drying Constraints

The advent of double cropping brought a substantial increase in wet paddy production during the off seasons which caused serious constraints to the local rice industry. The moisture content of the freshly harvested paddy typically ranged from 21 to 24% with some even higher in off-seasons.

During the off-season the drying problem is more acute as invariably the harvesting of the second crop occurs in the rainy season and the opportunity for natural sun drying at the farm or mill level is limited. Artificial drying is very much needed at such time to prevent deterioration as paddy at high moisture level if not dried within 48 hours after harvest, will undergo rapid bio-deterioration resulting in kernel discolouration or stack burn and poor milling yield.

When double cropping began, commercial rice mills were heavily dependent on natural sun drying and artificial dryers were quite rare with the exception of a few private mills in the Province Wellesley, Penang, which were among the first to invest in artificial continuous flow dryers. Incidentally, the mills in Province Wellesley are closest to the Krian District which was the earliest paddy area to adopt double-cropping.

Faced with the inadequacy of drying facilities and the marked increase in paddy output as a result of double-cropping, the government through FAMA (prior to the formation of the NAPRA, National Paddy and Rice Authority on 20 September, 1971) and the NAPRA, embarked on the construction of the large capacity centralised paddy drying complexes which were initially aimed at catering for some 70% of the increase in wet paddy output in the various scheme areas. This target was later revised to a lower level of 50%. Apart from providing adequate drying facilities for paddy farmers, these complexes were to enable the Authority to implement the Government Guaranteed Minimum Price policy effectively by purchasing paddy directly from the farmers.

Initially, after drying, these complexes still faced difficulty in disposing the dried paddy as the existing mills were unable to absorb the extra dried paddy even at a price premium of RM2.00/picul above the then prevailing paddy price of RM16.00/picul (US$105.00/tonne). Subsequently, some of these drying complexes were converted to fully integrated complexes with addition of milling facilities in order to allow the surplus paddy to be milled either for the stockpile or for trading.

As artificial drying is an expensive undertaking both in term of initial capital outlay and operating cost, it is best undertaken by the mills rather than at the farm or village level. Moreover, the Authority believes that the cost of drying should form part of the rice processing cost which is incorporated in the pricing of milled rice marketed to the consumers.

Available Drying Technologies

Generally, artificial drying systems that are available and utilised in this region are:

(a) The LSU continuous mixed flow dryers with throughput capacity of 10–25 t/hour.

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(b) The inclined bed batch dryers with drying capacity of 20-50 t/batch.
(c) The Japanese batch type grain recirculating dryers of capacity 3 t/batch.
(d) The conveyor type continuous flow dryers of throughput capacity of 10 t/hour.

Presently, only the first two types of dryers are widely used by the local mills. Hence the ensuing discussion will concern only the LSU continuous mixed flow dryers and inclined batch dryers.

The LSU Continuous Mixed Flow Dryers

Continuous flow dryers may be of varying construction but many that are adopted locally are of the 'Louisiana State University design' i.e. the LSU type.

In order to minimise the effective depth of drying, the whole dryer column is made up of a series of inverted V-shaped ducts channelling the artificially heated air into the mass of wet paddy and channelling the moisture laden air out of the dryer. The intake ducts and exhaust ducts are placed in alternate layers at a spacing of 30 cm centre to centre in staggered formation which are open into the hot air chamber or exhaust chamber respectively.

During drying, paddy descends slowly by gravity action through the dryer column while the hot air is forced through the wet paddy from the intake ducts into exhaust ducts, either by suction or blower fans.

Because of the alternate arrangement, each intake duct is surrounded by four exhaust ducts or vice-versa, as a result of which hot air travels through paddy towards all these four exhaust ducts. Consequently some of the air moves against the paddy stream, some moves with it while the rest moves across it. Hence, this has given the dryer its name 'mixed flow'.

Heat is added to the drying air with the aid of a diesel oil burner. Typically, air temperatures used to dry paddy range from 55 to 60°C. High grain kernel temperature during drying must be avoided at all times so as to reduce the effect of stress cracking and subsequent breakage susceptibility during milling which will lead to poor head rice yield.

The grain flow through the dryer is controlled by the speed of the discharge auger or oscillating rockers located at the bottom of the dryer. The rate of grain flow determines the retention time of grain in the dryer which together with the drying air temperature selection will regulate the amount of moisture removed in each pass of drying. In the continuous flow dryer a multipass procedure is followed to avoid excessive drying stress. During each pass, the paddy is exposed to heated air for some 45 minutes and only about 2–4% of moisture is removed. Between drying passes, the paddy is moved from the dryer to a tempering bin where the moisture within the grain is allowed to equilibrate for some 8 hours. For a continuous flow dryer to function effectively and efficiently, it must be provided with adequate grain handling facilities, tempering bins, paddy cleaners, and a dust control system.

The bulk of artificial dryers in the public sector mills are of the LSU type. Typical performance of such a dryer is as shown in Table 1.

Table 1. Typical drying performance of a LSU dryer.

Setting	1st Pass	2nd Pass	3rd Pass	4th Pass
a. Initial moisture (%)	24.5	20.5	17.5	15.5
b. Outlet moisture (%)	20.5	17.5	15.5	14.0
c. Moisture reduction (%)	4.0	3.0	2.0	1.5
d. Drying air temperature (°C)	55	55	60	60
e. Ambient temperature (°C)	30	30	30	30
f. Grain inlet temperature (°C)	30	30	30	30
g. Grain outlet temperature (°C)	35	38	40	40
h. Discharge rate (tph)	25	25	29	27

Inclined Bed Batch Dryers

The inclined bed batch dryer is similar to an earlier version of the flat-bed batch dryer except that its drying floor is inclined at an angle of about 37–40° from the horizontal.

This inclined arrangement is primarily to facilitate the subsequent discharge of paddy upon completion of drying. Larger inclination of the drying bed would certainly speed up grain discharge but it would also result in less uniformity in grain depth because of the effect of the grain's angle of repose.

The bottom section of the dryer is made up of an air plenum chamber which is connected to a centrifugal fan. The top of the plenum chamber is covered by wire mesh or perforated screen which serves as a false floor for the drying bed. Drying air which is slightly heated above ambient to the region of 38–42°C is distributed through the perforated screen. The normal source of heat input is by means of a diesel burner.

For ease of construction, each inclined bed batch dryer is normally constructed in two equal halves with opposing sloping floors with a capacity ranging from 20 to 50 t/batch/set.

The drying time per batch is around 14–20 hour for moisture reduction from 21 to 14% at a moisture removal rate of 0.50 to 0.75%/hour. The biggest problem associated with this form of static batch drying is the moisture gradient that occurs across the depth of grain. To minimise over-drying of the bottom layers of grain it is best to limit grain depth to about one metre.

Unlike the public sector mills, private rice mills when investing in artificial drying facilities have displayed a marked preference for the smaller scale, batch type dryer. From the miller's standpoint, batch dryers offer greater flexibility in terms of the degree of mechanisation to be adopted subject to budget requirements. In the early days, some millers installed flat bed batch dryers to supplement their drying needs, particularly during the off-season while they continued to depend on sun-drying which was less expensive whenever weather permitted them to do so. Currently, with the wide adoption of farm mechanisation, the harvest period is now very much shortened. This is further compounded by the severe shortage of farm labours especially during the harvesting season. The traditional practice of sun drying is practically phased out. At the same time, almost all existing manually operated flat bed batch dryers are replaced by inclined bed batch dryers which allow a larger extent of mechanisation both in feeding and discharge operations. Generally, a group of inclined batch dryers is provided with a common intake hopper complete with a simple reciprocating cleaner to enable removal of large impurities such as straws from the paddybefore loading into the dryers.

Effect of Farm Practices on Drying Needs

Size of dryers

In tandem with technological progress in other sectors of the economy, the local rice industry over the years has adopted modernisation in its various facets of operations, beginning with farm mechanisation in land preparation, crop establishment and care until harvesting with large capacity combine harvesters. This has included modern farm practices, planting of high yield varieties of paddy, and efficient utilisation of irrigation water, together with conversion from bag to bulk handling of harvested paddy. By choice or otherwise, all these changes have tremendous impacts on the handling of in-coming wet paddy at the mill level. On a seasonal basis, a particular locality may not experience a spectacular increase in total paddy production. On a daily basis, however, the pattern of paddy output undergoes tremendous changes, simply due to the fact that the harvesting period which previously lasted some 35–70 days has now been telescoped to between 14 and 21 days, resulting in much larger daily deliveries of wet paddy to the mills.

The handling capacity of a dryer installation is dependent on its daily drying capacity and the effective period of utilisation in a season. The shorter harvesting period renders the dryers which were adequate before, inadequate in the new situation. This phenomenon affects both the public sector and the private sector mills. Its cost implication could be easily realised from the sizing of dryer capacity in the public sector mills over the years as shown in Table 2.

Paddy appraisal system

The paddy quality appraisal system currently adopted by the public sector mills consists of a range of factors which are mainly physical, such as moisture content, immature grains, heat damage or kernel discoloration, and extraneous materials including flat head, chaffs, straws and foreign seeds, etc. Appropriate payment deductions are made on account of each of these factors according to a prescribed table (Table 3).

The table of deductions refers to the physical aspect of weight or shrinkage losses during the subsequent drying and cleaning of paddy. However, it does not really take into consideration the intrinsic aspect of grain quality particularly the milling yield and the percentage of whole grain kernels or head rice which are

Table 2. Size and configuration of dryer capacities in public sector mills.

Project	Year built	Seasonal capacity each complex	Dryer size/ configuration	Total drying capacity
Muda Phase 1 – 5 drying complexes[a]	1971	10,000 t	1 × 20 t/hour	20 t/hour
Muda Phase 2 – 3 drying complexes[a] – 1 Integrated Complex	1972	10,000 t	2 × 20 t/hour	40 t/hour
Muda Phase 3 – 6 integrated complexes	1974	10,000 t	2 × 15 t/hour	30 t/hour
Tg. Karang/Krian Phase 1 – 3 drying complexes	1975	10,000 t	2 × 15 t/hour	30 t/hour
Kemubu/Besut Phase 1 – 3 integrated complexes	1976	10,000 t	2 × 15 t/hour	30 t/hour
Muda Phase 4 Sg. Manik Phase 1 – 3 integrated complexes	1981	10,000 t	2 × 25 t/hour	50 t/hour
Muda Phase 5 – 1 integrated complex	1982	10,000 t	2 × 25 t/hour	50 t/hour
Trans Perak Scheme – 2 integrated complexes	1994	20,000 t	2 × 25 t/hour 1 × 50 t/hour	100 t/hour

[a] Two drying complexes were later converted to fully integrated complexes with milling facilities.

important in the rice business. Just like elsewhere, local market prices are to a large extent influenced by the percentage of whole kernels or head rice in the milled rice products. In other words, the whole grain kernels are worth much more than broken grains. Therefore, while maintaining penalty deductios for higher moisture content and impurities found in paddy there is a need to offer price incentives for better quality grain which produces higher milling yield particularly higher return of whole kernels. When implemented, these price incentives will encourage farmers to produce better quality paddy.

Table 3. Schedule of deduction applying to paddy delivered by farmers to BERNAS Malaysia.

(I) Moisture content (wet basis)	Rate of deduction (kg) for every 100 kg of paddy
14% and less	nil
14–15%	1
15–16%	2
16–17%	4
17–18%	5
18–19%	6
19–20%	7
20–21%	8
21–22%	9
22–23%	10.5
23–24%	11.5
24–25%	13
25% and above	negotiable
(III) Dirt	1kg for every 1%
(IV) Unripe paddy	1kg for every 1%
(V) Damaged or red grain	1kg for the first 1% 2kg for every additional 1%
(VI) Gunny sacks	1.2kg for dry gunny 3kg for wet gunny

Grain Cooling

As part of the improvement of public sector milling in its handling of drying and storage of paddy, grain cooling was introduced several years ago. Such technology was adopted from Germany and Spain with some modification to suit the local climatic conditions. The local experiences indicate that grain cooling could achieve better head rice yields compared with the conventional ambient air aeration practice. Further, the cooling process allowed partially dried paddy (in the region of 15 to 16% moisture content) to be safely stored in the bulk storages, thereby freeing the dryers to handle a large influx of wet paddy, especially during the peak harvest.

Depending on the storage time and moisture level, the cooling process can be repeated when necessary. It is envisaged that after the season the cooled grain will be sufficiently dry for it to be sent directly for milling which normally requires a moisture level of 14%.

Micro Processors for Dryer Control

To improve the operating efficiency of the existing LSU dryers, some have had incorporated a modern micro-processor controller (Dryer Master DR) which allows the continuous on-line measurement and monitoring of the actual moisture content of paddy entering and leaving the dryer. It enables better control of the drying operation and maintains uniform moisture content of grain leaving the dryer irrespective of fluctuation in moisture level of the incoming wet grain. This ensures the minimum number of drying passes for a particular batch of paddy thereby achieving better energy efficiency while maintaining grain quality consistency.

Conclusions

With the advent of double cropping in various rice growing areas, artificial drying facilities have to be provided, especially during the off-season harvest which occurs during the rainy season. This drying need is rendered more critical by the technological advances adopted by the local rice industry such as farm mechanisation high-yielding varieties, and bulk handling of paddy and which is further compounded by the severe shortage of farm labourers during peak harvest.

In its effort s to ensure paddy farmers are receiving a reasonable and stable price for their produce, the public sector embarked on a program to establish initially a number of drying complexes with LSU dryers some of which were later converted into fully integrated facilities with the addition of rice mills. Meanwhile, the private sector mills, for operational and budget requirements, have displayed a marked preference for batch dryers in their investment in artificial dryers in place of the discarded sun drying practice.

The capacity to handle the wet paddy crop depends very much on its actual daily drying capability, be it a public sector or private sector mill. Hence, the shortening of harvesting period brings about serious capacity and cost implication. In their continued efforts to improve drying efficiency, the public sector mills have in recent years adopted grain cooling and micro processor based controllers for its LSU dryers.

Further Reading

Fredricks, L.J. and Wells, R.J.G. 1983. Rice processing in Peninsular Malaysia: an economic and technical analysis. Kuala Lumpur, Oxford University Press, 1983.

Malaysia, Lembaga Padi dan Beras Negara 1973, Mid-Term Review of LPN's Capital Project Under The Second Malaysia Plan (1971–1975).

U Thet Zin 1969. Survey report of rice processing in West Malaysia, Parts 1 and 11. Rome, FAO.

Chilled Aeration for Pest Management in Stored Food Grains

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Abstract

A grain chiller utilises a portable refrigeration system to control the inlet air temperature and relative humidity in a storage. As a result, chilling allows for conditioning of large grain masses to desired temperature and moisture levels at any time during the storage season without pesticides. During the summers of 1994 and 1995, four and six bins, respectively, were evaluated for the chemical-free pest management and conditioning of popcorn. Each summer, two of the bins were managed with intensive aeration for moisture conditioning and several fumigations for pest control. In 1995, two bins were managed using an automatic aeration controller. The other two bins were managed with the Purdue grain chiller. These two bins were monitored and chilled only as needed. The grain temperature in the chilled bins remained below the critical 15°C limit for insect development. Grain temperatures in the bins conditioned with ambient aeration were 7–20°C higher during the same period. By late summer, the chilled bins had not required a single fumigation and had insect levels significantly below those found in the fumigated bins. An economic analysis of chilled storage versus traditional insect control and conditioning methods has shown grain chilling to be competitive.

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Rapid Fluidised-bed Drying: a Successful Postharvest Tool

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MECHANICAL drying is becoming more important in grain storage. Conventional column and continuous dryers have inefficiencies and restrictions in their operation. They are large and need large spaces to accommodate them; they entail high roofing costs; they have long drying times; they induce high breakage in the rice; they give uneven moisture contents especially when drying high moisture paddy; and the cost of drying is high.

The Rice Engineering Supply Co. recognised these problems, and in 1990 initiated an R&D project to study the application of the fluidisation technique currently used in the food industry to paddy drying, particularly high moisture paddy (over 20%). As a result of the project, a new fluidised-bed dryer with the following features has been developed.

- Rapid drying rate—moisture content is reduced 8–10% per passage with no untoward effect on broken rice yield. Due to high temperature airflow through the grain, only short periods (1.5–2 minutes/pass) of drying are required.
- Uniformly low moisture content of the output paddy, even if the moisture content of the input is very uneven.
- Reduced fuel cost, by recycling hot air to the drying process.
- Compact size compared with a column dryer, so it can be installed even in a small shed.
- High flexibility in operation. Large batches of paddy are not required. Each batch passes through in only few minutes.
- Low maintenance cost, as the main machine is stationary and the only moving part is the paddy.
- Immature kernels and dust are separated out during drying. This in turn reduces the heat consumed if a second pass through the dryer is needed.

The fluidised-bed rapid dryer (models DR-5F and DR-10F) was developed in collaboration with Professor Somchart Soponronnarit at King Mongkut's Institute of Technology, Thonburi. The prototype dryer, with a capacity of 1 t/hour, is now installed and in operation at the Royal Palace Rice Mill in Bangkok. Commercial models of 5 and 10 t/hour capacities are already launched and have been supplied to both local rice mills and overseas customers.

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Mechanical Drying, Horizon 2010: an Increased Role Predicted

F. Mazaud*

THE primary purpose of this paper is to provide a current overview of grain drying within the Asian region, and to project requirements forward to 2010. Notwithstanding the number of investigations taken or under way (at both regional and national level) the picture remains confused. Traditional drying methods predominate, with grain spread over open ground, exposed to the sun, and turned by hand.

Such techniques require space, time, and experienced labour, and produce mixed low quality grain which cannot enter international trade and, equally important, cannot compete successfully with imported grain in the domestic market.

In an effort to redress this and to enhance the ability of national industries, many governments have offered incentives for quality production, provided equipment, and generally encouraged producers and traders to become more quality conscious. Results have been mixed. Large numbers of plant have been constructed throughout the region to expand the capacity for artificial drying, but this plant remains woefully underused. Cost structures are high and the returns to the grower do not reflect the additional costs involved with artificial drying. Many domestic markets, for example, are not currently prepared to pay for high quality grains (when low quality grains at substantially reduced costs continue to be available).

None of this is new; the inadequacies and lost opportunities remain well-known and well-entrenched in spite of the efforts of a number of Asian countries during the past 10 years. At the last GASGA drying conference held in Canberra in Australia in 1988 (GASGA 1989), for example, the conclusions and recommendations stated that where quality was concerned: '... too little attention is paid to drying...'.

It remains equally valid for this conference. Natural drying techniques and the low quality grain that results will continue to create problems in the region in the short to medium term. Take the example of Vietnam. In that country the income generated by exports of rice in recent years has been considerable. It has been (and remains) essential for national development. But pressures on the use of land for production and for traditional methods of solar drying are such that they are rapidly becoming untenable. Increased population and enhanced expectations for quality of life are such that change is inevitable. Governments (in Vietnam and elsewhere) have little choice but to manage the changes required, or to face the consequences of disorganised food production and disrupted earnings from trade.

In addition to improving quality, artificial grain drying has an important role in the reduction of crop losses. Drying is an intrinsic part of the postharvest cycle required for crop care, and complementary to handling, transport, storage, and processing. Poor drying of rice, for example, decreases the head rice yield, and for maize it can lead to the development of high levels of mycotoxin contamination.

Traditional Methods of Grain Drying

Open-air drying with the grain exposed to the sun and wind is the most common method of drying used throughout the region. It is estimated that 90% of all grain is sun dried, even in the more advanced agricultural countries such as the Philippines and Indonesia. Many modern drying plants are available, but they remain little used by producers. The main users are milling, trading, and storage companies with the ability to pass on the additional costs involved. Most grain entering international trade receives supplementary drying and cleaning, to enhance the levels of quality required by the importer.

There is considerable variability across the region, with some countries more advanced than others in the use of improved grain drying and handling facilities. For example, in 1993 the Government of Thailand established a four-year program to improve grain quality and allocated 450 million THB (during October 1995, ca 25 Thailand baht (THB) = US$1) for the introduction and use of modern plant in major grain-producing areas of the country. This program is cur-

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rently more than 50% complete, but lack of technical information (concerning the principles of drying and of agro-industrialisation), lack of manufacturing ability, limited experience with the use of drying plant, and poor servicing has produced mixed results. The private sector has been overwhelmed by the constraints and opportunities involved.

A significant development across the region has been the number of manufacturers willing to become involved with the sector. Notwithstanding the constraints of pioneering new technologies, Asian manufacturers have been adept at handling the changes and competition involved. A survey of manufacturers and dealers in selected countries listed more than 60 available (Table 1).

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Publicly financed drying programs in the region have generally not been successful during the past 20 years. Large numbers of plant (comprising dryers and grain stores) have been constructed in an effort to improve the availability of food supplies, and numerous programs to encourage their use have been implemented. Lack of commercial acumen, limited knowledge of markets, and few incentives to produce quality grain have restricted producer uptake and use. Conversely, where drying has been shown to be profitable, for example, for industrial milling and mixing, dryers have become widely used. Discrete private sector businesses have evolved to take advantage of the equipment and incentives available.

Table 1. Dryer manufacturers and dealers in selected Asian countries.

Country	Numbers of manufacturers/dealers
India	16 (including 6 dealers)
Indonesia	7
Philippines	29 (including 11 dealers)
Korea, Rep.	8
Pakistan	Not available
China	4[a]

[a] The situation in China remains fluid with rapid changes in place as the result of the 'bag-to-bulk' project financed by the World Bank, and the work undertaken by research and development institutions such as the one in Jiangsu Province. More than 700 rice-husk or coal-fuelled drying plants have been established in the province in recent years.

The trends noted in the 10 years are likely to have a profound affect on the future use of postharvest crop care, including the use of dryers. Populations are expanding throughout the region, markets for all grains (and particularly for rice) have become more sophisticated, crop production has grown with demand, and the impact of recent international trade agreements is beginning to be felt. New commercial opportunities generated by the Uruguay Round accord between member states of the General Agreement on Tariffs and Trade (GATT) remain to be determined, but change is inevitable at all levels from producer through to consumer. Competition from imports is likely in most regional domestic markets. The situation is further confused with crop yields (for the major grain crops) remaining static, or declining. Agricultural land adjacent to urban centres is increasingly under pressure for housing or industrial use, further reducing the resource base available to agriculture.

A shift from traditional drying methods to the use of modern plant is likely to follow these trends. The costs involved will increase, but as markets for higher quality grains increase in line with the purchasing power of the local consumer, artificial drying will:

- help to maintain the nutritional value of staple grains with, for example, a reduction of fungal degradation;
- reduce the risks of crop losses and crop deterioration; and
- increase the storability of grains, and enhance the value of the crop (by allowing markets to be exploited to the full).

Improvements in other postharvest operations are closely linked to drying. Depending on the physical or economic factors that may apply, drying is an intrinsic part of postharvest crop care. *Drying should not be considered in isolation, for this involves risk.*

Traditional sun drying methods remain popular throughout the region because of low cost and experience, but also by choice. Access to drying plant remains strictly limited for most producers. Notwithstanding these opportunities and constraints, sun drying is likely to become more difficult to use and less viable. In Vietnam, for example, paddy is dried and threshed on the public roads. A recent government disposition has moved to forbid this (in an effort to improve transport systems), without providing alternative options to growers. Large open areas of relatively hard and clean surfaces suitable for crop threshing and drying are difficult to find in the traditional rice-growing areas. Constraints of this kind are also likely to be introduced in other Asian countries. In parts of the Philippines, for example, highway drying of grain has been banned, though the government is providing what it calls 'multipurpose drying pavements' as a substitute.

Adequate grain drying is essential for high quality conservation. What happens to paddy during the first 12 to 24 hours after harvest largely determines the yield of head rice or whole kernel, and the quality of the rice after processing. Delays with grain (or product) stabilisation can lead to physical and biochemical deterioration. This takes the form of general discoloration, yellowing, grain germination and, for maize, high levels of contamination with mycotoxins. Poor milling quality results. Yellowing of the kernels will begin within 24 hours of reaping, especially where the crop is stacked in the field before threshing. Grain drying immediately after threshing is the only practical method to prevent deterioration. Further, rice paddy stored in the open on packed earth or roads will become contaminated with foreign material. This will affect the quality of milling, increase costs (for the increased energy required for cleaning), and generally contribute to poor sanitary conditions at the store or mill.

The message to industry, from producer through to trader, is clear: the twenty-first century will present numerous new constraints and changes to both the production and postproduction sectors of agriculture. Major areas of change have already been identified.

Population

The population of Asia rose from 1.3 billion in 1950 to 1.56 billion in 1960, at the time that the green revolution was initiated in most countries in the region. By 1972 the regional population had passed 2 billion and in 1990 the population was estimated to be 2.7 billion. Thus, in just 40 years food requirements in the region have doubled. Forecasts suggest that by the year 2000 the total population in the region will be 3.2 billion, and by 2020 it will be 3.8 billion. Projections are always open to different interpretations, but it seems clear that the population in most countries will continue to expand, albeit at a slower rate. This is expected to result in a further doubling of the regional population during the next 40 years. By the year 2030 then, a regional population of 5–6 billion is likely. One outcome of these projections is that a vastly increased quantity of food will be required, to be produced by growers (and others within food industries) who face increasing constraints on production. The demand for wheat, for example, will increase from 582 Mt to 1173 Mt.

Population growth varies from country to country. In 1961, China had a population of 655 million and India a population of 452 million. Indonesia and Japan each had populations of nearly 100 million. At that time the population of Bangladesh was 52 million, five countries had populations of 22–35 million (Vietnam, Philippines, Thailand, South Korea, and Myanmar), and Pakistan had 16 million people.

Now, in the mid–1990s, significant changes have occurred. The population of China has reached an estimated 1153 million, India 846 million, Indonesia 184 million, and Japan 123 million. Bangladesh currently has a population of more than 113 million, Thailand 55 million, Vietnam 67 million, Pakistan 118 million, Myanmar 42 million, and South Korea 42 million (Table 2).

The message to this grain drying conference is clear:

- by the year 2010 the population density of the region will be such that it will create difficulties for regional food production and, as a consequence, national food markets will become significantly changed; and
- the extent to which food requirements can be met by national and/or regional production will have major implications on the international market for food grains within the region.

Table 2. Population projections for selected Asian countries ('000).

Country	1980	1985	1990	1995	2000	2005	2010
Bangladesh	88221	100862	113684	122210	155205	171703	188200
Bhutan	1242	1379	1539	1650	–	–	–
Myanmar	33821	37544	41825	44613	52607	56603	60600
Sri Lanka	114819	16110	17217	178994	196997	205999	215000
China	996134	1070574	1153469	1205640	1288120	1329360	1370600
India	688958	766561	846191	896567	1060034	1141767	1223500
Indonesia	150958	167332	184282	194617	220659	233679	246700
Japan	116782	120754	123537	124670	127835	129418	131000
Korea, Republic of	38124	40806	42002	44500	47000	48250	49500
Laos	3205	3594	4202	4605	5703	6251	6800
Malaysia	13763	15677	17871	19239	22220	23710	25200
Nepal	14858	17136	19571	21086	24993	26947	28900
Pakistan	85299	100676	118122	128057	166779	186139	205500
Philippines	48684	55395	62437	66543	79322	85711	92100
Thailand	46718	51187	54677	56868	64234	67917	71600
Vietnam	53711	59890	66688	70902	84151	90776	97400

Sources: Alexandros 1995; FAO 1995.

In parallel with these changes, the gap between rural and urban populations will continue to diverge (Fig. 1), thereby creating a greater need for the mechanisation of agricultural work that currently demands high rates of manual labour. These changes are likely to become effective throughout regional food industries. From the restriction of use of roads for crop drying in Vietnam to the competition on domestic markets for imported processed foods in the industrialising countries such as Malaysia, commercial forces and unrestricted trading will determine the most cost–effective means of production. Sun drying and other traditional grain drying methods are unlikely to survive the socioeconomic constraints that will apply.

Demand for Rice

Consumption of rice

Rice is a staple part of the diet of the people of Asia, and the region accounts for 90% of world consumption. Rice consumption is of the order of 100 kg per person per year. In western Europe or North America, by comparison, the consumption of rice is 5 kg/person/year. Typical of increasing affluence in the region is the increase in rice consumption, but only up to a point. Once incomes reach a certain level, alternative foods are substituted for rice; people demand greater variety and more novelty in their diet. Entertainment, pleasure, and luxuries begin to have an impact. People also demand better quality food, and readily reject foods which do not reach the standards required.

Thus, as communities in selected countries attain socioeconomic levels that match or surpass those of the more traditional industrialised countries, so the consumption of rice per head falls. Japan, Thailand, and South Korea are typical examples.

In the poorer countries of Asia (Bangladesh, Cambodia, China, India, Laos, Myanmar, Nepal, and Vietnam) cereals continue to comprise more than 70% of the staple diet. Changes are becoming apparent in those countries which are in economic transition, even when food requirements are just sufficient to meet national needs. For example, in Sri Lanka and the Philippines cereals represent only 50–60% of the diet. The trend towards reduced cereal consumption is also marked in those countries that have made a public effort to improve the living and socioeconomic conditions of rural communities, for example, in Indonesia (65%), South Korea (61%), Malaysia (44%), and Thailand (53%).

The contrast between the industrialised, developed countries of Asia and the remainder is also marked. In 1990, for example, the share of cereals in Hong Kong was 32%, in Japan 41%, and in Singapore 32%. These countries have effectively substituted imported wheat and maize (and processed products based upon them) in preference to rice. In the developing Asian countries, traditional foods including rice continue to dominate. In China and Myanmar, for example, the share of rice in the diet has increased slightly.

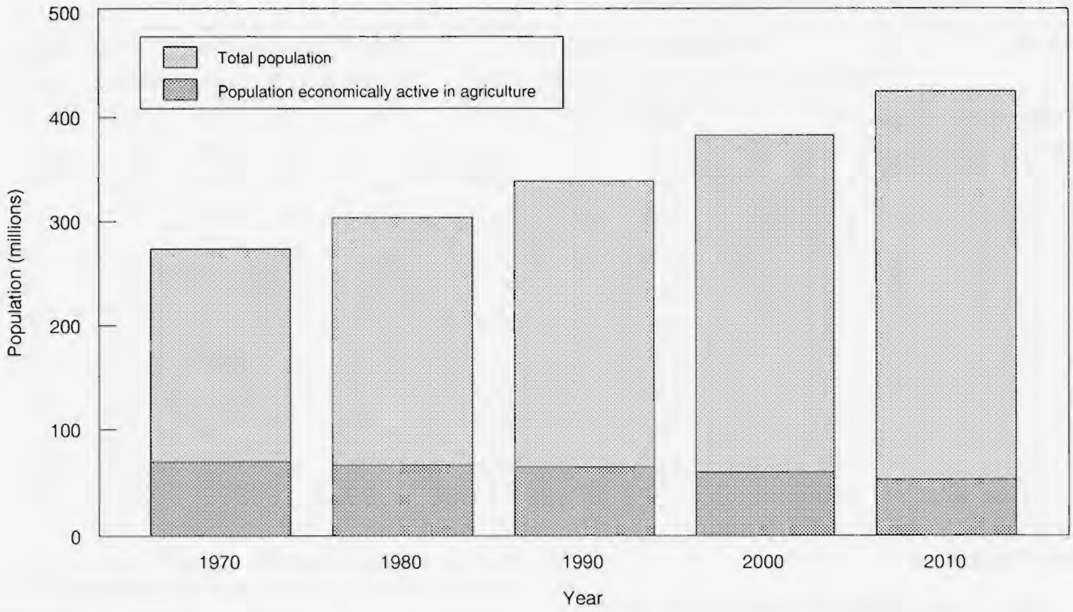

Figure 1. Trends in the proportion of the population economically active in agriculture in south Asia.

The choice of cereal and its importance to local diets depends largely upon domestic production—the range of crops that can be grown in the country. Pakistan, for example, is the only country in which wheat is a significant part of the local diet. The consumption of rice and wheat has remained stable in Pakistan, with rice comprising an estimated 10–12% of the diet.

The trends in rice consumption and the links with population growth and economic development are clear. In the poorer Asian countries rice has remained a major staple food through to recent times (with the exception of Pakistan). Economic development (of the country or community) reduces the importance of rice and alternative foods are preferred. A reduction in population growth in line with economic development leads to a reduction in the consumption of rice. The forecast for regional food production is equally clear: rice output per head has to be maintained in the poorer Asian countries. Economically strong countries will be able to import alternative foods, to replace rice in the diet (see Table 3).

Conceptions of rice quality

There is no universal comprehension of quality. Rice acceptable to one community may be completely unacceptable to another. A given quality that brings premium price in one market may be traded with a discount in another. The Japanese consumer, for example, prefers rice to be well-milled and processed just before eating. Short grain japonica rice sticks together when cooked and is claimed to have more flavour.

Consumers in Thailand also like well-milled rice but, by contrast, prefer long-grain indica rice which has been aged. This results in rice that separates freely and, according to the consumer, tastes better. Note that both the Japanese and Thai consumer claim a preference for taste and texture. Among examples of differing conceptions of rice quality include the preference for japonica rice in the southern countries of Europe and for indica rice in northern Europe.

The most valuable, large-volume markets exist for the best quality indica rice varieties, which are long grain and raw milled. These markets comprise approximately 25% of all rice entering international trade. Profit margins are significant given the lucrative prices involved and the high income potential of consumers in Europe, North and Central America, the Middle East, and the industrialised nations of Asia.

Consumer preferences will vary from one community to the next, but the choice of high quality remains firm. Consumers will choose rice with good physical appearance, where uniformity is consistent, where broken grains are not significant, and where all foreign materials have been screened out. Drying is an important postharvest operation that can enhance quality, and thus help with market exploitation.

Table 3. Food supply in selected Asian countries.

Country	Kilocalories/person/day					All cereals kg/person/year (milled rice included)				
	1961–63	1969–71	1979–81	1988–90	2010	1961–63	1969–71	1979–81	1988–90	2010
Bangladesh	2107	2117	1910	1949	2075	176	173	162	165	173
China	1664	2000	2338	2624	3136	124	153	190	211	221
India	2045	2037	2078	2309	2492	144	147	150	161	164
Indonesia	1839	2053	2448	2628	3040	101	125	158	177	192
Japan	2505	2678	2747	2903	3145	159	148	144	142	129
Korea, Republic of	2216	2819	3120	3283	3324	179	216	201	195	158
Malaysia	2343	2471	2695	2712	3156	152	154	150	128	127
Pakistan	1797	2177	2151	2345	2524	118	152	140	149	141
Philippines	1700	1766	2204	2292	2598	109	112	131	146	154
Thailand	2040	2185	2224	2333	2900	146	157	149	141	138
Vietnam	2065	2189	2103	2182	2519	168	178	157	159	172

Rice Production

Trends in rice production between 1973 and 1992 show three distinct periods: 1973–1984, 1985–1987, and 1988–1992. Following the world food crisis of 1973–1975, governments in south Asian countries invested heavily in irrigation, fertilizer use, and research and development. Higher yields and increased production from new varieties dominated development planning. As a result output grew quickly (3–4% per year) until 1984. A period of stagnation followed, due to adverse weather and weak economic conditions in the major producing countries. Growth in production has recovered since 1989 and crop yields have risen steadily. In 1991 a global production level for rice of 3.5 t/ha was recorded, demonstrating an average annual growth rate of nearly 3% during the previous five years. Yields are further expected to increase during the next 20 years, with projections estimated up to 50% in regional developing countries (excluding China) (Table 4).

The pattern of growth for this period is expected to be one of limited land expansion (Fig. 2), following a trend established during the 1980s. With rice production already largely Asian based (90% of global production) few opportunities for expansion into new crop lands is expected. Increased yields will come from greater cropping intensities: an ability to produce two, two and one half, or three crops per year where previously one was grown. In south and east Asia (excluding China), for example, only 5% more land is expected to become available for rice growing (Table 5).

Increased production will also come from a shift in production from non–irrigated to irrigated land. The harvest of rice from irrigated land is expected to increase by more than 20% during the next 20 years. An estimated 44% of rice is currently irrigated, a proportion which is expected to increase to approximately 50%.

The implications of this shift are important for postharvest crop care, for increased quantities of crop will require drying. Further, increased intensity of cropping will mean that seasonal drying will no longer be an option, and crops will have to be artificially dried to enable them to be stored, processed, and traded.

Rice International Trade

Present situation

The proportion of global rice production traded internationally has averaged just 3% during the last decade. This reflects the reality of markets which show that the major producers are also the major consumers. By comparison, 20% of wheat production enters world markets. Because of relatively high unit value the trade in rice is one quarter the value that of the wheat. Developing countries currently account for 79% of rice exports and absorb more than 85% of imports.

The trade in rice and rice prices are volatile and likely to remain so because of the small size of the market and the uncertainty of political developments in some major trading countries. The GATT agreement may result in further liberalisation of the world rice market, which is projected to stimulate a trend in international rice trading. The degree of protection provided for domestic rice producers in some countries is not expected to affect this trend.

Table 4. Rice, production of the principal Asian countries ('000 t) historical data and projections.

Country	1961–63	1969–71	1979–81	1989–90	1990–91	2010
Bangladesh	14555	16540	20125	26045	26980	40840
Cambodia	2348	3016	1248	2557	2294	2193
China	63463	106753	142538	179524	184425	–
India	52939	62861	74557	109399	110806	159000
Indonesia	12228	19136	29570	43860	44860	62242
Korea, Republic of	4611	5574	6780	8027	7705	7945
Laos	523	870	1025	1300	1373	2228
Malaysia	1135	1696	2053	1860	1980	1840
Myanmar	7432	8107	12637	13647	13658	21000
Pakistan	1707	3431	4884	4841	4862	7525
Philippines	3907	5456	7747	9250	9484	15526
Thailand	11190	13668	16967	19686	19398	31516
Vietnam	9456	9812	11808	18407	19281	31982

Source: FAO (1995).

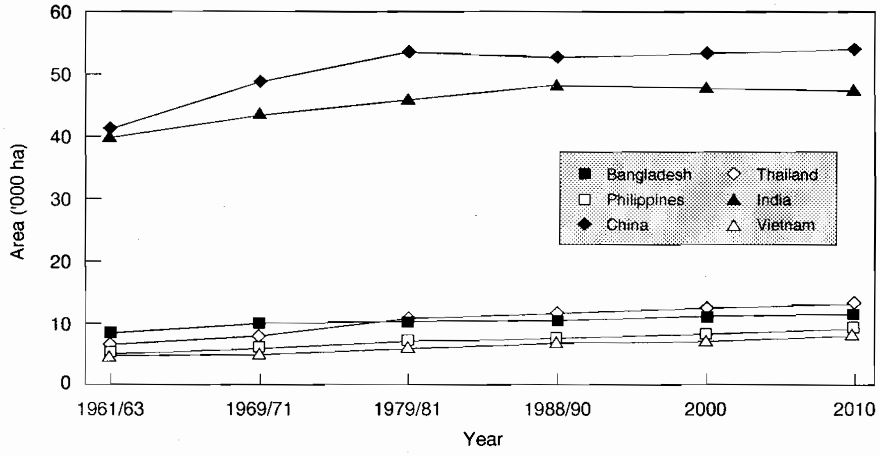

Figure 2. Historical data and projections in rice and maize cropping areas in selected Asian countries.

With the marked exception of a few countries such as Malaysia and Singapore, the importing countries in Asia pursue a policy of self-sufficiency in rice. The importance of rice in the national diet has led many Asian governments to take an active role in their domestic markets, and to manipulate prices and supplies. Purchases of rice in the international markets is made from time to time mainly to cover shortfalls in domestic production. These shortfalls may result from adverse weather and poor harvests; they lead to fluctuating levels of imports and difficulties with market predictions. Stability is likely to return with a regular supply of surpluses over and above domestic demand; policies of rice (and food) self-sufficiency are likely to assist in achieving this end. Markets are also responsive to the production of surpluses of high quality rice.

The volume of rice imported by Asian countries increased sharply during 1950–1970; thereafter it decreased slowly. However, the maximum recorded imports of rice reached only 3.4% of regional production during this period. In 1985, for example, rice imports represented only 1.1% of rice production. The point to note is that rice imports in the region have always been marginal when compared with rice production (and are likely to remain so).

Table 5. Rice, evolution of yields in Asia (t/ha)

Country	1961–63	1969–71	1979–81	1988–90	2010
Bangladesh	1.67	1.68	1.95	2.47	3.78
Cambodia	1.05	1.45	1.01	1.35	1.55
China	2.35	3.28	4.24	5.51	–[a]
India	1.50	1.67	1.86	2.59	3.86
Indonesia	1.76	2.35	3.26	4.22	5.23
Korea, Republic of	4.04	4.63	5.51	6.40	6.55
Laos	0.87	1.31	1.42	2.22	2.55
Malaysia	2.11	2.40	2.84	2.78	3.10
Myanmar	1.62	1.71	2.70	2.92	3.40
Pakistan	1.39	2.25	2.47	2.32	3.50
Philippines	1.24	1.68	2.21	2.72	3.99
Thailand	1.75	1.93	1.89	2.07	3.12
Vietnam	2.01	2.05	2.12	3.13	4.95

[a] Not available.
Source: FAO (1995).

The contribution of selected Asian countries to the volume of imported rice in the region is marked, however, and has changed extensively during the past 40 years. After a peak level of imports in 1955 (4.6% of the region) China managed to eliminate imports entirely by the early 1970s. However, this country's share of rice imports rose exponentially to 31% from 1975 to 1989, indicating the difficulties facing producers with domestic market demand. After a hike in imports (20.1% of the region) in 1965, India was able to eliminate imports during the early 1980s. However, this country's share of regional rice imports also rose exponentially, to 14.6%, from 1980 to 1989. This parallel between these two Asian giants in the recent growth of rice imports is worth noting.

In Indonesia, major rice shortages occur from time to time, and in 1980 the country was responsible for 39.5% of all rice imports into the region. Notwithstanding the highly successful food self-sufficiency programs implemented by government during the previous 20 years, the country had not been able to feed itself. The same situation, but to a lesser extent, occurred in the Philippines where rice imports reached 10.5 and 17.2%, respectively, in 1965 and 1985.

A further point of interest concerns rice imports into the industrialised Asian countries such as Japan and South Korea during the past 40 years. During this time Japan has reduced its share of rice in the region from 35% to almost zero. South Korea accounted for 13–18% between 1970 and 1980 and subsequently ceased importing rice.

Impact of the Uruguay Round agreement on the trade in regional cereals

The GATT agreements will have a profound effect on international trade in a range of goods and materials. They will change the context and the way in which food is traded. Countries which previously protected domestic producers from imported goods and materials are (or will be) obliged to open their borders to foreign foods. These changes have stimulated FAO to re-run projections for the production of most of the main agricultural commodities. Account has to be taken of the changes in national policies that will be in place by the year 2000. The new projections confirm earlier conclusions that prices on the international market will be higher, and point to significant changes in trading patterns.

For rice, world trade is projected to expand at 4% annually to reach 18.9 Mt by the year 2000. This is a substantially faster rate of expansion than seen in the 1980s. The projected acceleration in global import demand is expected to push the unit value of rice price significantly higher than that during the period 1987–89. This assumes that countries which have agreed to establish minimum market access will be importing the amounts stipulated and that such imports will not subsequently be released back onto world markets.

Overall, the Uruguay round will probably have a marginally positive effect on production and, similarly, a marginal impact on global consumption. However, its impact is projected to be substantially greater with trade and with international market prices for rice. The opening of previously closed markets for rice will increase the volume of global trade by an estimated 1.2 Mt, and international prices will grow by 7% (when compared to pre–agreement prices). Prices are expected to be 15% higher by the year 2000, when compared with the average prices for 1987–89. These changes should result in profitable trading opportunities for the region. This is likely to favour japonica rice exporters more than those trading indica rice.

For developing countries, the changes in world markets will be profound, as the challenge of competing with foreign suppliers and traders becomes a reality. The situation will be further confused with the need to establish new domestic policies that will take account of the competition that has arisen, and the opportunities for new markets that will come into existence. Policymakers and traders will require technical assistance across a range of commercial sectors and commodities, to enable them to cope with the new constraints and new markets. For example, sanitary conditions and standardisation will become more important than before; diversification, product appearance, and presentation of raw materials and processed goods will determine access to the market. Attention to detail and crop care at all times throughout the postharvest cycle, including drying, will be essential. The objective will be to produce high-quality grain.

Conclusions

The twenty-first century will present numerous constraints to the grain industry in Asia, although these will be offset by the opportunities that will also become available. The region, however, has become adept at meeting the challenges of new industrial opportunities and the same is likely to happen with grain production, processing, and trading.

There are hazards to be considered. The regional population will continue to expand, and it is not expected to stabilise until double the present population has been reached. Food requirements will also double. The per capita availability of arable land will decrease further, thus heightening the need to intensify agricultural production. This will lead to greater demands on the limited natural resources available. Intensified agricultural production will demand technical innovation, investment, and care throughout the production cycle. It will also demand attention to downstream and upstream activities relating to it. Postharvest activities downstream of production include storage, transport, transformation, and trading. They have a major impact on quality of the raw materials entering the market and the quality of the processed goods that may result.

Crop drying will have an important role within the portfolio of crop care treatments available to the trader or processor. A well-dried crop stores for longer periods, and in this way the spatial and temporal distribution of the product is improved. This clearly has a cost that can be shared between those involved with all the postharvest activities—the producers, traders, and the consumers.

Upstream of production, the opportunities for encouraging quality crops are equally important. Governments must realise that the absence of a premium price policy linked with the quality of the product is a major obstacle for the improvement of the postharvest cycle. Policymaking brings a challenge to agricultural management that is vested mainly in the public sector. This may ultimately determine both a firm role for grain drying within the region and the way in which it can best be introduced.

Finally, the technical (biological and engineering) requirements of grain drying require further development as they may apply to use of dryers in the region. If dryers and drying are to become better known and more widely used, programs of complementary investigations will have to be set in place. These should relate to the needs and constraints of the region, be undertaken by regional specialists and, ultimately, be supported by the development of a commercially robust manufacturing sector and a technical service industry.

Current research has shown the interrelation between crop varieties, quality of grain, and susceptibility to, for example, fracturing during drying. Varieties will have to be introduced that will sustain drying with minimum damage. It may also be interesting to instigate studies on crop homogeneity and the impact that this may have on the development of new designs of equipment. Cost of drying remains a major constraint in current markets. The optimisation of the choice and use of energy or the adaptation of new technologies (such as microwave or fluidised-bed systems) should be explored. Traditional technologies should be examined further. They should not be rejected before their use and value within the period of transition has made them obsolete.

References

Alexandros, N., ed. 1995. World agriculture towards 2010: an FAO study. Rome, FAO and John Wiley & Sons, Inc.

FAO (Food and Agriculture Organization) 1995. Agrostat 95: FAO statistical yearbook. Rome, FAO.

GASGA (Group for Assistance on Systems relating to Grain after Harvest) 1989. Research and development issues in grain postharvest problems in Asia. Proceedings of GASGA Executive Seminar No. 2, Canberra, 31 August 1988.

Traditional Paddy Drying in Bangladesh and Associated Problems

K.A.M.S.H. Mondal* and M.A. Malek†

BANGLADESH, population 120 million, is the most densely peopled country in South Asia. It has a generally subtropical monsoon climate. There are six seasons in the year. Three of them, namely winter (November–March), summer (April–June), and the monsoon (July–October), are prominent. In winter there is usually little fluctuation in temperature which ranges from a minimum of 7–13°C (45–55°F) to a maximum of 24–31°C (75–85°F). Summer maximum temperatures are around 37°C (98°F), although in some places this occasionally rises to 41°C (105°F) or more. The monsoon starts in July and runs till October. This period accounts for 80% of the total rainfall. The average annual rainfall varies between 119 and 145 cm (Anon. 1992).

Rice is the most important agricultural crop of Bangladesh. It is grown on approximately 80% of the total cultivated area, although the country is not self-sufficient in rice (Alim 1982; Anon. 1992).

Three different rice crops, namely Aus (summer), Aman (autumn), and Boro (winter) are cultivated. Moreover, various high yielding varieties (HYVs) of rice are cultivated throughout the year (BRRI 1984). The Aus crop suffers from drought, early floods, and heavy rain at the time of harvest and threshing (Hall 1970). Most of the farmers harvest their crop with sickles. In Aman and early Boro, the fields are dry, but in late Boro and Aus, the fields remain wet and are sometimes flooded (BRRI 1984).

Moisture content is the prime characteristic feature for the procurement of paddy. The standard moisture content (m.c.) of 14% is considered a maximum for safe storage (Baird 1987). The storage of paddy with too high a moisture content is common in Bangladesh. This results in quality deterioration and quantitative losses as a result of fungal, bacterial, insect, and mite infestations (Khan and Mannan 1991).

This paper briefly describes different sun-drying methods used by Bangladeshi farmers, and the problems associated with those methods.

Drying

Drying is practiced to prevent germination of seeds, to retain maximum quality of the grain, and to reach a level of moisture which does not allow the growth of bacteria and fungi. Drying also considerably retards the development of mites and insects. It is essential that grains be dried quickly and effectively before being stored (Hall 1970).

In Bangladesh several traditional, natural sundrying methods (Fig. 1) are used by farmers and traders. There is little or no mechanical drying. Some research organisations are trying to develop artificial dryers. One such is a mechanical dryer burning rice husks as the heat source for drying. The husks are fired in a locally designed furnace, which is placed under a drying chamber made from concrete blocks. The grain is placed on trays within the chamber. These are movable to permit 'respreading' of the paddy.

Natural drying

This is also commonly called sun drying and has been traditionally used throughout Bangladesh. This type of drying uses a combination of sun and air but also requires time and labour to spread and collect the grains. Both threshed and unthreshed paddy are dried. There are different methods of natural drying of paddy in Bangladesh, as follows:

Field drying. In some parts of Bangladesh where maturity of the crop coincides with the beginning of a dry season, the most popular method of drying is by exposure to the sun. Drying may commence before the crop is harvested, e.g. paddy panicles are left on the standing plant for 3–4 weeks after maturing before they are harvested. In the northern region the unthreshed cut paddy is dried in the field for a few

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days after harvest in the Aman season and is then bundled up and transported to the home yard (BRRI 1984). The postharvest losses in this case are usually primarily the result of shedding of grains and cutting of panicles by rodents.

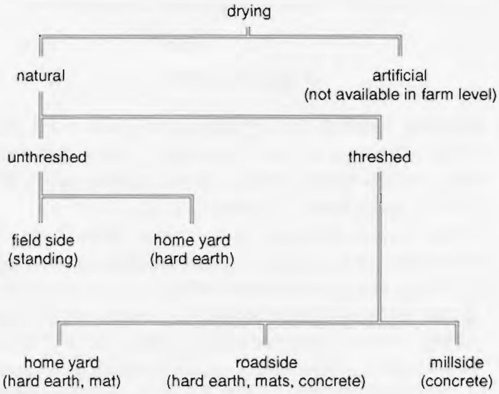

Figure 1. Flow chart of paddy drying in Bangladesh.

Home yard drying. At village level, several simple methods which avoid the need for building a storage container are used for drying paddy. The common practice is to spread the threshed grain on the ground or on a specially prepared area (e.g. bamboo mats (*Chatai*), sacking, on a mud and cow-dung plastered hard earthen floor, or on a concrete floor) and expose it to the sun and wind (Fig. 2). Unthreshed paddy is also brought from the field to the home yards where it is laid out on prepared areas or hard earth to dry in the sun for a number of days.

Roadside drying. Some poor farmers use the nearby highways (concrete) for drying threshed paddy (Fig. 3).

In both the home yard and on the roadside, drying is done after cleaning the paddy. In most cases raw paddy is dried but sometimes farmers soak the paddy and parboil it before drying. The parboiled paddy has a moisture content of more than 40% (BRRI 1984). The grains are spread and respread by the feet during both home yard and roadside drying methods. These tasks are performed mostly by women.

Mill-side drying. The traders usually use their large concrete floors for drying parboiled paddy (Fig. 4). People are employed on a daily basis for taking care of the paddy drying through such tasks as cleaning the floor, spreading and respreading of paddy and, finally, collecting the dried paddy and sending it for milling. The grains are spread and respread using wooden and bamboo implements, locally called *Sarpat.*

Figure 2. Home-yard sun drying of paddy.

Figure 3. Roadside sun drying of paddy.

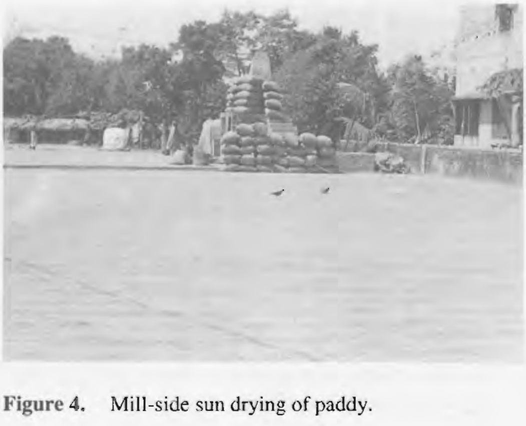

Figure 4. Mill-side sun drying of paddy.

Problems

Sun drying is safe for both humans and the environment because, unlike mechanical drying, it does not involve any oil, fuel and smoke. However, it has many disadvantages which may be summarised as follows:

- Over-drying or under-drying occurs, causing qualitative and quantitative losses.
- Excessive movement of the grains, particularly in roadside drying, causes damage or breakage.
- Dust and dirt from the surroundings mix with the grains. These extraneous materials accelerate deterioration by permitting an increase in moisture content and fungal contamination.
- Sun drying does not eliminate insects which contribute significantly to postharvest losses.
- Uniform drying is not possible, because uniform stirring is difficult.
- In both home yard and roadside drying, grains are exposed to rodents, and chickens, ducks, and other birds, which consume a considerable amount of grain. On cloudy days or in winter when the temperature is low drying takes longer, subjecting the grains to agents of loss for a longer time and thus leading to higher losses.
- Grains are lost due to scattering.
- There is grain spoilage, particularly during continuous rains.
- Sun drying, involving as it does hand spreading and collection of produce, is labour-intensive.
- With almost daily rainfall (in the rainy season) and heavy dews at night it is almost impossible to obtain satisfactory drying.
- During field drying some mature grains are dropped in the field through wind shattering, and loss of grain also occurs due to animal consumption.
- When drying is carried out on an outside concrete or hard-earth floor, sun cracks due to excessive heat may form in the grain. Moreover, alternate loss and absorption of moisture may cause development of internal cracks in the grains (Grist 1965).
- Interruption in drying during the day by sudden rain is experienced.
- Roadside drying creates traffic problems, especially on highways, and sometimes leads to serious accidents.
- Sun drying results in relatively high losses (1.6–2.1%) (BRRI 1984).
- Sun drying in the open space enhances the growth of moulds and fungus on produce, making favourable conditions for insect infestation if the weather remains cloudy and damp.
- It depends solely on a period of sunshine during the day, which does not occur throughout the year.
- Periodic stirring is required to obtain uniform drying, which is quite difficult.
- When it rains, and during the night, labour is required to pile up the paddy and cover it with a plastic sheet or bring to a safe place (Wattanutchariya 1987) which is labour-intensive.
- Long drying period is required, especially in the winter and rainy season.
- Finally, constant supervision is needed to protect grains from pilferage and animal consumption.

Suggestions

- Because wetting and drying cause grain crack formation the crop should be reaped before it is fully ripe, cracks being formed more readily when the grain is quite hard (Crauford 1962).
- To avoid sun cracking of the grain, slow drying is recommended because it gives a higher percentage of whole grains and the moisture content at milling is less critical. Sun-checking is immaterial if the paddy is to be parboiled, provided that it is dried slowly after parboiling (Crauford 1962). Too rapid, or overlong drying, should also be avoided. Some seeds may become bleached, wrinkled and scorched, or discoloured, and with some types of produce 'case hardening' occurs whereby the surface of the grains dries out quickly sealing the moisture within the inner layers.
- Alternate loss and absorption of moisture by the grain should not be allowed because it enhances the development of internal cracks in the grain (Grist 1965).
- Grains to be sun dried should be placed on a material that prevents dampness from the ground from reaching the produce.
- Sun drying of the grains in a container which has open sides to permit air movement through the bulk is recommended.
- Prevention of high moisture content is the best means of protecting grains against fungus or insect damage, while the efficient ventilation of grain may also be possible if the air available is drier than the air in intimate contact with the grain (Grist 1965).
- Care is required to minimise excessive movement of the grains, which damages the seed coat.
- Grains should not be exposed to rain and rewetting during and after the drying period because stresses set up may cause cracking in the grains.
- Care should be taken to eliminate dust and dirt, which represent extraneous material and accelerate deterioration by permitting an increase in moisture content and both fungal and bacterial infestation (Baird 1987; Khan and Mannan 1991). Fungi in foods and feedstuffs may produce substances (mycotoxins) that are hazardous to human and animal health. Moreover, fungi also encourage the

development of infestation by some species of insects and mites. Hence, the problem of the interaction of moulds and insects and mites on stored products becomes extremely complex (Hall 1970).

- Drying should take place as quickly as possible after harvesting (Baird 1987).
- Union, Thana, Municipal, District, regional, or cooperative drying facilities operating on a fully commercial basis, or large-scale mechanical commercial dryers, alone or in combination with the more recently developed in-store drying facilities and operated by private or government agencies, may be established, as suggested by Baird (1987). This would be of immense value in the prevention of qualitative and quantitative losses. But until then both the Bangladesh Government and international donor agencies should come forward with the financial support to help the farmers and traders to prepare 'high drying grounds of concrete' suitable for sun drying even during floods.

Conclusions

The greatest losses both at farmer and trader levels occur during storage, which is related to inadequacies in processing before storage, such as imperfect drying. In comparison with sun-drying methods, mechanical drying used in developed countries is relatively labour saving, with a low percentage of loss or damage and can protect paddy from rain during drying. Moreover, 'solar dryers' and 'husk-fired dryers' have also been developed and used in different countries. Unfortunately, Bangladesh, being one of the poorest countries in both financial and technological terms, is still devoid of such developed mechanical dryers. As a result, sun drying is still favoured by most farmers and traders because of its low cost and because it does not need a complicated physical handling system. Farmers do not always know the best level to dry, so that when paddy is subsequently stored, discolouration of the grain occurs which in turn results in poor quality and a reduced price for the product (Silitonga 1987). In order to improve the paddy/grain drying process, the farmers should be made aware of the disadvantages of the traditional sun-drying methods and advantages of mechanical methods. In this regard, collaborative programs with research groups in other countries would be useful for developing suitable mechanical dryers for large-scale commercial use. Also, Bangladeshi scientists should look for opportunities to train abroad in the principles and practices of grain drying.

Acknowledgments

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References

Alim, A. 1982. Bangladesh rice, 1st ed. Dhaka, Urmee and Abu Bakar, 90–93.

Anon. 1992. Statistical yearbook of Bangladesh, 11th ed. Dhaka, Bangladesh Bureau of Statistics, Statistics Division, Ministry of Planning, 675 p.

Baird, J.H. 1987. Grading and maintaining grain quality in storage. In: Champ, B.R., Highley, E., and Remenyi, J.V., ed., Technological change in postharvest handling and transportation of grains in the humid tropics. Proceedings of an international seminar held at Bangkok, Thailand, 10–12 September 1986. Canberra, Australian Centre for International Agricultural Research, Proceedings No. 19, 35–41.

BRRI (Bangladesh Rice Research Institute) 1984. Annual report for 1984. Joydebpur, Gazipur, BRRI, 235 p.

Crauford, R.O. 1962. Moisture changes in raw and parboiled paddy in West Africa and their influence upon milling quality. II. Changes during drying. Empire Journal of Experimental Agriculture, 30, 321–329.

Grist, D.H. 1965. Rice, 4th ed. London, Longmans, Green and Co. Ltd, 548 p.

Hall, D.W. 1970. Handling and storage of food grains in tropical and sub-tropical areas, 3rd ed. Rome, FAO, 350 p.

Khan, A.R. and Mannan, A. 1991. Stored-products entomology in the tropics. Agricultural Zoology Reviews, 4, 67–95.

Silitonga, C. 1987. The role of the public sector in postharvest technological change. In: Champ, B.R., Highley, E., and Remenyi, J.V., ed., Technological change in postharvest handling and transportation of grains in the humid tropics. Proceedings of an international seminar held at Bangkok, Thailand, 10–12 September 1986. Canberra, Australian Centre for International Agricultural Research, Proceedings No. 19, 127–140.

Wattanutchariya, S. 1987. Evaluation of solar and husk-fired grain dryers. In: Champ, B.R., Highley, E., and Remenyi, J.V., ed., Technological change in postharvest handling and transportation of grains in the humid tropics. Proceedings of an international seminar held at Bangkok, Thailand, 10–12 September 1986. Canberra, Australian Centre for International Agricultural Research, Proceedings No. 19, 183–187.

Development of Rice-husk Furnaces for Grain Drying

Nguyen Van Xuan, Truong Vinh, Pham Tuan Anh, and Phan Hieu Hien*

Abstract

Two types of rice husk furnaces have been developed at the University of Agriculture and Forestry, Ho-Chi-Minh City, Vietnam. Both have a lower and an upper combustion chamber. The lower chamber is for burning charred husk and discharging ash. The upper cylindrical chamber is for trapping ash and burning volatile matter.

The first type has an inclined step-grate in the lower chamber. Rice husk consumption and drying air efficiency are 20–25 kg/hr and 70–75%, respectively. No ash or sparks escape from the furnace exit. From 1994 these furnaces have been used in many flat-bed paddy dryers (4 t/6 hour batch) in the Mekong Delta of Vietnam.

The second type has a vortex-type combustion chamber and no grate. Control of husk feed rate and the drying air temperature are automatic by a simple vibrating mechanism. The furnace was used in 1994 with an in-store dryer (80 t/4 day batch) installed at Song Hau Farm in the Mekong Delta. Rice husk consumption and drying air efficiency were 10–12 kg/hour and 70–84%, respectively. Drying air temperature (29–30°C) was controlled within ±1°C.

Both furnaces are stable and simple to operate. They meet the requirement for low drying cost by the use of rice husk in the Mekong Delta.

ABOUT 2.5 Mt of rice husks are produced per year in the Mekong Delta, Vietnam. They have been widely used as a heat source for paddy drying since 1990. Current furnaces are box-type with an inclined grate (Fig. 1). They are built by farmers who adopted a prototype of the University of Agriculture and Forestry (UAF), Ho-Chi-Minh City in 1983. The UAF furnace was patterned after designs of Russian furnaces and an International Rice Research Institute (IRRI) rice-husk furnace. Box-type furnaces are simple and low cost. However, their disadvantage is that a great deal of ash and sparks is produced and sucked into the drying chamber. Also, in its current form it is difficult to improve its thermal efficiency.

UAF is applying in-store drying technology in Vietnam. This requires a furnace capable of long-term, continuous operation, stable temperature, and minimum labour requirement. Thus, a furnace with an inclined grate and a cylindrical combustion chamber, and one with a pneumatic feed system, have been developed by UAF in order to meet the objectives of:

- trapping ash and sparks more thoroughly;
- improving furnace efficiency; and
- incorporating a device to automatically control the combustion rate and drying temperature.

Materials and Methods

Design of furnaces

Furnace with inclined grate and cylindrical combustion chamber (IGC)

An IGC furnace was designed in 1994 (Fig. 2). The lower part is box-shaped, built from fire bricks, and has an inclined steel grate. The upper part (patent pending) consists of two metal concentric cylinders, with the thicknesses of the inner and outer cylinders 5 and 1 mm, respectively. The gap between the two cylinders is filled with ash. A pipe located in the centre of the cylinders is connected to the furnace exit. Rice husks flow down from the hopper and along the

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surface of the grate by gravity and vibration forces which were transmitted from the dryer fan to the hopper via a cable. The dryer fan sucks primary air through the grate to burn the charred husk. Secondary air is extracted from the dryer fan to create a vortex in the cylinder to precipitate ashes and sparks, and burn the volatile matter.

Pneumatic-fed furnace (PNF)

A PNF furnace was developed in 1995 (Figs 3 and 4). It has two main components: a combustion chamber and a rice-husk feeding system. The combustion chamber is built from metal sheet and has two parts—upper and lower—which have the same functions as described for the previous furnace.

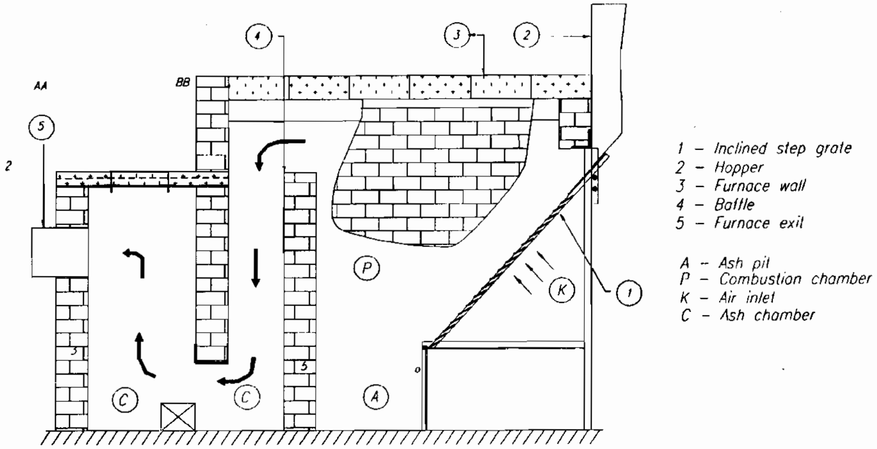

Figure 1. Box-type grate furnace

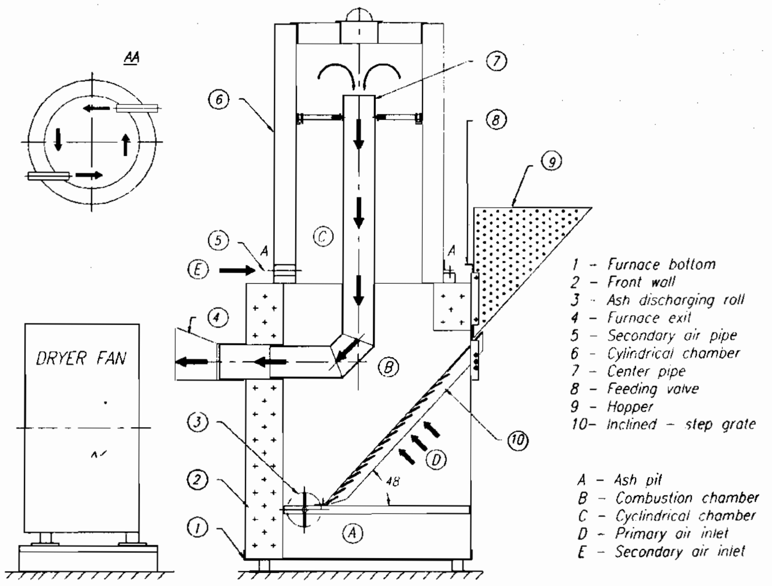

Figure 2. Furnace with Inclined Grate and Cylindrical combustion chamber (IGC)

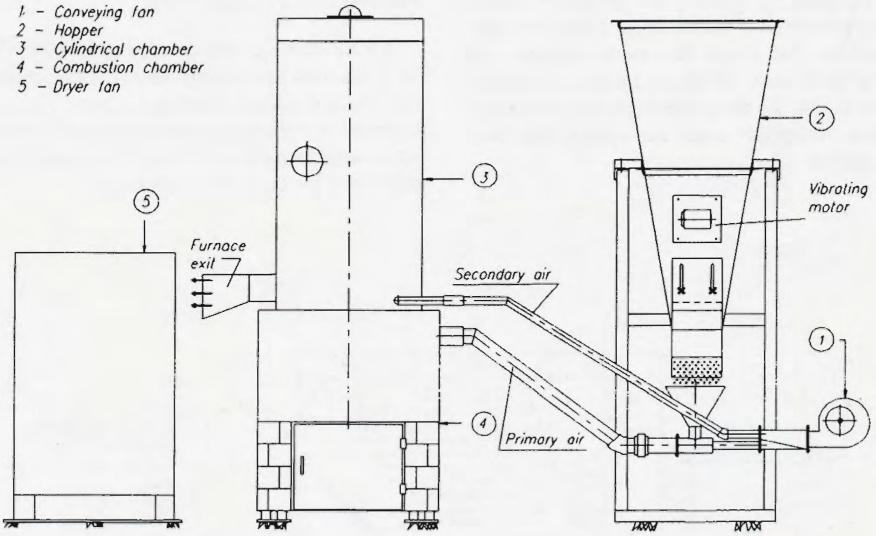

Figure 3. Pneumatic-Fed furnace (PNF)

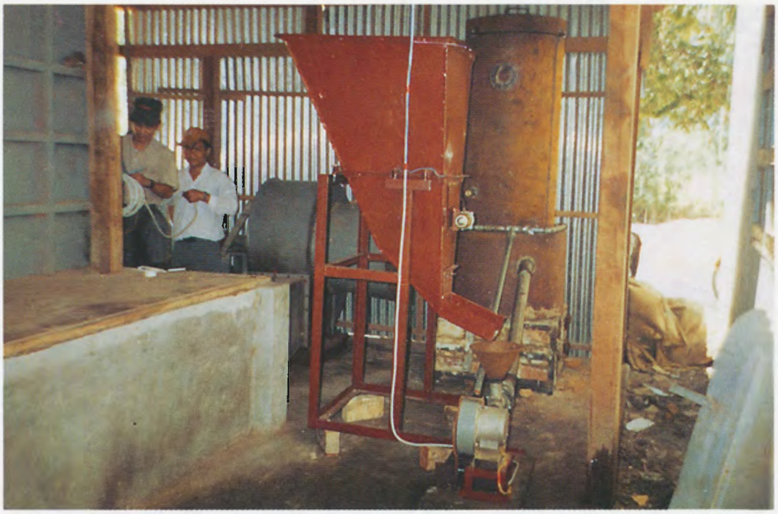

Figure 4. Pneumatic-Fed furnace (PNF) at Song-Hau Farm, 1995.

The rice-husk feeding system consists of a vibrating hopper and a pneumatic conveyer which is patterned after a design published by the NRI (Natural Resources Institute, U.K.; Tariq and Lipscombe 1992; Robinson et al. 1993). Rice husks from the hopper flow down to the entry of the pneumatic conveyer, assisted by a vibrating motor. Together with the primary air, husks are forced tangentially to the lower part of the combustion chamber and form a vortex. Rice husks are burnt as they fall to the bottom of the chamber. Secondary air is extracted from a conveying fan to create another vortex in the upper part of the chamber to precipitate ashes and sparks and burn volatile matter. The rice-husk feeding rate is controlled automatically by means of a thermostat which switches the vibrating motor on or off when the drying air temperature differs from the set value.

Instrumentation

A test duct 6 m long × 0.6 m diameter (Fig. 5) was used to simulate the dryer plenum so as to evaluate the characteristics of the furnace. Construction of the duct and setting of pressure and temperature measurement of air in the duct were adopted from the Japanese Industrial Standard code JIS B 8330-1962 (JMTI 1968). Air pressure was measured by pitot tube and digital manometer. A K-type thermocouple was used for measuring the ambient and drying air temperatures, and a shielded K-type thermocouple for measuring combustion chamber temperature. Temperature data were recorded by data logger. The CO_2 composition of the gas at the furnace exit was measured using Baccharach equipment. The primary and secondary air of the continuous furnace was determined by the orifice plate method (MacMillan 1992). This test was conducted to fix the position of the entry valve of the conveying fan.

Efficiency tests

Tests were conducted at three rice-husk feeding rates: 8, 10, and 12 kg/hour. During furnace operation, static and dynamic pressures and drying air temperatures were measured from the test duct, while the composition (e.g. $\%CO_2$) of the gas produced was measured at the furnace exit. Combustion chamber temperature measurement was taken at the centre of the cylinder and 60 cm above the furnace bottom. Samples of about 250 g of ash were collected after each experiment, and sent to the Service Center of Laboratory Analysis of Ho-Chi-Minh City for determination of unburnt carbon ($\%U_c$). The furnace efficiency (E_{ff}), the drying air efficiency (E_{ffdry}), and the excess air co-efficiency ($\%X_e$) were determined using following equations:

$$E_{ff} = \frac{24.5}{\%CO_2}(Tc - Ta) / Lhv \qquad (1)$$

$$E_{ffdry} = \frac{Mair * Cp(Td - Ta)}{Mf * Lhv} \qquad (2)$$

$$\%CO_2 = \frac{100 - \%Uc}{4.85102 - 0.01 * \%Uc + 0.048752 * \%Xe} \qquad (3)$$

where Tc = combustion chamber temperature, °C
Ta = ambient temperature, °C
L_{hv} = average heat value of rice husk, kcal/kg
M_{air} = airflow rate of dryer fan, kg/s
C_p = specific heat of dry air, kcal/kg
T_d = hot air temperature in test duct, °C
M_f = rice husk consumption rate, kg/s.

Equation 1 is derived from heat balance of rice husk furnace (INPC1986), and equation 3 from a combustion equation for rice husks (Phan Hieu Hien 1992). Proximate and ultimate analyses of rice husk were obtained from the literature (Beagle 1978; Tiangco and Lipscombe 1992).

Drying tests

The IGC furnace was tested as a heat source for a 4 t flat-bed paddy dryer. Tests were conducted at Long-An Province in the Mekong Delta. Other tests of box-type furnaces were carried out in Soc-Trang and Can-Tho provinces. The PNF furnace was used for an 80 t in-store dryer at Song Hau Farm, Can-Tho Province, also in the Mekong Delta. The data were used to evaluate practical performance indicators such as drying air efficiency, stability, labour requirement, drying cost, etc.

Results and Discussion

IGC furnace

Experiment with test duct.

Figure 6 shows the temperature difference between the air temperature in the duct and ambient temperature with respect to time. After 2 hours of operation, the temperature difference was stable at about 12°C. Average airflow rate was 4.37 m^3/s at a static pressure of 220 Pa in the duct. Furnace efficiency was about 70%.

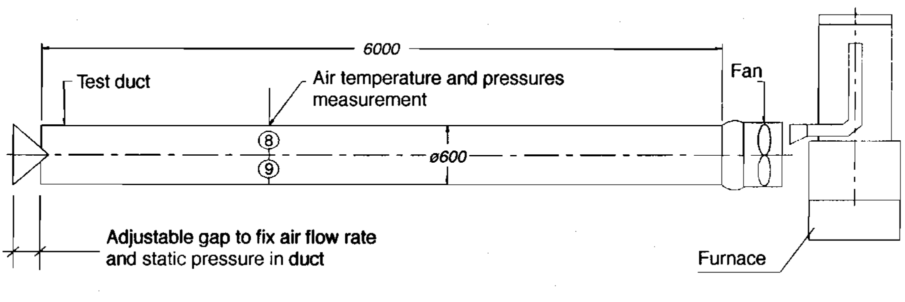

Figure 5. Fan test duct.

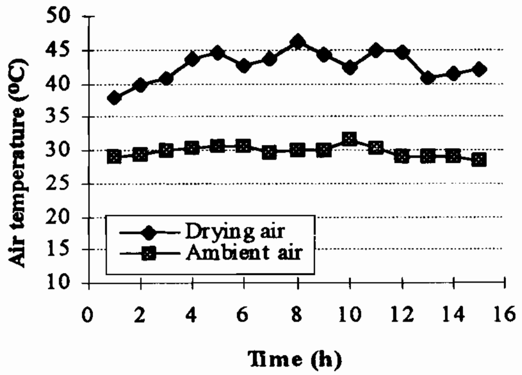

Figure 6. Drying air temperature of IGC furnace test

Experiment with flat-bed dryer

The batch of 4 t of paddy was dried from 26% moisture content (wet basis) to 14% in 6 hours. The rice husk consumption rate was 25 kg/hour with an average drying air temperature of 42°C. No ash or sparks were observed in the plenum. Ash was discharged manually every 20 minutes. Drying air efficiency was in the range 70–75% (Table 1).

Box-type furnaces

Table 1 shows the results of two box-type furnaces coupled to farmers' flat-bed dryers. The drying air efficiency was 41–65%. These results are noted here solely to illustrate the performance of most farmers' furnaces in the Mekong Delta.

PNF furnace

Efficiency tests

Rice-husk feeding rates of 8, 10, and 12 kg/hour were used. Results from experiments showed that the furnace operation was stable in the wide range of excess air coefficient ($X_e = 50–200\%$). The following quadratic functions show the relationships of the combustion chamber temperature (T_c), carbon conversion efficiency (C_{ce}) and furnace efficiency (E_{ff}) to the excess air coefficient.

$T_c = 728.94 + 0.5169\, X_e - 0.006990\, X_e^2 \quad R^2 = 0.98$

$C_{ce} = 72.46 + 0.2122\, X_e - 0.000522\, X_e^2 \quad R^2 = 0.96$

$E_{ff} = 37.78 + 0.4270\, X_e - 0.001268\, X_e^2 \quad R^2 = 0.96$

Maximum furnace efficiency was 75% at a rice-husk feeding rate of 10 kg/hour and an excess air coefficient of 160% (Figs 7–9).

Drying tests

In the experiments with an 80 t in-store dryer, a drying air efficiency of 84% was obtained. Drying air temperature fluctuated in a narrow range as shown in Figures 10 and 11. Average drying air temperatures were 28.3°C for recording interval 20 minutes, and 28.9°C for a recording interval of 2 minutes. Husk feeding and ash discharging were manual, at 2 hour intervals. Average ambient temperature was 22.8°C. Maximum deviation of the ambient temperature during the experiment was 4°C. The hot flue gas was clean in terms of ashes and sparks.

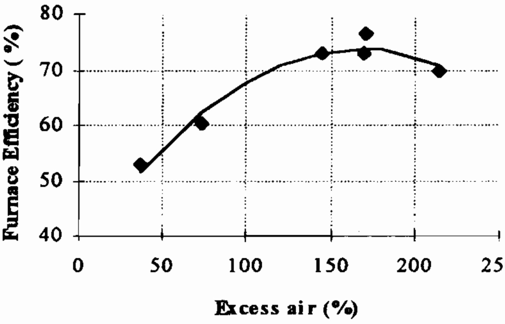

Figure 7. Effect of excess air on furnace efficiency of PNF furnace.

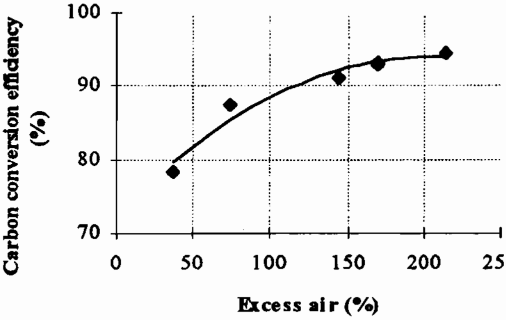

Figure 8. Effect of excess air on carbon conversion efficiency of PNF furnace.

Table 1. Results from drying tests of flat bed dryers with paddy in the Mekong Delta.

Dryers	Bin size (m)	T_a (°C)	T_d (°C)	Airflow(m^3/s)	E_{ffdry}	Flue gas
PhungHiep	4 × 8	29	48	3.04	40.8	ash & spark
Dai-Tam	4 × 9	26	32	4.68	64.5	ash & spark
UAF	4 × 8	29	41	4.37	72.0	clean

Note: T_a = ambient temperature; T_d = drying air temperature.

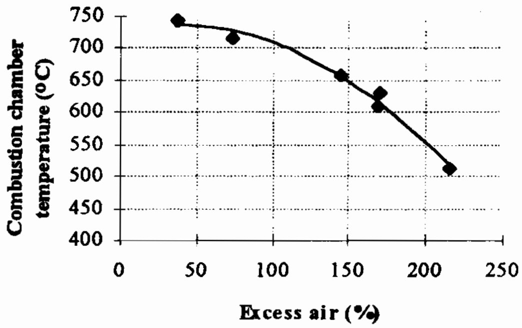

Figure 9. Effect of excess air on combustion chamber temperature of PNF furnace

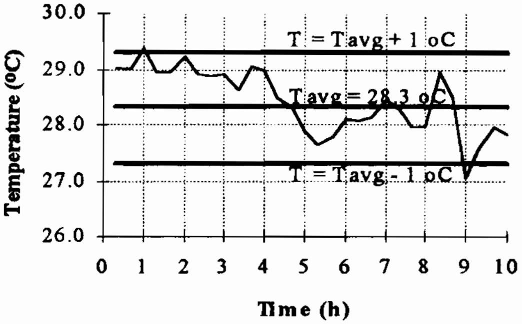

Figure 10. Air temperature in the plenum of in-store dryer (recording interval = 20 minutes) (PNF furnace)

Conclusion

The cylindrical chamber with a central pipe created a vortex resulting in cleaner flue gas and improved thermal efficiency of the furnace. The IGC furnace is now preferred by farmers for flat-bed dryers in the Mekong Delta. The PNF furnace, with its stable operation and automatic control of drying air temperature, is suited to a continuous operation system, such as in-store dryer or fluidised-bed dryer.

The construction of both furnaces is simple and they can be built by local medium-size workshops. They meet the requirement for low drying cost by the use of rice husk in the Mekong Delta.

Acknowledgments

The research reported here was supported by IDRC, ACIAR, and Song Hau Farm. Most of the measuring instruments were provided by the GTZ/IRRI project through Mr Martin Gummert. The research drew heavily on the experience in using rice husks gained by Phan Hieu Hien during his doctoral studies at IRRI in 1990–1992.

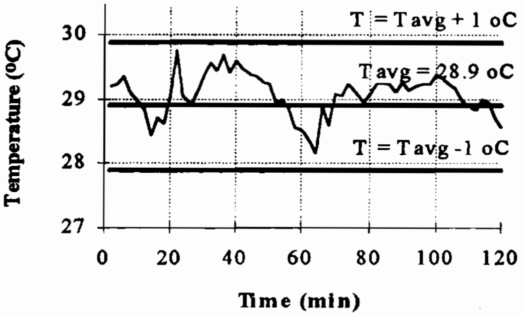

Figure 11. Air temperature in the plenum of in-store dryer (recording interval = 2 minutes) (PNF furnace)

References

Beagle, E.C. 1978. Rice husk conversion to energy. Rome, FAO Agricultural services Bulletin No 31.

INPC (Indian National Productivity Council) 1986. Performance evaluation of rice husk fired furnace systems. New Delhi, Indian National Productivity Council.

JMTI (Japanese Ministry of Trade and Industry) 1968. Japanese Industrial Standards S. Testing methods for fans and blowers. Tokyo, Japan, JMTI.

MacMillan, R. H. 1992. Measurement of air flow with orifice plates. University of Melbourne, Department of Civil and Agricultural Engineering. Equipment for teaching and research in agricultural engineering and development technology, No 1.2.

Phan Hieu Hien 1992. Rice husk combustion systems for crop drying. Ph.D. thesis, University of the Philippines at Diliman.

Robinson, A.P., Hollingdale A.C., and Reupke, P. 1993. The construction and operation of a rice husk burner. Chatham, Kent, U.K., Natural Resources Institute, Bulletin 52.

Tariq, A.S. and Lipscombe, R.J. 1992. Application of air injectors to biomass combustion systems. Chatham, Kent, U.K., Natural Resources Institute, Bulletin 52.

Tiango, A.S. and Lipscombe, R.J. 1992. Rice hull gasifier—engine system for power generation. American Society of Agricultural Engineers, Paper No 91800.

Pilot and Commercial Application of Ambient Temperature In-store Drying of Paddy in Northern Thailand

R.J. Parkin*

FORCED aeration of bulk grain has become an increasingly popular practice over the last 10 years for a variety of reasons. Not only is it beneficial for keeping grain cool during storage to better maintain quality, it can also be used for slow drying which increases head yield of rice following milling, compared with traditional sun drying or rapid drying using hot air. Furthermore, aeration reduces the likelihood of insect infestation.

There now appears to be adequate definitive research to be able to assess the value of ambient temperature aeration of paddy rice in particular, compared with other methods of drying. Soponronnarit et al. (1994) have provided four-quadrant graphs relating initial grain moisture (%), depth of grain, airflow rate, drying time, and energy use for both paddy and maize. Other workers have developed similar models, and computerised simulation of drying for a number of variables (Driscoll 1987).

Despite this definitive work, the application of this technology in industry in Thailand has been slow and restricted to a few demonstrations close to Bangkok.

Areas far north of Bangkok face lower temperatures and, in many cases, higher relative humidity. Average temperature at Uttaradit in August–September is 0.5–1.0°C cooler than Bangkok, and average relative humidity is about 5% higher over the same months. So there was some concern that the technique of ambient temperature aeration may not be as successful for paddy drying in the wet season as it is at more southerly locations.

The Thai–Australian Agricultural Project, which had been assisting a large farmer group at Tron in Uttaradit Province establish facilities at a central grain market centre, conducted a small demonstration of aeration drying in the 1994 wet season. This was done in one 50 t bay of a raised floor concrete store. In 1995, farmers and traders at the centre decided to build a new 300 t store suited to bulk handling and to incorporate in-store aeration.

Materials and Methods

In 1994, 600 mm wide semi-circular, corrugated ducting was used in a 6 × 6 m compartment of a 100 t concrete store. Ducts were 2 m apart and supplied by a backward curving centrifugal fan delivering 3.15 m^3 air/sec (specific airflow of 1.9 $m^3/min/m^3$ of paddy). Only one batch of grain was tested, as the facilities were not completed until near the end of the wet season harvest. The test was carried out on 54 t of paddy of initial moisture content 20.9%. The depth of the grain bed was 3.5 m. A comparable batch of paddy was sun dried on a concrete pad to 14.7% moisture content and stored in the other compartment of the concrete store. Grain moisture levels were monitored at the top of the stack only, at regular intervals during the drying/storage period, using a standard Kett moisture meter. Temperature of the grain mass was monitored continuously using thermocouples linked to a Delta-T data logger. Paddy samples were taken at the beginning and end of the storage period and analysed for head yield, moisture content, and grain yellowing.

In 1995 the new store was constructed and the aeration system installed. The store consists of three open-fronted bays each 15 m long and 4.8 m wide. Each bay has two in-floor air ducts, 2.25 m apart and 1.25 m from each wall. The ducts are 50 cm wide, while the duct plenum chambers are 40 × 40 cm at the fan end, tapering to 40 × 20 cm at the store entrance end. The ducts are fed by two 5.5 kW backward curving centrifugal fans, each supplying 3.15 m^3 air/sec. By means of a series of valves in the ducting manifold and the ducts themselves, six different airflow rates can be used, ranging from 0.3 to 3.8 $m^3/min/m^3$ of grain, assuming a full storage depth of 3.5 m.

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Thus, the system is very flexible, allowing for very low airflow rates for aeration cooling, through to the higher airflow rates required for grains such as maize, higher moisture grain, shallower depths of grain, or when storage time becomes more important than minimising specific energy consumption.

Thermocouples were installed temporarily in the rear of one bay only, to monitor temperature during the first drying cycle. Relative humidity and ambient temperature were also continuously recorded on a Delta-T logger.

To guide the operation of the aeration/storage system, a series of simulation drying runs was carried out using the computer program developed by the University of New South Wales, Australia (Driscoll 1987). As hourly temperature and relative humidity data are not available for Uttaradit, hourly data from Don Muang (Bangkok) for 1970 were used, as these most closely approximated the average data for Uttaradit. Based on these, a management manual was produced using a time clock basis of fan operation.

A record system was established to record market inflows and outflows of paddy for the whole of the wet season.

Results and Discussion

1994

While the testing of aeration drying did not commence until very late in the wet season harvest (16 August), it did provide the opportunity to test the approach at the most difficult time of the year. Because of the commercial nature of the market centre, strictly controlled conditions could not be enforced. Delays were experienced in starting because of the difficulty of concrete pad drying of paddy to the intended initial moisture content of 18–19%. Actual initial moisture content was 19.8% for the first 28 t loaded, and 21.9% for the remaining 26 t. Conditions were exacerbated by a motor failure after 2 weeks, resulting in a halt in aeration for 8 days. The temperature of the grain was approximately 50°C at commencement, and while aeration then maintained the stack at 28–31°C, during the period of motor failure, temperatures reached almost 64°C above the drying front.

The fan was run continuously for the first 2 weeks but after the motor failure the intention was daylight use only. For a variety of reasons, this was not adhered to. Over the period of the test (37 days) the fan operated for 490 hours. During that time, the estimated total time that relative humidity was below 80% was 172 hours so the fan was operated often to no effect. The fan size was larger than required (to allow for future extension of aeration) and the stack was over-dried (aeration continued until the top of the stack reached 14.5% moisture). As a consequence the cost of drying of approximately 100 Baht/t (about US$4/t) was unacceptably high.

Despite the problems there was no difference in grain yellowing between this grain and the paddy that had been concrete pad dried and stored without aeration. These and other details are shown below in Table 1. The large difference in percentage head rice yield shown in the Table can be largely but not entirely explained in that, due to error, the last 26 t of the aerated stack (48%) was Chainat variety, whereas all other grain used was Suphanburi 60 which has a lower average head yield. Irrespective of any differences, the trader purchasing the rice did not differentiate between the two stacks and paid the same price/t for each.

Table 1. Details of aeration and grain characteristics for paddy drying demonstration 1994.

Paddy characteristic		Aerated		Unaerated	
		Initial	Final	Initial	Final
Grain moisture (% wet basis)		20.9	13.0	14.7	12.1
Head rice	top	53.1	58.3	39.8	46.3
(%)	middle	–	55.9	–	41.4
	bottom	–	60.5	–	35.9
Grain yellowing	top	0.29	1.36	0.25	0.69
(%)	middle	–	1.41	–	1.22
	bottom	–	0.19	–	0.67
Storage period (days)			72		62

1995

Despite a much longer lead time in 1995, a series of mishaps delayed commissioning of the new store and aeration system until the end of July (the end of donor assistance). At the time of this conference, preliminary information obtained from Tron Central Grain Market was that 3 weeks of deliveries occurred after commissioning, yielding a total of less than 500 t of paddy. None was totally dried by aeration but approximately half was stored and aerated for 3–5 days and then sold. Thus, the system has yet to be evaluated for wet season drying.

The simulation runs carried out indicate that, over the period of wet season deliveries, some 800–1000 t of wet paddy could be aeration dried in the new store, at an estimated cost of 34 Baht/t. However, even given full use, this only represents 10–12% of the 1995 wet season deliveries (see Table 2). Furthermore, full and efficient use of ambient temperature aeration drying can occur only in conjunction with a hot air dryer used for first stage drying. Of the 95 days of wet season deliveries, only 47 were suitable for any degree of concrete pad drying.

Table 2. Pattern of paddy deliveries, Tron Central Market 1995 wet season.

Time period	Quantity received (t)	Quantity disposed (t)	
		Wet	Dried
27–31/5	313.6	n.r.	n.r.
01–05/6	615.7	272.3	166.9
06–10/6	509.8	198.3	178.1
11–15/6	627.1	181.5	513.2
16–20/6	711.7	286.5	372.6
21–25/6	800.2	275.0	430.0
26/–30/6	632.8	481.0	291.6
01–05/7	226.3	126.3	134.7
06–10/7	766.0	539.5	117.4
11–15/7	707.3	551.2	160.1
16–20/7	594.8	413.5	151.6
21–25/7	714.1	464.3	269.4
26–30/7	298.3	384.0	–
31/7–04/8	377.3	218.1	57.9
05–09/8	118.9	117.5	–
10–14/8	132.5	131.8	–
15–19/8	118.0	37.9	36.3
20–24/8	75.4	51.7	40.5
25–29/8	2.4	–	42.6
Total	8342.2	4750.4	2964.9

Conclusions

Ambient temperature aeration drying of paddy during the wet season can be successfully carried out in the northern region of Thailand, but heat-assisted aeration and 'dryeration' will be more practical than aeration drying alone. Despite training, farmer cooperatives have yet to determine how to best operate aeration systems.

Acknowledgments

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References

Driscoll, R.H. 1987. Grain drying strategies for the humid tropics. In: Champ, B.R., Highley,E., and Remenyi,J.V., ed., 1987. Technological change in postharvest handling and transportation of grains in the humid tropics:proceedings of an international seminar,Bangkok,Thailand, 10–12 September 1986. ACIAR Proceedings No. 19, 26–34.

Soponronnarit, S., Wongvirojtana, P., Nathakaranakule, A., and Chinsakolthanakorn, S. 1994. Maintaining paddy quality by appropriate ventilation under tropical climates. Proceedings of the 9th International Drying Symposium, 1–4 August 1994, Gold Coast, Australia, 825–832.

Use of Existing Pig Pens as Drying Bins for Wet Season Paddy Harvest

M.C. Pasikatan*, G.C. Salazar*, and E.U. Bautista†

THREE major constraints to farmer adoption of mechanical dryers are their high initial investment, high drying costs, and low utilisation rate. In the Philippines, farmers have to invest about PHP34 000 (during October 1995 ca 26 Philippine pesos (PHP) = US$1) for the lowest cost mechanical dryer—a flat-bed dryer with a kerosene burner—which will only be used for about a month per year. Generally, farmers think they need mechanical dryers only during the wet-season paddy harvest, when the least cost dryer—sunshine—is not available or is unpredictable. During the dry season and in the absence of incentives to deliver higher quality grain, mechanical dryers are no match for sun drying.

Farmers usually tend at least one pig for cash purposes and pig pens are thus common structures in farms. Farmers with more than one hectare landholding usually own a power tiller, or have means to rent one for their needs. A pig pen and an engine provide a means for facilitating farmer adoption of mechanical drying.

A scheme to reduce initial investment and drying costs, and offset low utilisation rate by utilising existing pig pens as flat-bed, batch type drying bins, existing power tiller engines as prime movers, acquiring dryer components by modules, and using rice hulls for drying fuel, has been tested in Tarlac, Philippines.

Materials and Methods

The dual-use drying bin

A farmer in Tarlac, Philippines, who owns a tiller powered by a 5 h.p. diesel engine was selected as cooperator. Beside his house was a 2.6 × 3.5 m pig pen. The concrete wall and flooring were utilised as a drying bin. A 50 × 150 mm wooden beam was placed transverse to its length to support six detachable 1.8 × 0.8 m wooden-framed BI sheet with 2 mm perforations. Concrete was poured on top of the existing pen wall to make an additional 0.36 m high enclosure. A 42 cm diameter blower housing was fitted permanently to the middle of the narrow side of the pig pen. Adjacent to this, a concrete base for the engine and straightener-vane blower system was installed. An IRRI-designed portable step-grate rice-hull furnace completed the system (Fig. 1).

The scheme involved raising pigs in the pen from November to July, then using it as a drying bin for the wet-season harvest months. The farmer either dries his own harvest and stores it for a better price, or provides paid drying services to his neighbours.

Performance tests

The pig pen drying bin–rice hull furnace (PDB–RHF) batch dryer system was tested using the RNAM test code for batch dryers and IRRI batch dryer test procedures, with slight modifications to suit available instruments. The furnace temperature, drying and ambient air temperature, ambient and exhaust relative humidity, grain moisture changes, and rice hull and diesel fuel consumption were monitored as drying proceeded. Batches of grain were dried under day- and night-time conditions.

Economic analysis

The profitability of the dryer was analysed, in comparison with that of a typical flat-bed dryer (FBD) and using utilisation rates of 30, 40, 50, and 60 t/year (15–30 days per year, 2 batches per day), and price differences of PHP1 to PHP6 (based on present prices). For other assumptions see Table 1.

Results and Discussion

Dryer performance

Under daytime ambient conditions (T = 34.6°C, r.h. = 56.6%) and a drying air temperature of 44°C, paddy of 21% moisture content was dried to 14% in 5.7 hours

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or 1.18%/per hour moisture removal (or 14.8 kg H_2O/hour). It was difficult to sustain the combustion of rice hulls, hence the variation in drying air temperature. This also caused losses in drying time. There was, at most, a 3°C drying air temperature variation within the plenum, which is typical of flat-bed dryers. The grain depth of a batch of 1 t was 16.5 cm, and for 2 t was 30.5 cm.

Under night-time ambient conditions (T = 26.6°C, r.h. = 76.5%) and a drying air temperature of 37.4°C, paddy of 21% moisture content was dried to 16% in 7.4 hours or 0.77%/per hour moisture removal rate. The drying air temperature could not be increased to 43°C because of low ambient air temperature and ambient relative humidity, characteristic of evening conditions.

It took 0.7–1.3 person-hours to load the wet grain and 1.5–2 person-hours to unload the dry grain. Rice hull consumption was 7.0–9.6 kg/hour and diesel fuel consumption 0.44–0.52 L/hour.

Economics of the PDB–RHF dryer

Like any mechanical dryer, the economics of PDB–RHF is sensitive primarily to the price difference between wet and dry paddy, and secondly to annual utilisation rate. However, because of lower initial investment and drying cost than the FBD, it is less sensitive to these two factors.

At a price difference of PHP1, investing in a 1 t dryer is not economical, even at an ideal utilisation rate of 60 t/year. At a price difference of PHP2/kg, the PDB–RHF dryer becomes profitable, while the FBD is still not so. At a price difference of PHP3/kg, the economics improved for both types of dryers, even for 30 t/year utilisation rate (Fig. 2), for which the annual net benefits for FBD and PDB–RHF were PHP27047 and PHP39197, respectively. This corresponds to payback periods (PBP) of 2.4 and 0.9 years, respectively.

The price difference for 1995 wet-season paddy was PHP6–7/kg, and for 1994 dry season paddy PHP3–P3.5, indicating that there are good prospects for increased adoption of mechanical dryers.

The drying cost as per cent of wet paddy was lower for the PDB–RHF system, ranging from 7.5–11.5% compared with the 12.7–19.6% of the FBD.

The lower investment and drying costs resulting from dual use of the drying bin, multiple use of the engine, and use of rice hulls for drying fuel mean that the owners of PDB–RHF systems would recover their investment more rapidly. In future applications, to further lower the drying cost, the dimensions of the pig pen-drying bin may be increased to bring its drying capacity per batch to 2 t or more.

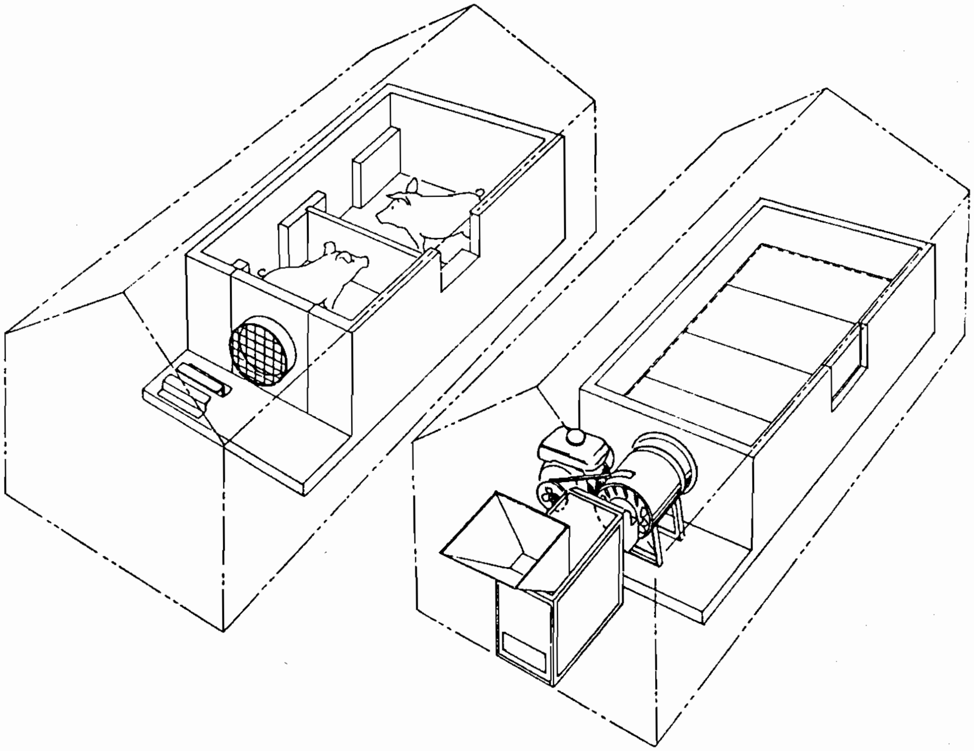

Figure 1. The pig pen drying bin–rice hull furnace (PDB-RHF) concept.

Table 1. Basic data used in economic analysis.

	FBD[a]	PDB–RHF[b]
Investment cost (PHP[c])	64,000	34,000
drying bin	34,000	22,000
diesel engine	20,000	n.a.[d]
rice-hull furnace	n.a.	12,000
shed	10,000	n.a.
Drying capacity	1 t in 8–10 hours	1 t in 8–10 hours
Utilisation rate (days/year)	15, 20, 30	15, 20, 30
No. of batches/day	2	2
Labour requirement		
operation	1/batch	1/batch
loading/unloading	1 person-hour/t	1 person-hour/t
Fuel requirement		
diesel	0.5 L/hour	0.5 L/hour
rice hull	n.a.	10 kg/hour
kerosene	2 L/hour	n.a.
Repair and maintenance cost	10% IC	10% IC
Labour cost	PHP100/person–day	PHP100/person–day
Price of wet paddy (26% m.c.)	PHP5/kg	PHP5/kg
Price of dry paddy (14% m.c.)	PHP6–12/kg	PHP6–12/kg
Interest rate	24%	24%

[a] FBD = flat bed dryer system (kerosene burner).
[b] PDB–RHF = pig pen drying bin–rice hull furnace system; assumes farmer already owns a diesel engine or can rent one at PHP10/hour.
[c] During October 1995, ca 26 Philippine pesos (PHP) = US$1.
[d] n.a. = not applicable.

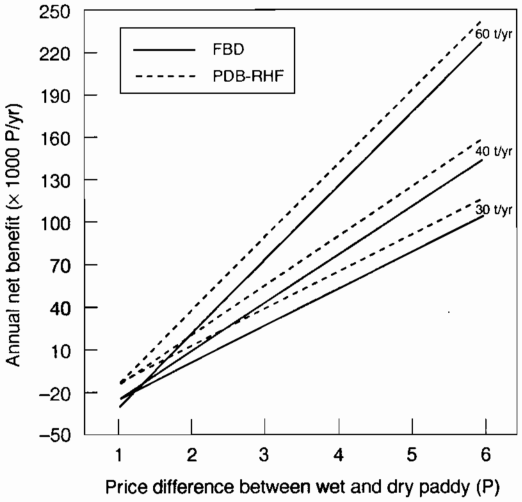

Figure 2. Annual net benefit of a flat-bed dryer and the pig pen drying bin–rice hull furnace (PDB-RHF) dryer system at varying price differences between wet and dry paddy, and various utilisation rates.

It was observed that the farmer's wife used the heated top surface of the furnace to roast *tupig* (a native sweet delicacy). This suggested the concept of a rice hull furnace-cum-stove to further increase the utility of the furnace.

Conclusions and Recommendations

The tests indicated typical flat-bed batch dryer performance in terms of factors such as drying air temperature variations within the plenum and grain moisture variations. With skilful tending of the furnace to maintain a plenum temperature of 40–50°C, a drying time of 5–6 hours is possible for a 1 t batch of wet paddy for typical daytime conditions, or 8–10 hours for a 1 t batch of wet paddy for typical nighttime conditions.

The average rice hull consumption during the tests was 8.32 kg/hour, while an average of 0.5 L/hour of diesel fuel was used.. The rice-hull feeding and ash removal system for the furnace need to be improved for a more uniform and sustained furnace temperature.

Based on shorter drying time and lower moisture variation, the recommended depth of grain on the bin is from 16.5–25.4 cm (this corresponds to 1–1.5 t of wet paddy per batch).

Raising of pigs must be timed such that the pig pen has been vacated before the wet-season paddy harvest.

The PDB–RHF was economically attractive because of its low investment and drying costs. It becomes profitable at a price difference between wet and dry paddy of PHP2 if its utilisation rate is at least 30 t/year. To make the PDB–RHF system more economical and thus more acceptable, the capacity per batch may be increased, and a rice-hull furnace-cum-stove may be designed for all-year round cooking, and as furnace during wet-season paddy drying.

Case Studies on Moisture Problems in Guyana Brown Rice

D. Permaul*

In 1991, the Guyana Government began to deregulate the rice industry. This started a steady increase in rice production culminating in the largest ever exports of rice from Guyana, some 183 000 t in 1994. Much of the rice exports are semi-processed. An analysis of rice export figures for the past 5 years from Guyana shows that increasing amounts of brown rice (known as 'cargo rice' in Guyana) are being exported (Table 1). Millers and warehouse managers thus have to manage increasing amounts of brown rice over several months, an aspect of the business which is largely unfamiliar to them since in the past they have handled mostly paddy and milled rice.

Table 1. Guyana brown (cargo) rice exports as a percentage of total rice exports.

Year	Total rice exports (t)	% Cargo rice(t)
1990	61 000	49.4
1991	41 000	74.1
1992	115 000	46.3
1993	124 000	61.7
1994	183 000	84.2

Source: Guyana Rice Export Board, unpublished data.

Within the past two years there have been cases in which Guyana brown rice began to deteriorate in storage. This study examines three of these cases and tries to determine what went wrong to cause the spoilage both from a scientific and managerial perspective. Specific recommendations designed to minimise such losses are discussed.

Case 1

Facts

Rice storage and processing facility A produces about 20 000 t of rice annually. Paddy at high moisture is processed into brown rice for export. Rice is stored in 400 t steel silos until ships arrive. Recently, rice in 4 silos (1600 t) heated up, and eventually developed a strong musty odour. Samples collected from various depths in the grain bulk were examined by the Government Analyst Department and found to contain fungi, mainly the genera *Aspergillus* and *Penicillium*. Moisture content of the samples was determined using a calibrated Motomco Model 919 meter. The moisture content of all samples was between 15 and 16%. The entire consignment of 1600 t was declared unfit for human food and had to be sold as animal feed at about 20% of its unspoiled value.

Findings

The main findings of discussions with company personnel were as follows:

- Management experimented with varying paddy moisture content so as to obtain optimum head rice recoveries. It was determined that using variety Rustic at 14% moisture content, the best head rice yields were obtained.
- After each pass through the artificial dryer, paddy was immediately returned to the dryer without being allowed time to equilibrate. Upon achieving 14% moisture content the grain was immediately dehulled for storage prior to shipping.
- Moisture content of rice was not determined after processing or during storage in silos.
- Silos were not equipped with temperature sensors to detect changes in the grain bulk.

Solution

It seems that in this case the grain, after passing through the dehulling process, might have been at a moisture content which was unsafe for storage or was still equilibrating, resulting in a higher storage mois-

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ture content. In either case, this high moisture could have resulted in fungal proliferation.

Secondly, the quantities with which the moisture content/head yield experiment was carried out were far too large and hence became costly in the event of failure.

Monitoring moisture and temperature is an integral part in loss prevention in stored grain. Moisture meters were available to the officials but were not used. The silos too need to have a reliable system of measuring temperature rises in a bin. Additionally, the experimental methodology adopted must be more rigorous so that scientific conclusions can be gleaned.

Case 2

Facts

Rice storage and processing facility B produces about 15 000 t of rice per year. As in case A, paddy at high moisture is processed into brown rice for export. Rice is packaged in woven 50 kg polypropylene bags and stored in stacks of about 1000 t until shipped.

One of these stacks heated up and a mild odour was evident. Before it had been observed that the rice was beginning to deteriorate, 300 t were loaded onto a ship and eventually had to be removed manually. The entire consignment of 1000 t was redried and milling yield was reduced.

Findings

- The moisture content of paddy at milling was high as shown by records.
- There was a delay between the time the Quality Control Department indicated that the milling moisture was high and the time action was taken to arrest the problem.
- Weekly quality reports on cargo rice were not made.
- A cargo rice moisture chart was only recently procured.
- Silo drying staff lapsed in the amount of moisture removed from a given consignment of paddy at a specific moisture content.
- Paddy of different moisture has been stored in the same bin.
- Staff involved in the processing and storage of rice were poorly supervised.
- The national regulatory body was tardy in determining the moisture content and temperature of the affected shipment.

Solutions

- Moisture content at the time of milling should not exceed 13%. This can be achieved by the following
  - appropriate solar or artificial drying;
  - moisture checks on incoming paddy, paddy leaving after each drying pass, paddy that has been tempered for a minimum of 8 hours, paddy that is stored in bins and bags and, on a half-hourly basis, paddy that is going to the mill. Results must be used to make timely decisions on drying, storage, and milling;
  - twice daily physical examination of paddy storage bins for heating, condensation, and increase of moisture, and taking appropriate action such as drying and aeration.
- Quality control reports with the following information should be made on all cargo produced:
  - half-hourly moisture content of cargo rice produced. This should not exceed 13.8%. As soon as this happens, milling should be stopped and only paddy of suitable moisture milled. The rejected batch should be dried;
  - quantity of cargo in stacks;
  - factors such as discoloration, yellowing, insect infestation, moisture content, paddy, chalky, green, insect damaged, etc. This should be done weekly;
  - temperature of the stacks and bins. Bin temperature will need engineering work. Stack temperature can be measured with a grain thermometer.
- The Quality Control Department should be empowered to stop the mill if the moisture content is unacceptable.
- Management supervision must be improved to a level where timely decisions can be made, especially with reference to critical factors such as moisture content.

Case 3

Facts

Private entrepreneur C exports Guyana cargo rice in 20 t steel containers. These are fumigated, sealed, and stored in the open at wharves before export. One consignment of 20 containers stored for 4–5 weeks deteriorated. Several sections within the grain bulk of each container were caked, musty smelling, and were rejected for export. Much of this rice was sold at a very low price as animal feed.

Findings

- Moisture content was not measured before loading. Samples taken showed a moisture content of 15–16%.
- Monitoring of containers after fumigation was not carried out. Such monitoring was not easy as a result of wharf and customs regulations.

Solutions

The grain in this case might have been at a safe or unsafe storage moisture. Even if it had been safe initially, moisture condensation caused by differential heating during the day might have created conditions for spoilage.

- Moisture content of potential export rice must be measured with an accurately calibrated meter and should not exceed 14%. Ideally, moisture content should be about 13.5% for cargo rice.
- There should be timely shipping of containers. When not possible, containers should be kept under cover.

Discussion

Spoilage organisms

In each of the three cases described, high moisture seems to have contributed to the deterioration. The fungi most consistently associated with incipient grain deterioration are members of the genera *Aspergillus* and *Penicillium* (Lin 1986). Apart from the requirements of a suitable substrate and atmospheric conditions, the most critical conditions for the growth of fungi are summarised in Table 2. Clearly, once rice is stored at an equilibrium moisture content which is equivalent to slightly less than 70% relative humidity, fungal deterioration can be avoided.

Once rice is moist enough for fungi to grow there is rapid proliferation which may be associated with discoloration (Phillips et al. 1989), increase in chalky grains (Quitco and Ilag 1982), mycotoxin contamination (Pitt 1991) and, finally, a caked, musty, rotting mass (Christiansen and Sauer 1982), if conditions remain favourable.

Integrated strategies

Spoilage can be reduced if integrated strategies are applied along the whole postharvest chain in Guyana.

Maintenance of machines and equipment

Faulty or inefficient machinery takes longer to process rice and increases the risk of fungal attack. Critical pieces of equipment such as elevators, conveyers, dryers, and cleaners deserve much more care and maintenance than others. Maintenance and calibration of moisture meters must also form part of this program.

Sanitation and hygiene

Good sanitation eliminates conditions which favour storage pests and minimises infestation arising from such reservoirs. Insect infestation is known to initiate heating in grains (Howe 1962).

Harvesting

Before harvesting, the combine should be cleared of previous grain debris or treated with an insecticidal fog to eliminate residual infestation. Combine setting and speed must be adjusted and fine-tuned to derive maximum yield, minimum damage to the grain, and low dockage. Dockage may contribute to 'hot spot' formation in grain (Hall 1963).

Drying

Proper paddy drying is probably the single most important act to reduce fungal spoilage in cargo rice. Where artificial dryers are used, the manufacturer's recommendations should be followed.

Storage

Having dried the incoming paddy to 12–13% moisture content it may then be stored in clean bags, silos, or flat-bulk stores. Stocks should be built on dunnage to minimise 'wetting' of bottom bags. Adequate space must be left around stocks to facilitate inspection, sampling, pesticide application, and grain removal.

Inspection and sampling

Once paddy is stored, the need for inspection and sampling, followed by accurate measurements, becomes critical. These activities are to:

- locate unsanitary conditions conducive to pest multiplication;
- find infestation that already exists; and
- determine what, if any, control measures are needed.

During this procedure, moisture content of stored paddy and temperature of stacks and bins should be closely monitored so as to provide timely information on incipient deterioration.

Table 2. Approximate conditions of relative humidity and temperature for the growth of common storage fungi.

Fungus	Minimum relative humidity (%)	Minimum temp.	Optimum temp. (°C)	Maximum temp. (°C)
Aspergillus restrictus	70	5–10	30–35	40–45
Aspergillus glaucus	73	0–5	30–35	40–45
Aspergillus candidus	80	10–16	45–50	60–65
Aspergillus flavus	85	10–15	40–45	45–50
Penicillium spp.	80–90	5–10	20–25	35–40

Source: Lin 1986.

Processing of paddy

The moisture content of paddy entering the mill must be rigidly controlled so as to produce cargo rice not exceeding safe storage moisture levels.

Cargo rice stacks produced must also be monitored during storage. This kind of monitoring is the responsibility of quality control personnel and a practical regime must be worked out. The regulatory body can also be asked to monitor moisture content of cargo rice entering trade.

Stock management

Whenever it is compatible with the objectives of management, rice brought into storage should be the first to leave, whether it is being sold or scheduled for milling. This lowers time spent in storage and minimises the risk of spoilage.

Record keeping

Properly kept records are especially helpful in making decisions which may affect grain moisture levels, and over a period of time provide a source from which in-depth analyses can be carried out pertaining to drying.

Conclusions

High moisture brown (cargo) rice can deteriorate rapidly under Guyanan conditions, leading to severe economic losses. In all three cases examined, high moisture and subsequent fungal proliferation seem to have been responsible for the spoilage. If high moisture cargo rice is produced, then it means that moisture content in rough rice or paddy is not controlled adequately. None of the series of measures identified can individually ensure safe levels of moisture in cargo rice, but collectively can minimise the kind of damage detailed in the cases here. Many of these measures are interdependent. Failure to store dried paddy on pallets or dunnage, which helps to prevent moisture migration from the floor to the grain, serves to illustrate this interdependence. As Guyana begins to deal more in brown rice, the need to apply the strategies outlined here will become more critical if spoilage is to be kept within manageable limits.

Acknowledgment

The author is grateful to the Alesie Group of Companies in Guyana for their complete support on this study and to the Faculty of Agriculture, University of Guyana for its steadfast encouragement.

References

Christiansen, C.M. and Sauer, D.B. 1982. Microflora. In: Christiansen, C.M. ed., Storage of cereal grains and their products. St. Paul, Minnesota, American Association of Cereal Chemists, 219–240.

Hall, D.W. 1963. Some essential considerations on the storage of food grains in tropical Africa. Rome, FAO Agricultural Engineering Board, Informal Working Bulletin No. 24, 176 p.

Howe, R.W. 1962. A study of the heating of stored grain caused by insects. Annals of Applied Biology, 50, 137–158.

Lin, Y.S. 1986. Microflora in stored grains and control measures. In: Post-harvest prevention of paddy/rice loss. Taipei, Republic of China, Council of Agriculture, 158–170.

Madramootoo, H. 1973. The story of rice in Guyana. Georgetown, Guyana Rice Corporation, 52 p.

Phillips, S., Mitfa, R., and Wallbridge, A. 1989. Rice yellowing during drying delays. Journal of Stored Products Research, 25, 155–164.

Pitt, J.I. 1991. Penicillium toxins. In: Champ, B.R., Highley, E., Hocking, A.D., and Pitt, J.I. ed., Fungi and mycotoxins in stored products. Proceedings of an international conference, 23–26 April 1991, Bangkok, Thailand. Canberra, Australian Centre for International Agricultural Research, Proceedings No. 36, 99–103.

Quitco, R.T. and Ilag, L.L. 1982. Fungi as the cause of yellowing and other discolouration of rice. In: Teter, N.C. and Frio, A.S., ed., Progress in grain protection. Proceedings of the 5th Annual Grains Post Harvest Workshop, 19–21 January 1982, Thailand, 118–121.

Grain Drying in a Batch Fluidised-bed Dryer

Pham Cong Dung*

Abstract

Fluidisation has long been used for grain drying around the world. The principal advantages of this technology are: the heat and mass transfers between the airflow and grain are very great; the dryer is simple and small, so the initial investment is rather low; and the moisture content of the product is uniform. In Vietnam, fluidisation has not yet been used widely, so it is necessary to study the effect of factors such as air temperature and velocity on time of grain drying in order to optimise fluidised-bed drying. A series of laboratory-scale experiments was conducted on maize and paddy using a batch fluidised-bed dryer. The following conclusions were drawn.

- The air velocity has no significant effect on drying rate. After fluidisation, further increases in air velocity do not affect drying rate. It is thus necessary to determine a stable hydrodynamic regime for the fluidised bed.
- The drying air temperature has a significant effect on drying rate. The drying rate with air at 95°C is approximately twice as fast as with air at 15°C. An empirical formula which shows the relationship between drying time and the air temperature for some agricultural products was obtained by applying the least square method to the experimental results.

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Development of a Conduction-type Dryer for Paddy

Banshi D. Shukla* and Robert E. Stickney†

SUN DRYING is an inexpensive and convenient method of drying crops. In rice-farming areas, however, it is undependable when paddy is harvested in the wet season and, because of clouds and rain, drying is delayed. This problem has led to the development of a variety of low-capacity paddy dryers. None of the present designs has been widely accepted, generally because the cost is high for a device that is used only when sun drying is prevented by rain or overcast weather. With this in mind, a simple, low-cost 'heated floor dryer (HFD)' which complements sun drying and utilises rice straw as fuel has been designed and developed, and a pilot model tested.

The basic concept is that the HFD will be used only when sun drying is prevented by weather and it will serve to pre-dry paddy to a moisture content of about 18%, which is adequate for temporarily storing the grain until weather allows complete drying under the sun. This is an extension of the concept of conduction drying, in which a metal floor is heated by circulating hot water, and the paddy is dried on the hot floor in a way similar to traditional drying on a hard floor under the sunlight. The principal attribute is that it is a simple technology that, during cloudy or rainy periods, complements sun drying. Moreover, the same labour force used for sun drying is used for heated floor drying at the time when workers would otherwise be idle due to cloudy or rainy weather.

As shown in Figure 1, the main components of the HFD are:

- a furnace in which rice straw is burned to heat water to the desired temperature (e.g. 90°C);
- a pump for circulating the water from the furnace water jacket to the drying floor;
- a metal drying floor, heated internally by circulating water; and
- a roof to protect the floor from rain.

By locating the HFD next to the conventional sun-drying floor, it is easy to push the paddy from sun dryer to HFD when clouds appear. The capacity of the dryer is 1 t/day, which meets the needs of small groups of farmers such as milling and marketing cooperatives in areas where labour-intensive drying is more appropriate than mechanised drying.

The drying rate is controlled by the vaporisation process rather than by heat or mass transfer processes in such types of drying systems, and the following equation represents the true picture:

$$\text{drying rate} = K_1/\theta = K_2 \exp(-h_{fg}/RT)$$

where, K_1 and K_2 are constants, θ is drying time, h_{fg} is latent heat of vaporisation of water, R is the universal gas constant, and T is absolute temperature in kelvins (K). On solving the above equation and substituting the value of h_{fg} = 9714 cal/mole for water and R = 1.987 cal/mol K, we get:

$$\delta/\delta\,(1/T)\,[\log \theta] = 1803.97 \text{ K}$$

Therefore, as shown in Figure 2, the solid line drawn through the data has slope of the curve equivalent to 1803.97 K, which confirms the hypothesis that the rate-controlling step of HFD is vaporisation of water rather than heat and mass transfer.

The quality parameters of milled rice dried with HFD were also analysed. As shown in Figure 3, the grain breakage (per cent broken grains) is lower for HFD than conventional sun drying, even at a temperature of 90°C. The drying process appears to be satisfactory under conditions of high atmospheric humidity (80–90%), as occur during rainy periods. The grain breakage is substantially lower for HFD than traditional sun drying (e.g. 7–25% versus 30–66%). No parboiling effect was observed after drying the paddy with HFD.

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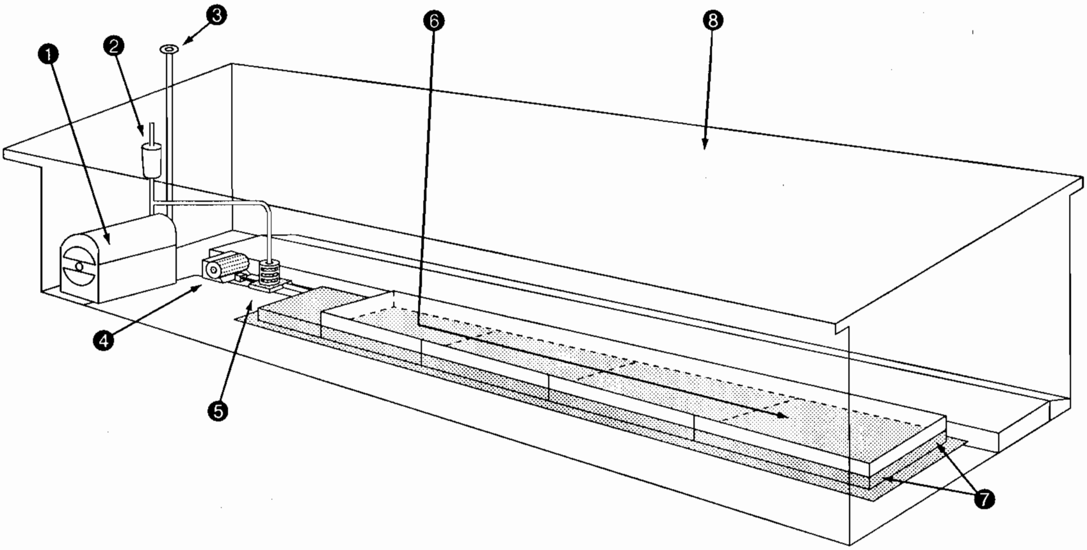

Figure 1. Schematic diagram of heated floor dryer showing different components: 1, boiler; 2, expansion tank; 3, chimney; 4, electric motor; 5, water pump; 6, drying plates; 7, wood support; 8, dryer shed.

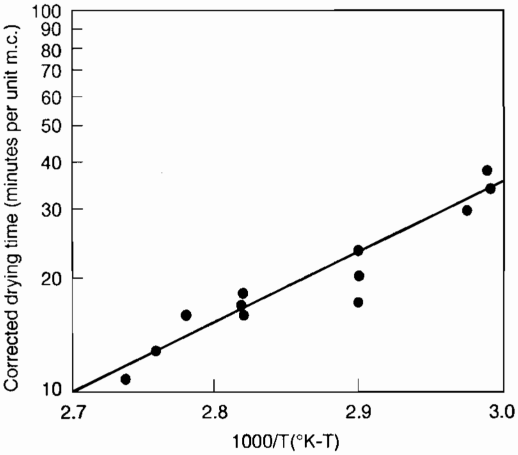

Figure 2. Logarithmic plot of corrected time versus the reciprocal of the floor temperature. The corrected drying time is the total drying time divided by the difference of initial and final moisture content of the paddy, i.e., in minute per unit moisture content change.

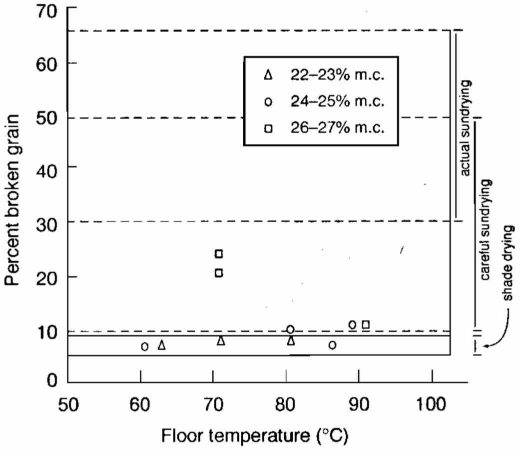

Figure 3. Comparison of grain breakage by heated floor dryer with sun and shade drying at different initial moisture content of paddy.

Rice Husk Furnace and Reversible Airflow Grain Dryer

P. Kuizon*

RICELANDS in the Philippines are mostly in small lots, less than 10 ha, having been inherited from generation to generation by an increasing number of heirs.

Land reform subdivided further the lots for tenant-farmer beneficiaries, most of whom have organised into cooperatives. Cooperatives need dryer capacities from 5 to 10 tons daily or several units of such capacity because rice is planted in at least 5 varieties.

If a single large dryer is used, the different varieties have to be mixed for drying. Mixing varieties of different kernel sizes does not promote efficient milling. For efficient milling, the different varieties must be dried and milled separately.

Furthermore, because paddy comes from many sources (members of the cooperative), it arrives at the dryer site in different moisture contents providing another reason for separate drying.

Use of Rice Husk in Grain Drying by Direct Heating

How the rice husk furnace came to be developed

When my wife and I put up a rice mill in 1970, we could mill only during sunny days as paddy was sun dried. Unfortunately, in the Philippines, the harvest season coincides with the rainy season.

We experimented with a kerosene-heated flat-bed dryer. After developing the dryer in about one year, farmers and millers brought their paddy to us for drying. They subsequently asked us to build dryers for them, and thus began our commercial production of dryers. Kerosene then was very cheap, P 0.20/L. Later, when an energy crisis hit the country, kerosene became too costly as a drying fuel: its cost went up more than 30 times.

Meanwhile, abundant unwanted rice husk was available in our rice mill. It had low moisture content and was probably the driest among the agri-wastes. This made it a good heating fuel if properly burned.

We experimented with three furnace designs that should produce not only smokeless combustion but also zero or negligible fly ash. Heating was direct for high thermal efficiency and lower production cost. It took almost two years to come up with a model of acceptable performance. It had stepped-grate, updraught flow of flue gas through the expanding volume of the combustion chamber, and was equipped with an ash settling chamber. Induced draft from a drying fan provided combustion air.

The two-face furnace

As demand for drying capacities grew, larger heat generating capacities of furnaces became necessary. The first model was good only up to 3 t paddy capacity. For larger heat generating capacity, we came up with a design of 'two-face' stepped-grate furnace which had two furnaces installed facing each other (Fig. 1). The advantage in this design is that the two furnaces facing each other without any wall between them, *burned each other* by their radiant heat, resulting in a more complete combustion. Each furnace face had an inclined feed hopper. A vibrating ash grate unloaded ash.

Fuel consumption

As tested by the National Postharvest Institute for Research and Extension (NAPHIRE) in 1982, fuel consumption was 4.26 kg/hr rice husk per t of paddy loaded into the dryer. The same test also showed our dryer had the highest drying system efficiency among the six Philippine-made dryers tested and evaluated that year.

Improvements on furnace

1. Fuel hopper is equipped with a rotary-vane feeder
2. Scraper-type ash grate for uniform unloading of ash
3. Positive temperature-control damper at furnace outlet for quick temperature regulation
4. Semi-circular refractory top cover for durability.

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At present, commercial furnace models are:

1. One-face furnace type for dryer capacities of 3 t and below
2. Two-face model for capacities larger than 3 t (at present, the most saleable dryer size has 10 t paddy capacity)
3. Multi-fuel model to burn not only rice husks but also peanut hulls for peanut drying and maize cobs for maize drying. However, dry maize cobs are not readily available during the wet season when their moisture content is as high as 50% (the required moisture content for smokeless combustion is 12%). Such dryers should have a backup kerosene or diesel burner for full dryer usage.

The Ricehull-fired Reversible Airflow (RFRA) Grain Dryer

In a flat-bed dryer, the tendency is for the bottom layer of the grain to overdry, while the the top layer remains wet, if the drying airflow is upward only. To remedy the excessive moisture gradient it is necessary to stop dryer operation at about half the expected drying time to mix the grain. This is a very laborious, dusty and itchy job, and time is lost. The purpose of mixing is actually to exchange the top and bottom layers of grain. It is much simpler to reverse the airflow rather than to turn over the grain batch.

We experimented with a drying bin so that drying airflow could be reversed alternately, upward and downward (Figs 3 and 4). An air reversing valve ARV was installed between drying bin DB and drying fan DF. Wide grain-loading doors GLD and vent doors VD at lower plenum chamber were provided. When airflow is upward, grain-loading doors are opened to allow used air to exhaust, vent doors are closed; when airflow is downward, grain-loading doors are closed and vent doors are opened. For rain-wet or dripping-wet paddy initial downward airflow enables gravity to aid in the removal of excess moisture. Air reversal is usually done only once. However, for dripping wet paddy, two air reversals are necessary

In manual mixing of paddy, it took approximately 2 hours by four men per ton. To reverse airflow with the air reversing valve, it takes less than 5 minutes. With reversible airflow feature, moisture content differences at top, bottom and middle layers are within 1%.

Multicrop capability

The RFRA dryer has multicrop capability, being able to dry copra, peanut, maize, etc.

Environmentally friendly dryer

The RFRA is environmentally friendly: i.e. noiseless (does not disturb neighbours during night-time operation), smokeless and dustless in operation. It is dustless because exhaust air with high relative humidity exits at a velocity below that which supports dust in air.

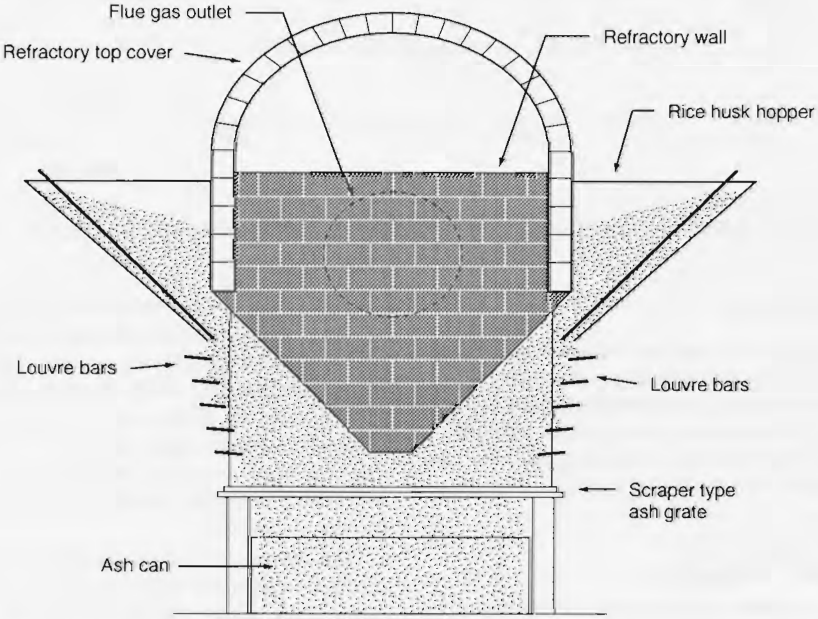

Figure 1. Double-sided rice-husk furnace.

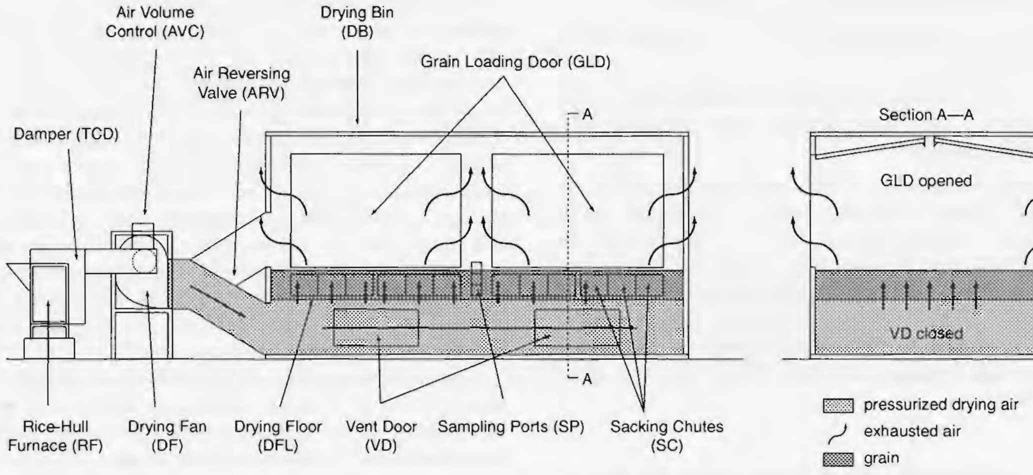

Figure 2. Rice-hull-fired reversible airflow grain dryer showing airflow in upward airflow mode.

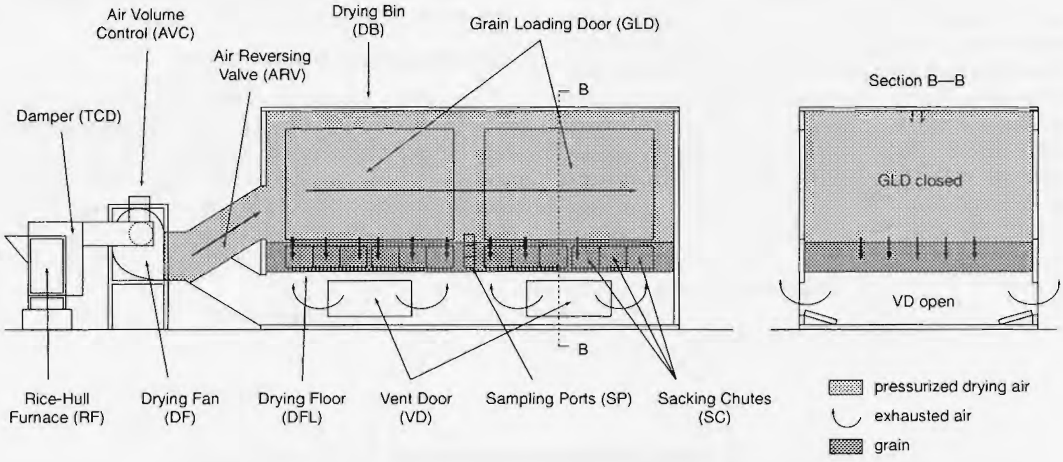

Figure 3. Rice-hull-fired reversible airflow grain dryer showing airflow in downward airflow mode.

Dryer standby power

Power interruption is not uncommon in the Philippines. Most of our installations have a standby diesel engine. Both the electric motor for the drying fan and the diesel engine are mounted on a special tilting base so that transferring the belt from one to the other can be done easily in one minute.

Marketing

The dryer was promoted by:

1. Sending brochures to prospective buyers
2. Visits by our sales representatives and dealers
3. In later years when the RFRA dryer gained acceptance, promotion was enhanced by favourable comments from our clients, especially those who made repeat orders for one or more dryer units.

At pesent, the RFRA dryer is probably the fastest-selling rice-husk-fired dryer in the Philippines because of its relatively low capital cost, low operating costs, negligible maintenance cost and being the easiest to operate.

The absence of sophisticated electric or electronic controls makes the dryer suitable for the Philippine countryside where skilled technicians are not available. The problem with the high-tech imported dryers is that when controls fail, it means weeks or months of down time before costly repairs can be made by a competent technician.

Acknowledgments

P. Kuizon Enterprises acknowledges with gratitude the following for their valuable contribution to our efforts to develop a grain dryer that is probably the most practical for the Philippine countryside today:

1. International Rice Research Institute (IRRI) in Los Baños, Laguna, Philippines, for drying data
2. National Postharvest Institute for Research and Extension (NAPHIRE) for their test and evaluation in 1982 from which we obtained complete technical (operating) data
3. National Cottage Industry Development Authority (NACIDA) for extending a loan which served as the initial capital in the commercial production of the dryer
4. Kalayaan Engineering Co., Inc. in Makati, Metro Manila, Philippines for supplying us with the drying fan and kerosene burner during our initial research and development.

Further Reading

The RFA dryer was featured in the following publications:

- 'Catalogue of Commercially Available Agricultural Machines in the Philippines' by the University of the Philippines in Los Baños, 1986
- Asia Pacific Monitor, United Nations, 1988
- 100 Selected Technologies from Asia and the Pacific, 1989.

Some Socioeconomic Aspects of Plans for Increased Grain Production in Papua New Guinea

Levi B. ToViliran*

PAPUA New Guinea (PNG) lies between latitudes 1 and 12°S, and longitudes 141 and 160°E, north of Australia, its closest neighbour. The country has a population of about four million, which depends almost entirely on agriculture. Agriculture is the main source of livelihood for over 85% of the population, contributing over 27% of gross domestic product (GDP) and over 14%, by value, of exports. The agriculture sector involves more than 75% of the country's labour force.

Agriculture Background

Over 90% of agricultural exports by value are contributed by the three major tree crops: coffee, cocoa, and coconut. Cardamom, chillies, and pyrethrum are minor cash crops, contributing less than 1% of exports by value.

The largest contributor to exports, at 60% by value, is the mining industry (copper, gold, and oil). The mining sector's contribution to GDP—22%—is lower than that of agriculture, and its capital-intensive and enclave features mean that it has weak linkages to the rest of the economy.

Agriculture will continue to be the main source of employment and the sector will provide broadly based growth of the economy in the future. It has enormous potential for development if continuing attention and emphasis are given to the production and marketing of food commodities such as beef, pigs, poultry, fish, fruit and vegetables, and rice. Recent additions to this commodity list include sugar, sheep, and honey.

Grain and Cereal Production

PNG produces little grain and cereals, with the exception of small amounts of maize and sorghum grown commercially and for subsistence. An estimated PGK200 million (during October 1995 ca 1.33 Papua New Guinea Kina (PGK) = US$1) is spent on the importation of grain and cereal products, rice being most important, followed by wheat for livestock.

Rice

Rice has become an increasingly popular staple food. Currently, 130,000 t are imported annually, at a cost of over PGK100 million.

Rice can be grown in PNG but there is little scope for promoting rice production in the smallholder sector without substantial protection.

Exploratory development projects are already under way, and rainfed or irrigated rice is grown by smallholders in a range of locations including Bereina and Cape Rodney in Central Province, the lower Markham Valley and Finschhafen in Morobe, Bogia in Madang, Maprik in East Sepik, Warangoi in East New Britain, and Oro Province.

Maize

Most maize is grown in the Markham Valley by two large-scale operators who produce 3500 t annually for stockfeed. The domestic stockfeed market requires approximately 12,000 t of maize annually, but only one third of this is produced locally.

Public investment project funding is provided to smallholders for grain and credit. Also provided is part funding for variety and fertilizer trials, both on station and farmers' fields.

Peanuts

Peanuts are a subsistence crop and have also been grown commercially for some years. Current production of only 100 t is sold on the open market and as confectionery in the retail formal market. Smallholder commercial production was established in the Markham Valley, but due to the unavailability of a market, the peanut butter factory was closed.

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Sorghum

Though sorghum used to be grown in large quantities for the livestock feed industry, pest and disease incidences and poor drying facilities have caused a large decline in production.

Sunflower

A limited amount of sunflower is grown in PNG, but some preliminary work has been undertaken by the agricultural research department.

Pulses

Pulses being grown in PNG include peas and beans. They are the main source of vegetable protein supplements. Pulse production needs to be expanded through research and extension-supported varietal introduction and crop improvement. For the industry to develop, processing and marketing assistance is also required.

Constraints

The lack of developed infrastructure, insufficient technology, ineffective and inefficient policy and planning strategies, difficult physiographic features, and lack of developed markets pose threats to the development of grain production.

Social and cultural factors have implications for the transfer of modern technology. Climatic conditions with unexpected unfavourable weather are also constraints that need to be considered.

Conclusion

PNG has the potential for local grain production (rice, maize, peanuts, sorghum, sunflower, and pulses). Climatic and environmental conditions are provisions contributing to the ability and/or potential. If given the proper direction and support, PNG can produce a significant part of its needs for these products. Any expansion in grain production to cater for the existing markets appears feasible, if support is provided for machinery and equipment acquisition and technical assistance to farmers.

Recommendation

The intention of the PNG Government's proposal for the establishment of a Grain Development Industry Corporation (GIDC) would be to boost production of rice and other grains. The Government has recommended that the corporation play a major role in assisting semi-commercial farmers to produce rice and grain consistently. It should also seek to facilitate the efforts of non-government organisations, the private sector, and credit suppliers in their endeavours to develop a smallholder industry. This would support the Department of Agriculture and Livestock's objective of promoting production of a range of food crops, some of which are currently imported, through industry-orientated research, development, and extension.

Further Reading

Stein, L. 1991. Papua New Guinea—an economic situation and outlook. Canberra, Australian Government Publishing Service.

Development of a Fluidised-bed Dryer for Paddy in Vietnam

Truong Vinh, Phan Hieu Hien, Nguyen Van Xuan, Nguyen Hung Tam, and Vuong Thanh Tien*

A two-stage drying technique has been tested and promoted at Song-Hau Farm in the Mekong delta of Vietnam (Phan and Hung 1995). The farm introduced a second-stage, 80 t in-store dryer in 1994, which could gently dry paddy at 18–20% moisture content (m.c.) wet basis (w.b.) to 14% in about 4 days. The need now is to find some compatible, first-stage dryer, wherein freshly harvested paddy at high moisture (25–32% m.c.) is quickly dried to 18–20%.

Current dryers, such as columnar continuous-flow devices, cannot handle the above range of high moisture; paddy that is too wet simply does not flow in the drying column or sticks to the conveyor. Fluidised-bed drying is a promising alternative (Sutherland and Ghaly 1992; Tumambing and Driscoll 1993). The advantages and disadvantages of fluidised-bed drying have been discussed by several authors (Porter et al. 1984; Reay 1986; Hovmand 1987; Bahu 1991; Brooker et al. 1992). Two main advantages are: homogeneous drying due to thorough mixing of air and grain; and short drying time due to high heat and mass transfer rates with high air velocity.

The most recent development has come from Thailand, where a 1 t continuous fluidised-bed dryer has been adopted on a commercial scale (Soponronnarit 1995). Two disadvantages of fluidised-bed drying, namely high heat energy requirement and dusty output, have been overcome by using air recirculation and a suitable cyclone.

This paper describes the development of a fluidised-bed dryer in Vietnam for first-stage drying of grain. It outlines the design and the results of tests of the dryer, and gives an estimate of the cost of fluidised-bed drying.

Materials and Methods

Design of equipment

A 1 t fluidised-bed dryer (Fig. 1) has been designed at the University of Agriculture and Forestry (UAF), Ho-Chi-Minh City. The design has drawn much relevant information from Thailand. Soponronnarit and Prachayawarakorn (1994) reported parameters for a batch-type fluidised-bed dryer as follows: superficial velocity V_{af} = 4.4 m/s; grain thickness d = 0.095 m; specific airflow V_s = 0.1 kg/s.kg dry matter; drying temperature T_i = 115 °C; recirculation of drying air = 80%. Another recent development is a 1 t/hour continuous fluidised-bed dryer which could dry paddy from 25% m.c. (w.b.) to 19% in 2–3 minutes (Soponronnarit et al. 1996). Parameters used in this dryer were: V_{af} = 2.3 m/s; d = 0.100 m; T_i = 115°C; recirculation = 80%. The drying floor was 0.3 × 1.7 m. Paddy was pre-cleaned before entering the dryer. We also received drawings of the drying bin components from King Mongkut's Institute of Technology, Thonburi, Thailand (KMITT); and suggestions from the KMITT team led by Professor Somchart Soponronnarit.

Based on the ample supply of rice husks in the Mekong delta, and the requirement of reducing drying cost, we have designed an automatic rice-husk furnace, rather than using an oil burner as in the KMITT design. Due to the low cost of rice husks, the recirculation was reduced to 50% while maintaining a drying temperature of 115°C. Dimensions of the drying bin and cyclone were modified slightly, to fit the current practice in Vietnam of not precleaning paddy before it enters the dryer. Calculations based on the balance of heat and mass transfer resulted in the following: drying bin surface = 0.3 × 2.0 m; drying air velocity = 3.6 m/s; and drying time = 2 minutes. Also, the drying fan was redesigned based on the airflow requirement of 2.2 m^3/s at 2600 Pa pressure.

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Figure 1. The 1 t/hour fluidised-bed dryer fabricated at the University of Agriculture and Forestry, Ho-Chi-Minh City.

Experimental procedures

The fluidised-bed dryer has been fabricated at the mechanical workshop of UAF and installed at the Song-Hau Farm, Can-Tho Province in the heart of the Mekong delta (Fig. 2).

Tests were conducted in September 1995. The fan performance was measured before the tests (Fig. 3). Drying temperature was measured using a type-K thermocouple; exit grain temperature was measured by digital thermistor. Static pressure at various points was monitored with U-tube manometers. Dryer capacity was calculated by weighing the paddy leaving the exit spout over a 1.5 minute interval. Also measured were grain layer thickness, furnace temperature, and rice husk consumption.

Paddy used in the experiments was very wet (>30% m.c. (w.b.)), which is common during the summer–autumn harvest season. There was one exploratory experiment with maize.

Results and Discussion

First experiment (14 September 1995)

Test conditions

Paddy: Initial moisture content = 34.7% (w.b.).
Variety = IR-1055
Bulk density = 480 kg/m^3

Ambient air: Temperature = 28.5°C
Relative humidity = 82%

Grain layer thickness = 8 cm

Drying temperature = 115°C

Results

Final moisture content = 18% w.b.
Drying capacity = 630 kg/hour
Exit grain temperature = 71°C .
Total quantity dried = 2 t

Discussion

This was the experiment with several initial dryer adjustments, leading to low capacity, long residence time, and too low a final moisture content.

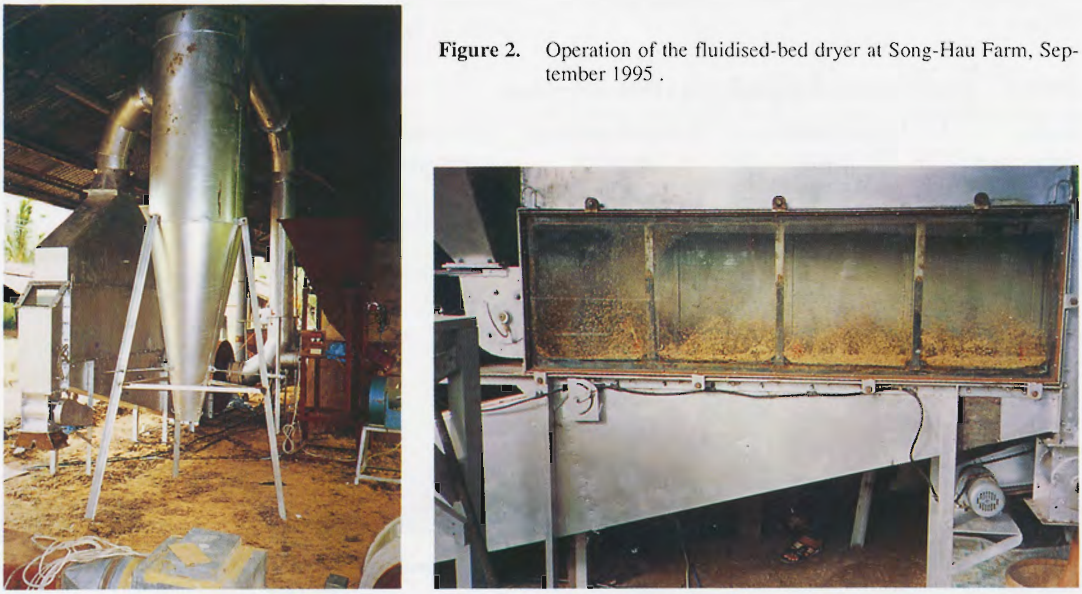

Figure 2. Operation of the fluidised-bed dryer at Song-Hau Farm, September 1995 .

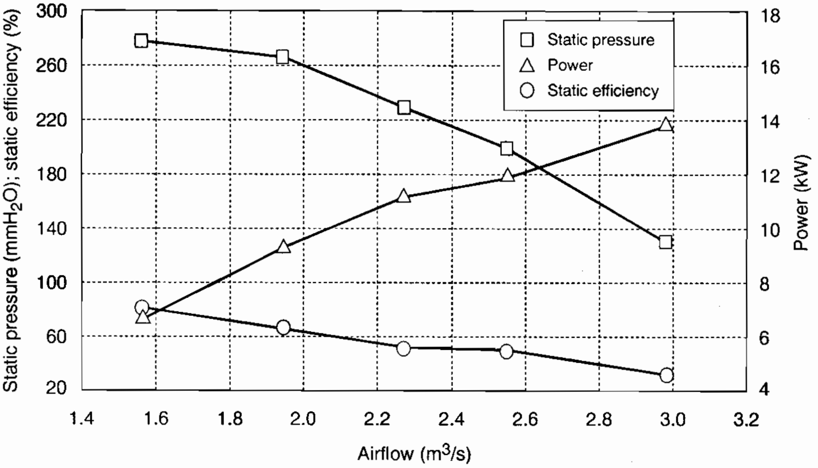

Figure 3. The fan performance curve of the fluidised bed dryer.

Second experiment (15 September 1995)

Test conditions

Paddy: Initial moisture content = 31.0% w.b.
Variety = IR-1055
Bulk density = 520 kg/m^3
Impurities: 2% by weight (7% by volume)
Ambient air: Temperature = 28°C
Relative humidity = 89%

Results

Nine test runs were made. The results are given in Table 1.

Discussion

The tests had been planned as a factorial experiment. However, during the course of the experiments we found that the furnace thermostat could not maintain the drying temperature within the expected ±1°C; the actual variation was ±5°C. Thus, the results in Table 1 were pooled to obtain the average and standard deviation. Nevertheless, the data show the overall performance in the temperature range of 105–115°C. The dryer was operated with stable performance, with a capacity of over 1 t/hour. No blocking or jamming was observed during tests with a total quantity of 3 t of paddy. The distribution of the bubble layer was uniform. A 10% moisture reduction in wet paddy (from 31 to 20–22%) was confirmed.

Table 1. Results of paddy drying trials with a fluidised-bed dryer.

Drying temperature (°C)	Grain thickness (cm)	Exit grain moisture (% w.b.)	Exit grain temperature (°C)	Capacity (kg/hour)	Head rice recovery[a] (%)
105	12	20.8	55	1032	48.7
110	10	22.8	66	1020	58.7
115	8	19.6	63	1260	52.5
115	12	22.0	59	996	53.4
110	10	22.7	65	1356	57.7
105	8	20.1	65	1500	56.7
110	10	22.0	59	–	56.2
110	10	21.4	60	–	–
110	10	21.4	60	–	51.5
	Average	21.4	61.3	1194	54.4
	S.D.	1.1	3.6	210	3.5

[a] Fluidised-bed dried samples were further dried to 12% w.b. under the same conditions as shade dried samples, for which the head rice recovery was 52%.

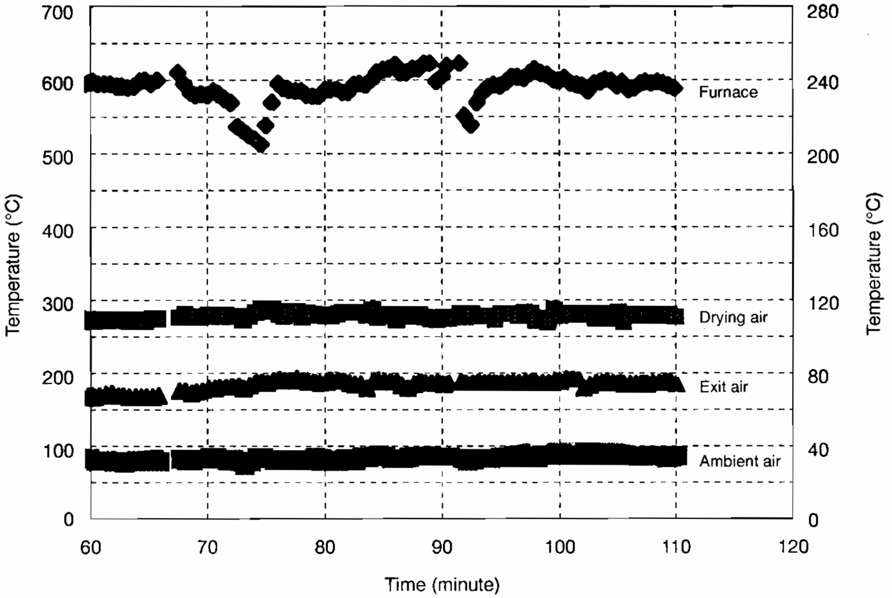

Figure 4. Temperature variation in 50 kg/hour pneumatic-fed rice husk furnace, October 1995, Song-Hau Farm.

Even with a ±5°C temperature variation, the furnace was considered stable. Rice husk consumption was 45–55 kg/hour.

The head rice recovery was analysed at UAF laboratory. It was comparable to shade drying. No difference in milled rice whiteness could be seen with the naked eye. No parboiling effect was noticed .

Experiment with maize

A batch of 400 kg of maize at 24% m.c. (w.b.) was dried in two passes with 30 minutes of cooling between passes. A drying temperature of 130°C was used. The capacity for one pass was 1200 kg/hour. The final moisture content after two passes was 16.3% (w.b.). While further experiments need to be made to optimise the dryer operation with maize, it can be safely conjectured that this fluidised-bed dryer can operate as a continuous-flow dryer, using much less space than a columnar dryer.

Drying cost

The drying cost was estimated based on the data and assumptions given in Table 2.

In terms of kg of water removed, the calculated drying cost is US\$0.044/kg H_2O. The drying cost is near the limit acceptable to farmers in the Mekong delta. Taking into account the short time needed to remove excessive moisture, the dryer is likely to be adopted from an economic viewpoint .

Table 2. Estimate of drying cost using the fluidised-bed dryer.

Item	Data
Capacity	1 t/hour (31% m.c. (w.b.) to 21%)
Investment	70000000 VND[a] (US\$6400)
Life	4000 hours (= 5 years × 40 days/ year × 20 hours/day)
Interest rate	23% per year
Electricity consumption (total)	15.5 kWh/hour
Electricity price	780 VND/kWh
Rice husk consumption	50 kg/hour
Rice husk price	100 VND/kg
Labour	3 person.hours/hour
Labour rate	5000 VND/person.hour

Cost component (Cost/hour = cost/tonne)	VND
Depreciation and repairs	20000
Interest	10000
Electricity	12000
Rice husks	5000
Labour	15000
Total	62000 VND/t = US\$5.60/t

[a] During October 1995, ca 11000 Vietnam dong (VND) = US\$1.

A desk comparison of oil and paddy husks as the energy sources indicated costs per kg of paddy of US$0.00355 for oil and US$0.00046 for paddy husks in reducing mositure content from 31 to 21%. Thus, it can be projected that using oil would incur a heating cost seven times higher than with paddy husks.

Conclusions

For paddy with very high moisture of over 30% (w.b.) harvested during the wet season in the Mekong delta of Vietnam, fluidised-bed drying has shown positive preliminary results technically. The calculated drying cost is reasonable under the economic conditions of Vietnam.

Further work is in progress to enhance technical operations, and further reduce the drying cost.

Acknowledgments

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References

Bahu, R.E. 1991. Fluidised-bed drying. SPS Harwell Laboratory, U.K.

Brooker, D.B, Bakker-Arkema, F.W., and Hall, C.W. 1992. Drying and storage of grains and oilseeds. New York, Van Nostrand Reinhold.

Hovmand, S. 1987. Fluidised-bed drying. In: Mujumdar, A.S., Handbook of industrial drying. New York, Marcel-Dekker Inc.

Phan H. Hien and Nguyen L. Hung 1995. Drying research and application in the Mekong delta of Vietnam. Paper presented at the 17th ASEAN Technical Seminar on Grain Postharvest Technology, 25–27 July 1995, Lumut, Malaysia.

Porter, H.F., Schurr, G.A., Wells, D.F., and Semrau, K.T. 1984. Fluidised-bed systems. In: Perry R.H., Green, D.W., and Maloney, J.O., ed., Chemical engineer's handbook, 6th ed. New York, McGraw-Hill Book Co.

Reay, D. 1986. Fluid bed drying. In: Geldart, D., ed., Gas fluidization technology. New York, John Wiley & Sons, Inc.

Soponronnarit, S. 1995. Drying of paddy and maize in Thailand. In: Champ, B.R., and Highley, E., ed., Posthavest technology for agricultural products in Vietnam. Proceedings of an international workshop, Hanoi, Vietnam, December 1994. Canberra, Australian Centre for International Agricultural Research, Proceedings No. 60, 61–65.

Soponronnarit, S., Prachayawarakorn, S., and Sripawatakul, O. 1996. Development of cross-flow fluidized bed paddy dryer. Drying Technology, in press.

Soponronnarit, S. and Prachayawarakorn, S. 1994. Optimum strategy for fluidised-bed paddy drying. Drying Technology, 12(7), 1667–1686.

Sutherland, J.W. and Ghaly, T.F. 1992. Rapid fluid bed drying of paddy rice in the humid tropics. In: Proceedings of the 13th ASEAN Technical Seminar on Grain Postharvest Technology, Brunei Darussalam, 4–7 September 1990, 168–177.

Tumambing, J.A. and Driscoll, R.H. 1993. Modeling the performance of a continuous fluidised-bed dryer for rapid pre-drying of paddy. In: Naewbanij, J.O. and Manilay, A.A., ed., Proceedings of the 14th ASEAN Technical Seminar on Grain Postharvest Technology, Manila, Philippines, 5–8 November 1991. Bangkok, Thailand, ASEAN Grain Postharvest Programme, 193–213.

Rice-husk Gasifier for Heat and Electricity Production for Small to Medium Mills

G. Vaïtilingom*

MORE than one billion people around the world are concerned with the production of some 500 Mt of paddy on 150 million ha of land. Since the husk surrounding the kernel of rice accounts for about 20% by weight of the paddy, about 100 Mt of rice husk are available. Although some of these rice husks are used for fuel or for other purposes, most of the residues are disposed of by burning or dumping. In most rice-growing countries, rice residues represent one of the largest potential fuel supplies for biomass energy projects (Mahin 1990). Each tonne of paddy generates about 200 kg of husks, the energy content of which is about equal to that of 60 L of fuel oil.

Use of Husks in Rice Mills

In medium-sized and large mills (processing more than 2 t of paddy/hour) rice husks are commonly used. Parboiling mills typically use steam generated with husks for both parboiling and drying. Where parboiled rice is not produced, steam is used from husk-fired boilers in steam engines or turbines for mechanical power and electricity generation.

In small to medium mills, the use of heat from rice husks is possible if electricity is available from a diesel plant or the grid to run the fans of heat exchangers. However, most of the commercial equipment and systems for the production of mechanical and electrical power from rice husks is suitable only for use in larger mills.

Most of the husks are available in small quantities at tens of thousands of small mills. In developing countries, the great majority of the rice mills are small mills processing paddy at a rate of less than 1 t/hour, and with an energy requirement of around 20 kWh per tonne of paddy. This is where there is strongest interest in small rice-husk gasifiers.

Rice-husk Gasification for Small and Medium Mills

Gasification could provide energy for drying and for electrical power. The major part of the gases could feed a gas engine to run the electric motors of the mill and of the gasifier itself; the remaining gases may provide enough heat for drying.

With the support of FAO, much research has been done to improve the design of gasifiers. Very few small units are available commercially at present. The main problems are the bulk density of rice husks, the high ash content (15–20%), and the characteristics of the ash (92–95% silica). These characteristics impose severe requirements on the design of gasification systems using rice husks (Vaing 1989).

Major Technical Problems of Husk Gasification

To provide the power needed for a small to medium-size rice mill processing paddy at 1 t/hour, the gasifier must burn husks at a rate of at least 100 kg/hour. This means that feed of husks to the gas generator must be almost continuous. To avoid slagging problems internal temperature must be controlled. Because of the high volume of ash it must be removed during operation with no contact allowed with atmospheric oxygen. The gas produced contains particulates, soot, tars, and moisture which must be removed before use in burner or engine. There are gasifiers able to produce gas continuously but they often fail because of inefficient cleaning units. Because of the low calorific value of the gas produced, high flow rates are needed to feed burners or engines. Even in the largest cleaning units the dirty gases have only some tens of seconds to be cooled, dried, cycloned, filtered, and purged of tars and, unfortunately, some tars do not condense at tropical ambient temperatures.

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A New Gasifier Design for Small and Medium Mills

To overcome the difficulties associated with gasifying rice husks, CIRAD—which has much experience in gasification of wood or agricultural wastes (coconut husks and shell, cotton stalks, peanut shells, briquettes, etc.)—has worked for several years to develop a new concept in rice-husk gasification.

A throatless gasifier with air inlet control has been designed. It is a downdraft gasifier with automated husk feeding and ash removal. Husks are fed by a screw conveyor to the air-sealed top of the gasifier. The air inlet is controlled by two series of nozzles. Ash is removed through a very simple water-sealed conveyor.

The cleaning unit consists of an air–gas cooling system, a collector for small ash, a wet scrubber with high flow-rate of water, a turbine and, finally, a paper filter. The scrubbing water passes through a cooling system, a procedure that is very important for the efficiency of the unit. Most of the soot and tars are collected in a large tank where they are concentrated and from which they can be easily removed for further processing. Cooled water is also injected into the turbine to improve the centrifugation of soot, particulates, and the remaining tars which are pushed into the tank with the help of the pressure delivered by the turbine. Pressured gases are able to pass through the very efficient paper filter. Low-pressure cooled and cleaned gases are finally available both for engine operation and for use in a very simple gas burner.

During the operation of the gasifier, the cycles of ash removal and husks feeding are controlled by off-the-shelf electric timers.

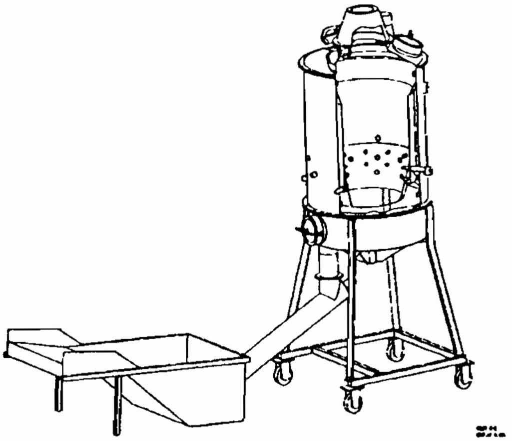

Figure 1. Section of the CIRAD gasifier.

In a version of the gasifier producing 150 m^3 of gas per hour, the total power needed by the electrical devices to run the gasifier is 5 kW, which consumes 10–15 kg of husks, i.e. about 10% of the total consumption per hour.

Table 1. Typical composition of gas produced by small- to medium-scale rice-hull gasifier.

Gas	Percentage of total
H_2	8.7
CH_4	2.5
O_2	4.3
N_2	51.8
CO_2	12.2
CO	20.5
Energy value	4440 kJ/m^3

This gasifier was designed to be able to produce 75–150 m^3 of gases per hour, with an average energy value of 4.2 MJ/m^3. Table 1 gives typical gas composition. Special care was taken in the design to ensure it used technologies no more sophisticated than encountered in a small or medium-size mill. This allows for local manufacture of such units, which are adapted for mills processing paddy at a rate of 0.5–1 t/hour (Vaïtilingom 1993).

Conclusions

Most of the commercial equipment and systems for the production of heat and mechanical and electrical power with rice husks are suitable only for use in large mills. In small to medium mills, processing less than 1 t of paddy per hour, gasification could provide energy for drying and for electrical power. A gasifier scaled for small and medium mills and designed and built using technologies appropriate to such mills could be of interest and its cost would be attractive if it were locally made. The market for such a gasifier comprises tens of thousands of rice mills in many developing countries.

References

Mahin, D.B. 1990. Energy from rice residues. Winrock International Institute for Agricultural Development, 40.

Vaïtilingom, G. 1993. Conception d'un gazogène à balles de riz intégrable dans une ligne d'usinage de 500 kg à 1500 kg par heure. CIRAD–SAR, Rapport, 45.

Vaing, G. 1989. La gazéification de la balle de riz: conception d'un nouveau type de gazogène pour la balle de riz. CEEMAT, Rapport, 40.

Rice Drying Technology in China

Zhao Simong*

Abstract

The characteristics of rice drying in China are discussed. There are three main high-temperature drying systems and one low-temperature drying system being applied. Rotary grain dryers have the features of simple structure and homogeneous drying effect. Two types of fluidised-bed grain dryers are used in China, namely single-bed dryer and multi-bed dryer. A new type of rice dryer which has come into use in China is the concurrent-counterflow dryer. The low-temperature drying system is the so-called mechanical ventilation equipment. The technological characteristics of high- and low-temperature dryers are discussed and analysed. To avoid reducing the quality of rice during drying, the correct way to select parameters relating to the drying technology are also covered.

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Heat and Mass Transfer in Grain Bulks of Arbitrary Shape

G.R. Thorpe*

Abstract

Bulks of grains may assume an infinite number of shapes. Although the equations that govern the rates of heat and mass transfer in such bulks are independent of the size and shape of the grain bulk to be modelled, the choice of a numerical solution procedure depends on the geometry of the grain bulk. This paper describes a method of transforming the shape of a grain store into one that has a simple geometry such as a cube or right circular cylinder. Works are cited that detail how the method has been used to simulate heat and mass transfer phenomena in two- and three-dimensional grain bunkers, rail cars and hopper bottomed grain stores.

THE shapes and sizes of bulks of stored grain are quite arbitrary. For example, when a hopper bottomed farm silo is filled with grains, the upper surface of the grain usually forms a cone. The grain bulk therefore has the shape of a right cylinder, capped with a cone of grain and with an inverted cone on its base. Although the bulk of grain may be axi-symmetric the temperature of the outer surface varies both spatially and temporally as a result of solar radiation which varies with time. Regions of the silo facing away from the equator are generally cooler than those facing towards the equator. The system must therefore be considered to be truly three-dimensional. Similarly, when a grain storage shed is filled with grain, a ridge of grain usually forms under the inloading conveyor, and at each end of a ridge truncated cones form, that may intersect retaining walls. Again we have a bulk of grain that must be treated as a three-dimensional entity.

Grain storage technologists are often concerned with manipulating the ecosystem within bulks of grain, and this requires some understanding of the processes of heat and mass transfer that occur within them. The equations that govern these processes are well established (Thorpe 1996a,b), and they apply to grain bulks of any shape or size. To solve them one must specify the appropriate initial and boundary conditions such as the temperature and moisture content of the grain as it is loaded into the store, and the temperatures of the surfaces of the store, say. The equations are usually solved numerically using some form of finite difference approximation. When the grain store has a simple shape such as a cube or a right cylinder, or a triangle (see Nguyen 1987) the solution is quite straight forward because an orthogonal finite difference mesh can be forced to coincide with the boundaries of the store. In this situation, the finite difference forms of the boundary conditions are quite easily imposed (see Singh et al. 1993). In the case of a peaked bulk of grain placed in a hopper bottomed silo, coincidence of the nodes of a finite difference mesh with the boundaries of the grain is unlikely. This problem may be overcome by using interpolation and other techniques outlined by Carnahan et al. (1969), or the geometry of the grain store may be mathematically transformed into a simple shape, such as a right cylinder or a cube as described by Singh and Thorpe (1993b). Casada and Young (1994) have used the transformation method to simulate heat and mass transfer in agricultural commodities transported in rail cars. The latter approach has the advantage that it is quite general, and easily programmed. A disadvantage of the method is that it cannot readily account for the case when one linear dimension of a grain bulk tends to zero, such as when a bulk of grain rests on a floor. At the point of intersection of the grain and the floor the height of the bulk is zero.

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In this paper we shall describe the method of grid transformation which has the above mentioned advantage of generality, and outline how it has been applied to the problem of moisture migration in two- and three-dimensional peaked bulks of grains, and the aeration of a hopper bottomed circular silo.

Grid Transformation

The aim of grid transformation is to map the shape of the grain store into a simple shape on which it is possible to impose an orthogonal finite difference grid. Figure 1 shows how Singh and Thorpe (1993a) transformed the cross-section of a bulk of grain, as may be found in a grain bunker, into a square.[1]

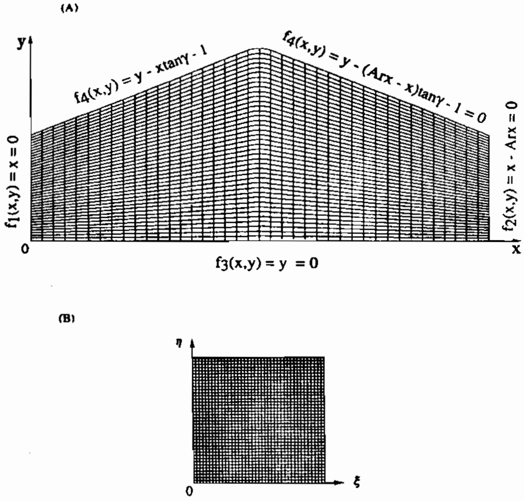

Figure 1. The transformation of the cross-section of a grain storage bunker into a square.

The geometry and its associated fields, such as grain temperature and moisture distributions, are described in terms of (x,y) coordinates, whereas the transformed system is described in terms of the dimensionless (ξ,η) coordinates. In the case under consideration, the relationship between the two coordinate systems is

$$\xi = \frac{x - f_1(x,y)}{f_2(x,y) - f_1(x,y)} \tag{1}$$

$$\eta = \frac{y - f_3(x,y)}{f_4(x,y) - f_3(x,y)} \tag{2}$$

By the chain rule of differentiation we are able to write

$$\frac{\partial T}{\partial x} = \alpha_1 \frac{\partial T}{\partial \xi} + \alpha_2 \frac{\partial T}{\partial \eta} \tag{3}$$

and

$$\frac{\partial T}{\partial y} = \alpha_3 \frac{\partial T}{\partial \xi} + \alpha_4 \frac{\partial T}{\partial \eta} \tag{4}$$

in which

$$\alpha_1 = \frac{\partial \xi}{\partial x}, \alpha_2 = \frac{\partial \eta}{\partial x}, \alpha_3 = \frac{\partial \xi}{\partial y}, \text{ and } \alpha_4 = \frac{\partial \eta}{\partial y}$$

We can similarly write a laplacian as

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = \beta_1 \frac{\partial^2 T}{\partial \xi^2} + \beta_2 \frac{\partial^2 T}{\partial \eta^2} + \beta_3 \frac{\partial^2 T}{\partial \xi \partial \eta} + \beta_4 \frac{\partial T}{\partial \xi} + \beta_5 \frac{\partial T}{\partial \eta} \tag{5}$$

in which

$$\beta_1 = \alpha_1^2 + \alpha_3^2,\ \beta_2 = \alpha_2^2 + \alpha_4^2,\ \beta_3 = 2(\alpha_1\alpha_2 + \alpha_3\alpha_4)$$

$$\beta_4 = 2\left(\frac{\partial^2 \xi}{\partial x^2} + \frac{\partial^2 \xi}{\partial y^2}\right),\ \beta_5 = 2\left(\frac{\partial^2 \eta}{\partial x^2} + \frac{\partial^2 \eta}{\partial y^2}\right)$$

The equations that govern heat, mass and momentum transfer in the physical (real) domain are easily transformed into a domain with the simple geometry by substituting into them equations 3, 4 and 5. As an example, let us consider the thermal energy balance presented by Thorpe (1995), i.e.

$$\begin{aligned}&\frac{\partial T}{\partial t} + t_{pi}\left(\frac{\partial (uT)}{\partial x} + \frac{\partial (vT)}{\partial y}\right) + \left(t_{mx}\frac{\partial T}{\partial x} + t_{my}\frac{\partial T}{\partial y}\right)\\ &= t_{pd}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) + t_r + t_l\end{aligned} \tag{6}$$

which in the transformed domain becomes

$$\begin{aligned}&\frac{\partial T}{\partial t} + t_{pi}\left(\alpha_1 \frac{\partial (uT)}{\partial \xi} + \alpha_2 \frac{\partial (uT)}{\partial \eta} + \alpha_3 \frac{\partial (vT)}{\partial \xi} + \alpha_4 \frac{\partial (vT)}{\partial \eta}\right)\\ &+ \left(t_{mx}\left(\alpha_1 \frac{\partial T}{\partial \xi} + \alpha_2 \frac{\partial T}{\partial \eta}\right) + t_{my}\left(\alpha_3 \frac{\partial T}{\partial \xi} + \alpha_4 \frac{\partial T}{\partial \eta}\right)\right)\\ &= t_{pd}\left(\beta_1 \frac{\partial^2 T}{\partial \xi^2} + \beta_2 \frac{\partial^2 T}{\partial \eta^2} + \beta_3 \frac{\partial^2 T}{\partial \xi \partial \eta} + \beta_4 \frac{\partial T}{\partial \xi} + \beta_5 \frac{\partial T}{\partial \eta}\right) + t_r + t_l\end{aligned} \tag{7}$$

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[1] A diskette containing an annotated FORTRAN computer progam that models moisture migration in a two-dimensional peaked grain store is available from the author (GRT) free of charge.

This equation is discretised using the method described by Thorpe (1995).

The method is readily extended to three-dimensional systems as described by Singh and Thorpe (1993b) who modelled moisture migration in grain bunkers. In this case, the grain bulk was transformed into a cube, as shown in Figure 2. More recently, Thorpe (1996c) has transformed a hopper bottomed silo into a right cylinder, as indicated in Figure 3. Figure 4 shows the calculated pressure distribution generated by a linear aeration duct placed along one side of the base of the silo. Needless to say, the air flow pattern is three-dimensional in nature, and Thorpe (1996c) shows how the pressure distribution may be used to model heat and mass transfer phenomena in the such silos.

Conclusions

Bulks of grain assume an infinite variety of shapes. This paper describes a convenient method of modelling heat and mass transfer phenomena that occur in such bulks. The method is based on transforming the geometry of the grain store into a simple one which readily accommodates an orthogonal finite difference mesh. The method has been applied to grain bunkers with a uniform cross-section, three-dimensional grain bunkers, rail cars containing agricultural produce and to hopper bottomed cylindrical silos.

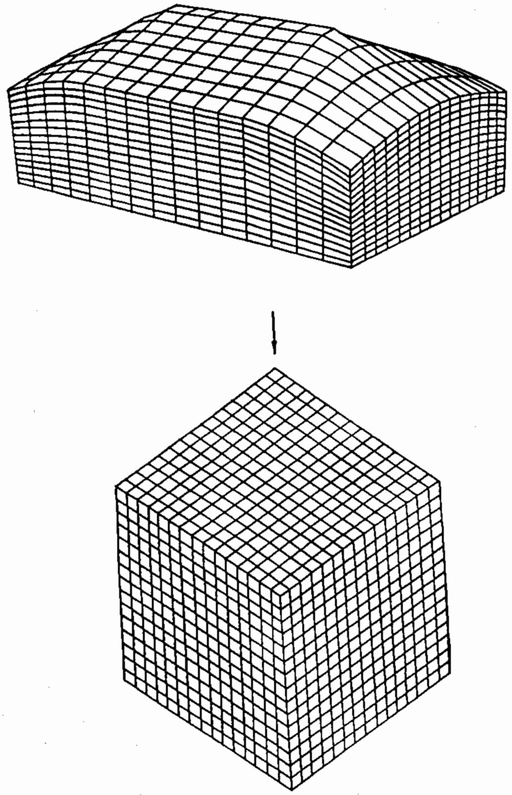

Figure 2. The transformation of a peaked bulk of grain into a cube.

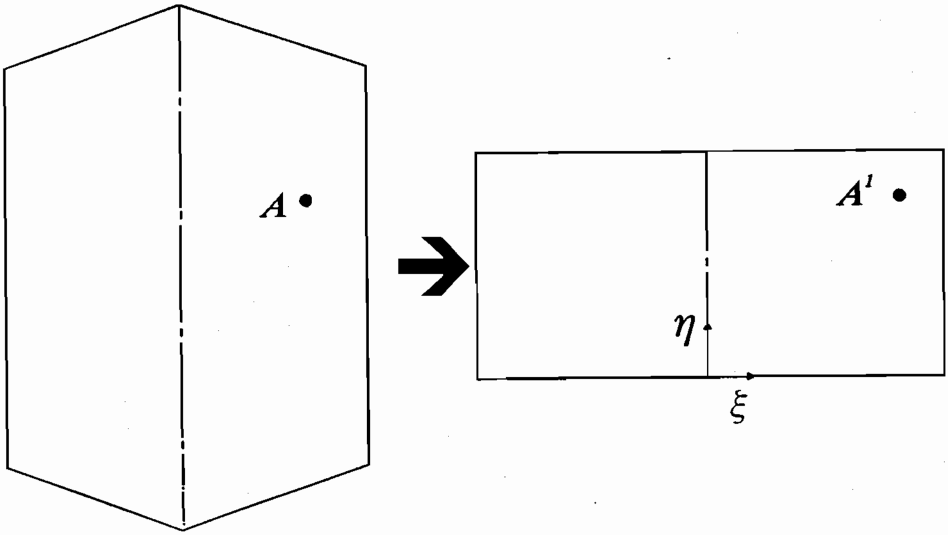

Figure 3. The transformation of a peaked bulk of grain contained in a hopper bottomed silo into a right cylinder.

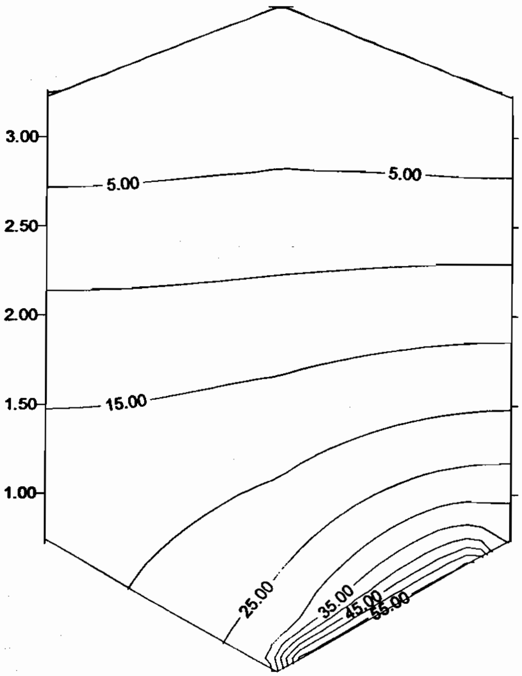

Figure 4. The predicted pressure distribution in an aerated hopper bottomed circular grain silo.

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References

Carnahan, B., Luther, H.A. and Wilkes, J.O. 1969. Applied numerical methods. New York, Wiley.

Casada, M.E. and Young, J.H. 1994. Model for heat and moisture transfer in arbitrarily shaped two-dimensional porous media. Transactions of the American Society of Agricultural Engineers, 37, 1927–1938.

Nguyen, T.V. 1987. Natural convection in stored grains—a simulation study. Drying Technology, 5(4) 541–560.

Singh, A.K. and Thorpe, G.R. 1993a. The application of a grid generation technique to the numerical modelling of heat and moisture movement in peaked bulks of grain. Journal of Food Process Engineering, 16, 127–145.

Singh, A.K. and Thorpe, G.R.(1993b. A solution procedure for three-dimensional free convective flow in peaked bulks of grain. Journal of Stored Products Research, 28, 221–235.

Singh, A.K., Leonardi, E., and Thorpe, G.R. 1993. A solution procedure for the equations governing three-dimensional free convection in bulk stored grains. Transactions of the American Society of Agricultural Engineers, 36(4), 1159–1173.

Thorpe, G.R. 1996a. Modelling moisture migration in stored grains. These proceedings.

— 1996b. More complete mathematical descriptions of heat and moisture transfer in ventilated bulks of respiring grains. Agricultural Engineering Australia, Journal of the Society for Engineering in Agriculture, A Society of the Institution of Engineers Australia (in press).

— 1996c. Modelling ecosystems in conical bottomed farm grain silos. Ecological Modelling (in press).

Nomenclature

$f_1(x,y)$,..	Descriptors of the physical boundaries of the grain store.	**Greek symbols**	
t	Time, s.	$\alpha_1, \alpha_2, \alpha_3, \alpha_4$	Coefficients in the transformation equations 3 and 4.
T	Temperature, K.		
t_l, t_{mx}, t_{my},..	Coefficients in equations 6.	$\beta_1, \beta_2, \beta_3$,...	Coefficients in the transformed laplacian, equation 5.
u	Horizontal component of velocity, m/s.		
v	Vertical component of velocity, m/s.	ξ, η	Coordinates of the computational domain.
x,y	Coordinates in the physical domain, m.		

An Evaluation of the Returns to Research on Grain Drying and Storage in the Philippines

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POSTHARVEST losses and wastage in grains in the humid tropics are attributed to several factors, such as weather, climate, and inadequate drying and storage facilities. In the Philippines in recent years about 60% of paddy and 72% of maize are harvested during the wet season, July–December (BAS 1994). Harvested grain is not dried properly, especially during the wet season, resulting in high moisture contents: 26–28% for paddy and 36% for maize (Tumambing 1984). When high moisture grains are stored at high temperature and humidity the results are dry matter reduction and weight loss, quality deterioration, and grain damage. Insect infestation exacerbates postharvest losses. These losses increase marketing costs, and contribute to a drain on the country's buffer stock of rice.

In addressing the problem of postharvest losses, the National Postharvest Institute for Research and Extension (NAPHIRE) in the Philippines and the Australian Centre for International Agricultural Research (ACIAR) have conducted closely interrelated research on alternative grain drying and storage in the Philippines. The results of those projects suggest a potential for reducing postharvest losses of grains in the Philippines.

This paper aims to present an alternative analytical framework for evaluating the economic impacts of research on grain drying and storage. That framework is used to measure the economic impact of a series of ACIAR-supported research projects on two-stage grain drying (NAPHIRE n.d.), storage of grain using plastic covers, and pesticide use (NAPHIRE n.d.) (Table 1).

An Alternative Economic Framework for Evaluating Research on Postharvest Losses

Research evaluation methods have evolved from the subjective checklist and scoring models, to more objective methods such as production function, linear programming, and economic surplus. The application of more objective methods is part of an international trend to subject agricultural research to more careful economic evaluation in an effort to use research resources more efficiently (Mangabat 1995).

The economic surplus approach, which uses the concepts of producer and consumer surpluses, has now been widely used as a framework in measuring changes in economic welfare from research. Consumer surplus is the maximum amount that consumers are prepared to pay over what they actually pay for a given quantity of a commodity. Analogously, producer surplus refers, in general, to the excess of what producers receive for supplying a given quantity over the minimum amount that they would need in order to willingly supply that quantity (Hertford and Schmitz 1977). This section of the paper presents a postharvest waste reduction model developed by Davis (1994) that is based on the economic surplus approach. This model is adapted to evaluate a series of ACIAR–NAPHIRE collaborative research projects on alternative grain drying and storage in the Philippines. The postharvest wastage research model is an extension of research on multistage production systems (Freebairn et al. 1982; Alston and Scobie 1983).

The effects of research that reduces postharvest wastage are illustrated graphically in Figure 1. The

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lines in the II and IV quadrants represent wastage transformation lines from the farm to retail store (a 45° line gives the case of zero wastage. The postharvest services sector (transport, drying, handling) is assumed to have a perfectly elastic supply, implying that the cost of the activities in this sector represents only a small share of the total cost of the agricultural commodity activity.

Fixed proportions are assumed, implying that postharvest services are used in the same proportion as the farm product for whatever price and quantity. With the use of existing postharvest technology (without research) wastage is assumed to be, say, 40%. The supply curves are S_f (farm sector), S_m (postharvest sector), and S_r (retail sector). The demand for postharvest services is a derived demand from the retail sector. A new postharvest technology reduces wastage of the farm product to 35%. If the new technology increases postharvest costs, the postharvest supply curve shifts to S_m'. The wastage reduction and cost effect due to retail supply curve to shift to S_r'. The new equilibrium conditions are lower retail price (P_r'); increased grain consumption (Q_r'); decreased farm output (Q_f') due to a slight fall in farm price; and a change in postharvest services (an increase in this case).

The welfare effects of research are measured as the areas suggested in Figure 1. Consumers (CS) gain by the area P_rxyP_r'; gains to producers depend upon the change in resource cost, and the supply and demand elasticities. Producer gains increase as demand becomes more elastic and supply becomes more inelastic.

Alternatively, prices and quantity changes are used to measure research welfare effects. Following Davis and Lubulwa (1994), supply and demand equations characterising market equilibrium conditions in without and with research are specified as follows:

Without research

Farm level supply [Fig. 1 (III)]

$$Q_f^S = a + b\,P_f \tag{1}$$

Farm to retail production linkage [Fig. 1 (III)]

$$Q_r^S = c + Q_f^S \tag{2}$$

Farm to retail price linkage [Fig. 1 (IV)]

$$P_f = cP_r - M \tag{3}$$

Retail sector supply [Fig. 1 (I)]

$$Q_r^S = c[a + b\,(cP_r - M)] \tag{4}$$

Retail demand [Fig. 1 (I)]

$$Q_r^D = d - gP_r \tag{5}$$

Retail market equilibrium [Fig. 1 (I)]

$$Q_r^S = Q_r^D \tag{6}$$

where P_f and P_r are farm and retail prices; a, c, and d are the intercept terms; b and g are the supply and demand slopes, where $b = ef\ Q_f/P_f$, $g = nr\ Q_r/P_r$, where e_F is price elasticity of supply at farm level, nr is the price elasticity of demand at retail; c is farm to

Table 1. ACIAR–NAPHIRE collaborative postharvest research projects for evaluation.

Category/ Project no.	Project description	Commodities	Research type
Grain drying			
8308	Drying in bulk storage	Paddy	Wastage reduction
8608	Development of a two-stage drying system	Paddy, maize, peanuts	Wastage reduction, quality change
9008	Application of in-store drying	Paddy	Wastage reduction, quality change, cost change
Use of plastic cover storage			
8307	Application of plastic covers for grain storage	Paddy	Wastage reduction
8845	Design of an outdoor storage to complement indoor storage	Paddy, maize	Wastage reduction
Pesticide use in grain storage			
8309	Development of effective pest control treatments in storage of high moisture grains	Maize, mungbeans	Wastage reduction
8609	Complete the development of effective pesticide treatments	Paddy, maize, mungbeans	Health effects, cost change
9009	Minimising pesticide residues in grain using mixtures of protectants and concentrates	Maize, mungbeans	Health effects, cost change

retail level conversion factor. The wastage rate of a commodity from farm to retail level is (1 – c) where $0 < c < 1$. For example, if wastage rare is 30%, then $c = 0.7$. Equations (1) to (6) can be solved for the without research conditions.

With research

Reduction in postharvest wastage:

$$c' = (c + c) \tag{7}$$

Change in postharvest input costs:

$$M' = (M + M) \tag{8}$$

where the superscript (') denotes the with research conditions. Equations (7) and (8) can be substituted into equations (1) to (6) to solve for the with research equilibrium prices and quantities, P_f, P_r, Q_f, and Q_r and to measure changes in total surplus (TS) and its distribution to producers (PS) and consumers (CS). The algebraic expressions in measuring the benefits to research are :

$$CS = (P_r - P_r')\,Q_r + 0.5[(P_r - P_r')(Q_r - Q_r) \tag{9}$$

$$PS = (P_f' - P_f)Q_f + 0.5[(P_f' - P_f)(Q_f' - Q_f)] \tag{10}$$

$$TS = CS + PS \tag{11}$$

Evaluation of ACIAR–NAPHIRE Research Projects

Some of the ACIAR-supported postharvest research projects have previously been evaluated using standard financial and economic analyses: costs of projects compared with benefits, and allocation of benefits between ACIAR and NAPHIRE (see Chudleigh 1991; Ryland 1991).

Related research projects under each category are evaluated based on their collective effect. For example, the research impact of grain drying projects

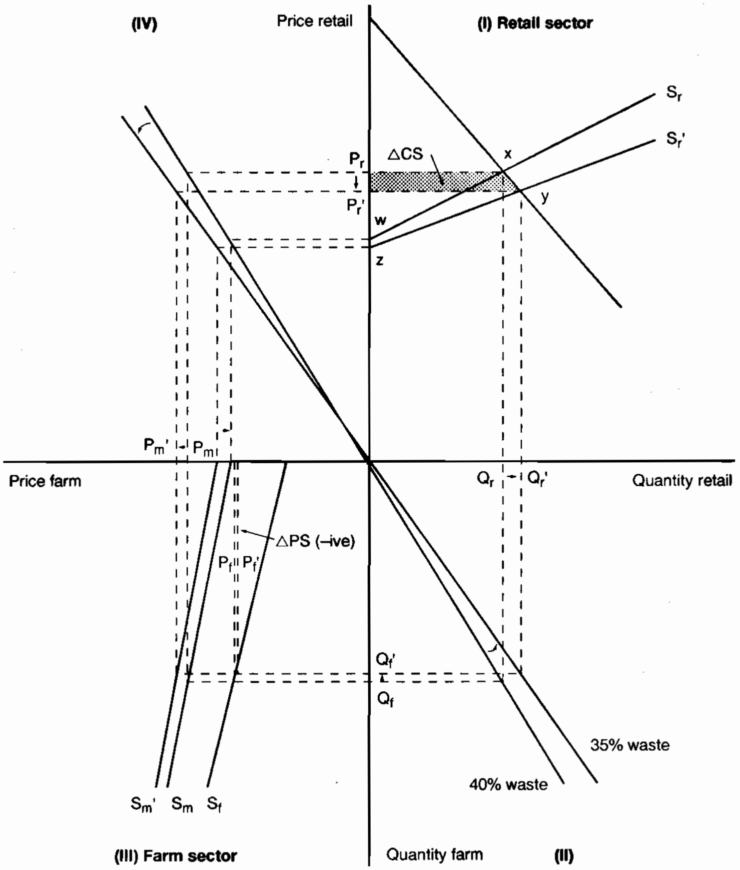

Figure 1. Postharvest wastage reduction model.

(ACIAR PN8308, 8608, and 9008) will be on changes in wastage reduction and cost of paddy drying. There are other assumptions adopted in the present research evaluation. An ex-ante research assessment is used because the dissemination of the postharvest technologies is at an early stage. The wastage reduction and cost effects introduce a parallel shift of the farm supply curve implying a uniform rate of technology adoption and equal cost reduction across all producers. The analysis is partial equilibrium, focusing on a specific grain industry. Measurement of research gains is annual static, interpreted as gains accruing in a year. Adoption of improved technologies and adjustments in supply and demand occur within the year. Research costs are not included, so the estimated research gains represent gross benefits.

Table 2. Parameter values for postharvest research evaluation.

Parameter	Description	Values
	Marketable quantity[a]	
Q_f	Paddy	4,345,198 t
	Maize	3,550,503 t
Q_r	Rice	3,490,180 t
Q_w	Maize	3,550,503 t
	Farm price	
P_f	Paddy	\$236.4/t
	Maize	\$188/t
P_r	Rice	\$532/t
P_w	Maize	\$214/t
	Price elasticity of supply	
e_f	Rice	0.40, 0.62
	Maize	0.42, 1.03
	Price elasticity of demand	
n	Rice	–0.523 3/, 0.8
	Maize	–0.63 4/, 0.8
	Wastage reduction	
c	Paddy	0.75 5/, 0.8
	Maize	0.75, 0.8
	Cost reduction	
M	Paddy	\$5/t
	Maize	\$10/t

[a] Quantities sold and landlord share (BAS 1994). On average, marketable quantity from total production is 15% for paddy and 74% for maize.

Sources: Estrada and Bantilan (1991); Tumambing (1995).

The values and definitions of the parameters used in the present research evaluation are provided in Table 2. A sensitivity test is conducted for price elasticities of supply (e) and demand (n), percentage change in wastage reduction, and postharvest cost.

Results

The values of the yearly gross benefits resulting from research are shown in Table 3.

Table 3. Size and distribution of Philippine benefits from research on grain drying and storage (in US\$ per year).

e	0.40		0.62	
n	–0.528, –0.4,		–0.528, –0.8	
c' = 0.75, m' = \$5/t				
Grain drying				
PS	481.3	(137.9)	20.3	297.4
CS	(134.7)	364.8	162.2	(138.4)
TS	346.6	226.9	182.5	159.0
c' = 0.08, m' = \$10/t				
PS			39.3	
CS			143.2	
TS			182.5	
Plastic storage (without M')				
PS	467.5		5.0	284.3
CS	(145.3)		150.0	(147.9)
TS	322.2		155.0	136.4
c' = 0.8				
PS			5.1	
CS			115.0	
TS			120.1	
Use of pesticide				
e	0.42		1.03	
n	0.63		–0.63	– 0.8
c' = M' = \$5/t				
PS	170.1		(154.8)	257.0
CS	(51.5)		246.4	(163.5)
TS	118.6		91.6	93.5
c' = 0.8, m' = \$10/t				
PS	178.2			
CS	167.72			
TS	110.5			

The costs of research are not included, as the individual research projects under each category (grain drying storage and use of pesticide) are evaluated collectively. Benefits to research range from US$110.5 (use of pesticide) to US$346.6M (grain drying). The size and distribution of aggregate benefits are sensitive to the assumptions of the price elasticities of supply and demand, and the size of wastage reduction and change in postharvest costs.

From the baseline data for paddy and maize (e = 40, n = –0.528; e = 0.42, n = –0.63, respectively), aggregate benefits are larger the less elastic is the supply of the commodity compared to its demand. Research that reduces wastage in postharvest activities and at the same time induces a decrease in postharvest costs, results in greater benefits than when research reduces wastage alone. The latter assumes that the costs of postharvest activities in the without and with research conditions are the same.

References

Alston, J.M. and Alston, G.M. 1983. Distribution of research gains in multistage production systems; comment. American Journal of Agricultural Economics, 65, 353356.

BAS (Bureau of Agricultural Statistics) 1994. Regional rice statistics handbook. Quezon City, Philippines, PhilRice-BAS Collaborative Project.

Chudleigh, P.D. 1991. Integrated use of insecticides in grain storage in the humid tropics. Canberra, ACIAR, Economic Assessment Series No. 9.

Davis, J.S. 1994. A model for evaluation of waste reducing postharvest research. Canberra, ACIAR, Working Paper Series No. 4.

Davis, J.S. and Lubulwa, A.S.G. 1994. Evaluation of postharvest research. Results for an application to tropical fruit research projects and some further methodological issues. Canberra, ACIAR, Economic Evaluation Unit Working Paper Series No. 8.

Estrada, J.U. and Bantilan, C.S. 1991. Supply and demand elasticities for major agricultural commodities in the Philippines; national and regional estimates. Canberra, Australia, ACIARPhilippine Country Study, No. 36.

Freebairn, J.W., Davis, J.S., and Edwards, G.W. 1982. Distribution of research gains in multistage production systems. American Journal of Agricultural Economics, 64, 36–46

Hertford, R. and Schmitz, A. 1977. Measuring economic returns to agricultural research. In Arndt, T.M., et al., ed., Resource allocation and productivity in national and international agricultural research. Minneapolis, University of Minnesota Press.

Mangabat, M.C. 1995. Assessment of research in multistage production systems: the case of Philippine coconut products. Unpublished Ph.D. thesis, La Trobe University, Victoria, Australia.

NAPHIRE (National Postharvest Institute for Research and Extension) n.d. Drying of high moisture grains in the humid tropical climates. Nueva Ecija, Philippines, NAPHIRE, Terminal report for ACIAR Project No. 8608.

— n.d. Integrated use of pesticides in grain storage in the humid tropics. Nueva Ecija, Philippines, NAPHIRE, Progress Report for ACIAR PN 8609.

Ryland, G.J. 1991. Long term storage of grain under plastic covers. Canberra, ACIAR Economic Evaluation Series No. 8.

Tumambing, J.A. 1984. Rice postproduction practices in the Philippines. Manila, National Postharvest Institute for Research and Extension, 45 p.

Tumambing, J.A., et al. 1995. Application of in-store drying in the grain industry in Southeast Asia. Paper presented at the 7th DABAR National Research Symposium, Quezon City, Philippines.

Preservation of Grain with Aeration

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Abstract

Aeration involves moving relatively low volumes of air through bulk stored grains for the purpose of controlling grain temperature. Grain temperature is the primary stored grain management tool to minimise the risk of fungal spoilage and insect damage. The primary objective of aeration is to maintain temperatures in grain as uniformly as possible, and as low as practical. Grain moisture is the second critical grain management factor. Generally, aeration airflow rates are too small to dry grain. However, excessive aeration can reduce marketable grain weight. Grains with harvest moisture contents above the safe storage limits must first be dried with forced heated or natural air. Under certain climatic conditions and in various geographic locations, aeration with ambient air cannot completely inhibit insect activity and preserve grain quality. When grain temperatures cannot be sufficiently reduced, aeration with chilled air is a technically feasible alternative for grain temperature management. Chilled grain aeration, in contrast to ambient aeration, cools grain independently of the ambient temperature and humidity. To be effective, aeration has to be part of an overall preventive postharvest management system involving sanitation, loading, aeration and monitoring (S.L.A.M.) of bulk stored grains. In addition to a review of grain aeration principles, the effectiveness of preserving grain quality utilising both ambient and chilled aeration is presented for Thai, Brazilian and U.S. conditions using both maize and paddy rice.

Aeration is the forced movement of ambient air through stored grain to decrease or increase the grain temperature to the desired level. Although ambient airflow rates are generally too low to significantly change grain moistures by more than 0.5 percentage points, excessive aeration can reduce marketable grain weight, or cause swelling of grain kernels near the air inlet. The approximate fan run times for a range of common airflow rates are listed in Table 1. The recommended U.S. design airflow rate for aeration is 0.1 m^3/min/t. In warm, humid regions airflows of at least 0.125–0.25 m^3/min/t should be considered to minimise fan run times and maximise utilisation of cooler weather.

Grain temperature is the major stored-grain management tool that regulates insects and moulds (Noyes et al. 1995). Harvest temperatures vary widely for grain and seed crops across the world. In temperate latitudes, grain is generally harvested later and can be stored at higher moisture levels than in tropical latitudes. For example, the maize harvest in the southern U.S. typically occurs from mid-July through September at moisture contents (m.c.) of 12–18% wet basis (w.b.), but in the northern U.S. harvest is usually in October and November at moistures of 18–25% (w.b.). Thus, producers and elevator operators in the north can cool grain much sooner after harvest than those in the South, who generally do not have to dry artificially. Most insect and mould activity is greatly reduced at grain temperatures below 15°C. Planned temperature reductions with controlled aeration can significantly reduce insect development.

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Grain moisture is the other critical grain management factor that regulates storability. Higher levels of grain moisture increase the potential for both insect infestations and mould development, although moisture content is more critical in its formation. To achieve safe storage moisture contents, forced heated or natural air drying of crops is necessary, especially for maize harvested in the midwestern U.S., rice in Southeast Asia, and wheat in the Canadian prairies. At times, soybeans, sorghum, oats, rye, and other grains may also need to be dried after harvest. Table 2 summarises safe grain storage moisture levels for southern, central, and northern regions of the U.S. Grain is at higher risk in warmer, humid regions than in temperate, drier regions due to higher temperatures and relative humidities between harvest and aeration cooling. Thus, lowering storage moistures by at least 1–3 percentage points of those listed for the southern U.S. are recommended for warmer and more humid regions outside the USA.

Table 1. Airflow rate and approximate fan run times (hours) for aeration of grain in different seasons to equalise grain temperature (from Brooker et al. 1992).

Season	Airflow rate (m^3/min/t)		
	0.05	0.1	0.25
Fall	300	150	60
Winter	400	200	80
Spring	240	120	48

Stored grain insect populations and mould growth accelerate rapidly under extended favourable growing conditions. As illustrated in Figure 1, if temperature and grain moisture levels are favourable, stored grain insects and moulds will increase exponentially. Stored grain managers must be aware of the increase in risk, based on the time the product has been stored at grain temperatures and moisture levels suitable for development. The predicted effects of two grain moistures and temperatures on insect levels in wheat harvested 1 June in the central plains of the U.S. but not aerated before 1 October closely model field experience (Hagstrum and Flinn 1990). On the other hand, if aeration was started earlier, insect development could be controlled below the critical 1 live insect per 0.5 kg limit (Fig. 2).

As grain is dried slowly and/or aerated, its moisture content comes into equilibrium with the surrounding (interstitial) air temperature and relative humidity of the drying or storage environment. Figures 3–6 illustrate moisture equilibrium conditions for several common grain types, based on published ASAE Standards (Anon. 1992). If air temperature increases at a constant relative humidity, the grain's equilibrium moisture content (EMC) will decrease. If relative humidity increases at constant temperature, EMC will increase. As shown in Figure 3, maize stored at 15% m.c. (w.b.) and 10°C has an equilibrium relative humidity of about 68%. If, due to excessive aeration, the interstitial relative humidity was measured to be 60% at 10°C, the grain moisture level would have been reduced to about 13.5% w.b. Thus, knowing the relationship between EMC and air conditions is important in properly managing aeration systems to prevent overdrying or condensation.

Table 2. Maximum moisture contents recommended for aerated grain storage across the U.S. (from Noyes et al. 1995).

Grain type and storage time	Maximum moisture content[a] for safe storage (% wet basis)		
	South	Central	North
Shelled maize and sorghum			
Stored up to 6 months	14	15	15
Stored 6 to 12 months	13	14	14
Stored more than 1 year	12	13	13
Soybeans			
Stored up to 6 months	13	14	14
Stored 6 to 12 months	12	12	13
Stored more than 1 year	11	11	12
Wheat, oats, barley, rice			
Stored up to 6 months	12	13	14
Stored 6 to 12 months	11	12	13
Stored more than 1 year	10	11	12
Sunflower			
Stored up to 6 months	10	10	10
Stored 6 to 12 months	9	9	9
Stored more than 1 year	8	8	8
Flaxseed			
Stored up to 6 months	9	9	9
Stored more than 6 months	7	7	7
Edible beans			
Stored up to 6 months	14	15	15
Stored 6 to 12 months	12	13	14
Stored more than 1 year	10	11	12

[a] Values for good quality, clean grain and aerated storage. Reduce one percentage point for poor quality grain, such as grain damaged by blight, drought, etc. Reduce each entry by two percentage points for non-aerated storage. Reduce the values for the Southern U.S. by one to three percentage points for warm, humid regions.

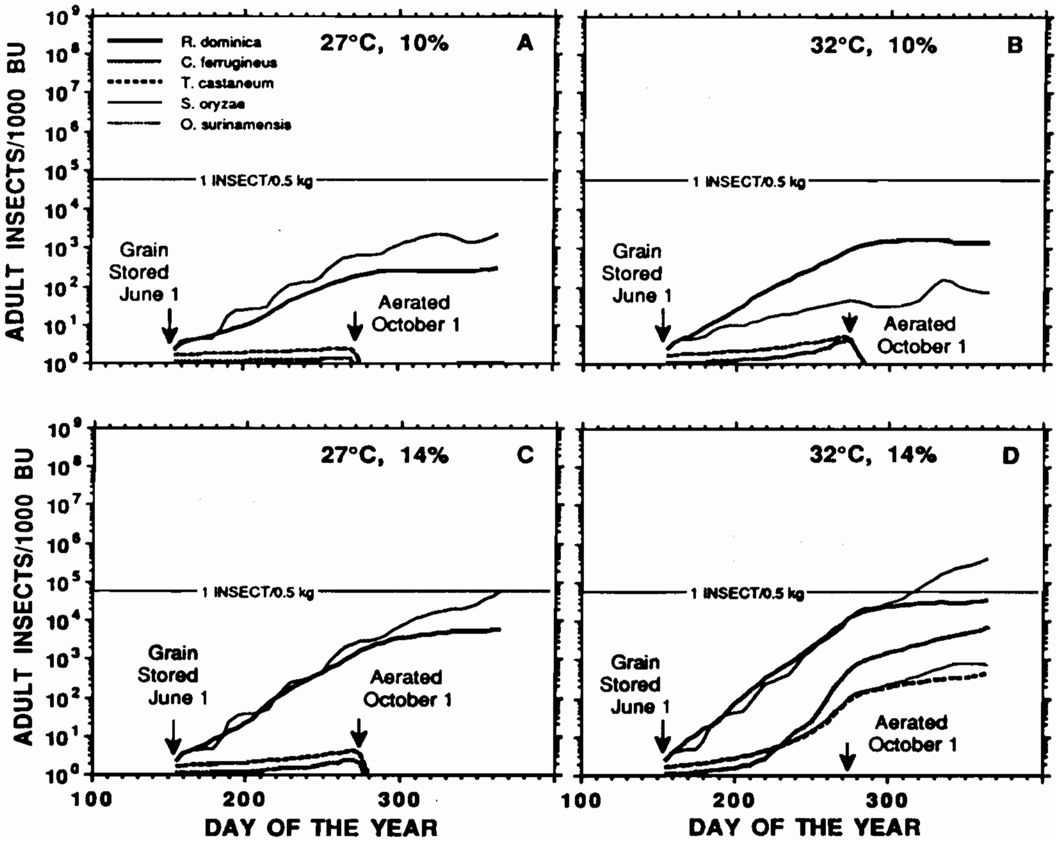

Figure 1. Predicted effects of initial grain temperatures and moisture contents of (A) 27°C and 10%, (B) 32°C and 10%, (C) 27°C and 14%, and (D) 32°C and 14% on the population growth of five species of stored-grain insects with wheat aeration completed on 1 October (from Hagstrum and Flinn 1990).

Moisture Migration in Non-aerated Storages

Grain at the right moisture content and temperature can be stored safely for long periods. However, maintaining grain storage conditions within an acceptable range requires close management (or thermally insulated storages). When grain is stored at safe moisture levels but is not aerated, moisture migration can develop from one part of the storage to another. Moisture migration is caused by significant temperature differences that develop within a non-aerated grain mass. Cold weather causes temperatures in the outer 0.5–1 m (top and sides, and bottoms in storages with ducts or plenum floors) of a grain mass to cool significantly faster than the grain closer to the centre. This temperature differential results in slow-moving convection currents (Fig. 7). Cold, dense air settles by gravity through the cold, outer grain. The air warms and expands as it moves inward near the bottom of the storage, and then rises in the inner grain mass. As air warms, its relative humidity (r.h.) decreases, and its moisture-carrying capacity increases. For each 10°C rise in temperature, the relative humidity is halved. Air at 0°C and 80% r.h. will drop to 40% r.h. when warmed to 10°C. As this warm, moist air moves up to the grain surface, it cools to its dew point and begins condensing moisture on the colder grain near the surface. For cold grain, such as maize carried over into the summer, convection currents are primarily driven by the solar radiation on the sun-exposed walls. Air rises along the warmed walls of the bin and downward along the cooler shaded walls on the opposite side. In this case, moisture may condense and grain spoil along the shaded walls.

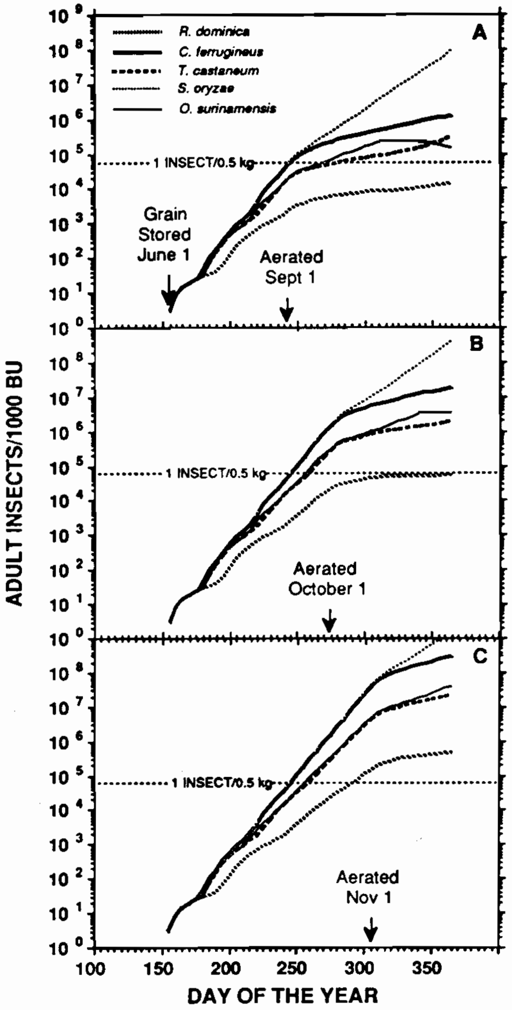

Figure 2. Predicted effects of time of aeration on population growth of five species of stored-grain insects at 32°C and 14% grain moisture content (from Hagstrum and Flinn 1990).

Warm, moist headspace air activates moulds, causing grain to crust and seal-over, especially when grain is left peaked and uncored. Top crusting can occur when warm air is exhausted from the grain mass during cooling in cold weather, and during storage after grains were initially dried to moistures as low as 9 to 11%. This is a typical condition when maize or rice are transferred hot from a dryer into a tempering (dryeration) or cooling bin (in-bin cooling). Significant condensation occurs on bin walls and roofs, and extended fan operation is needed to minimise excessive dripping. Peaked grain has a larger exposed surface area for moisture to condense on. Increased levels of moisture are also caused by condensation from downspouts, and leaking roofs and hatch covers that allow rain and snow to enter the headspace. The development of "hot spots" in storage is a typical indicator of grain spoilage due to excessive moisture. The grain under the loading spout is more densely packed with fine material and thus more prone to self-heating.

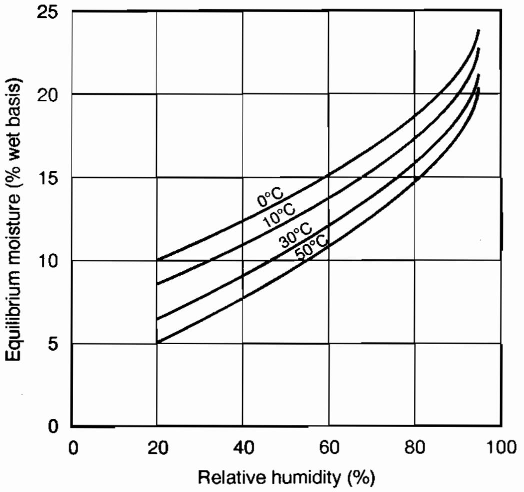

Figure 3. Equilibrium moisture content of yellow dent corn (from Anon. 1992).

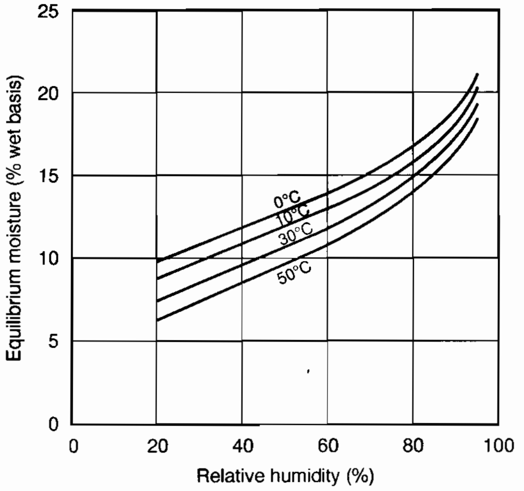

Figure 4. Equilibrium moisture content of rough rice (from Anon. 1992).

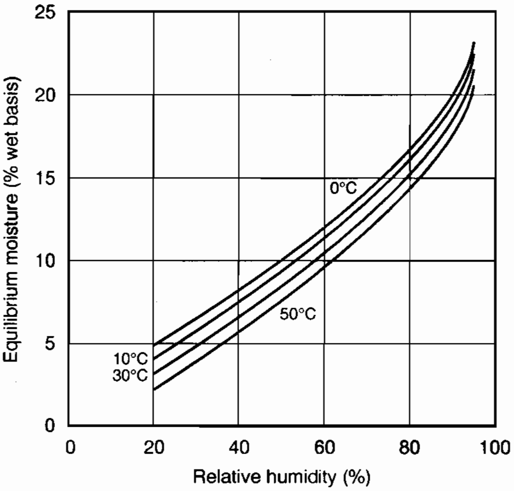

Figure 5. Equilibrium moisture content of soybean (from Anon. 1992).

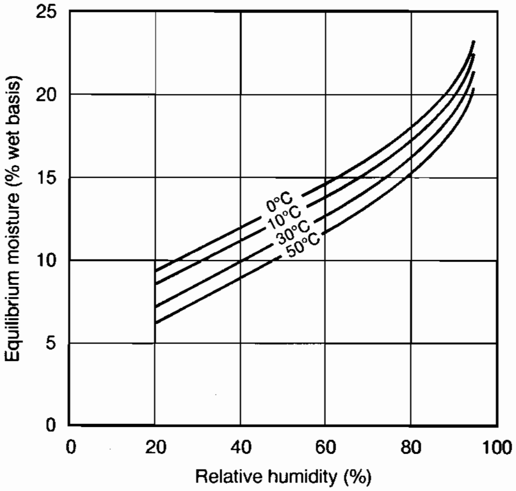

Figure 6. Equilibrium moisture content of hard wheat (from Anon. 1992).

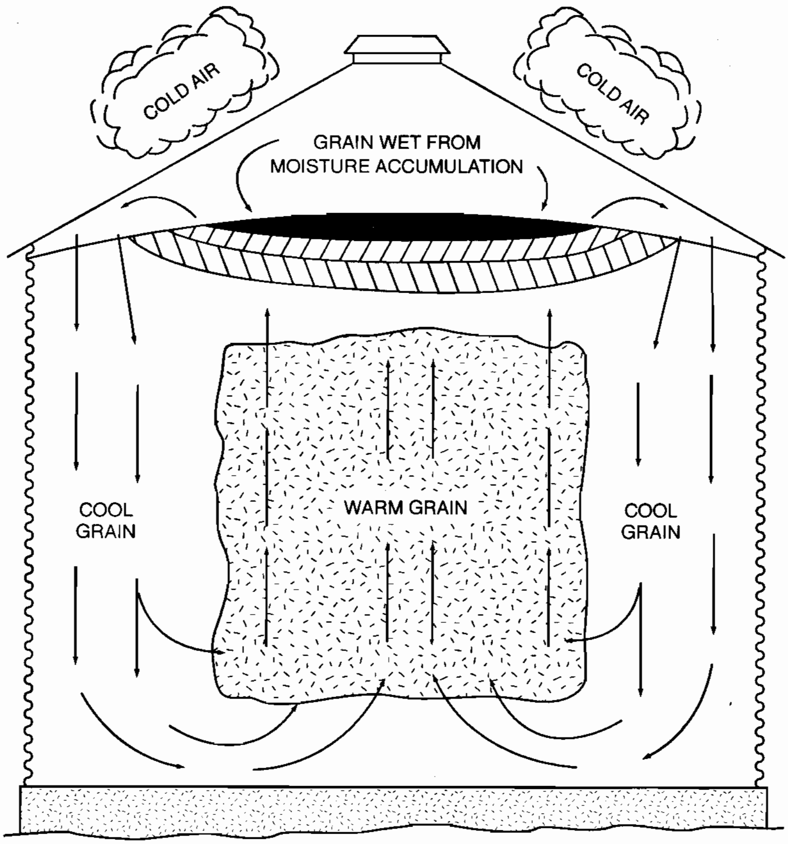

Figure 7. Moisture migration in non-aerated, warm grain when outside ambient temperatures are consistently cold (from Brooker et al. 1992).

Generally it is recommended to maintain grain temperatures within 5–10°C of the average ambient temperature for the geographic location of the storage to minimise the potential for convection currents. Also, sealing the fan inlets when the aeration system is not operating reduces the chance for moisture migration, premature grain warming, and pest and rodent infiltration.

Aeration Systems

An aeration system consists of a fan, an air supply duct (or transition), aeration ducts (or perforated floor), and a fan controller (ranging from a simple on–off switch operated manually to a state-of-the-art computer-based system). The fan can be either centrifugal or axial-flow type, depending on the static pressure and airflow requirements of the grain storage. It is critical that the fan be properly sized to deliver the recommended aeration airflow rate for a particular grain storage. Software tools, such as the FANS program available from the University of Minnesota (Anon. 1995), which includes the curves of over 200 commercially available fans, should be consulted in the design of any new structure, as well as in the verification of any existing aeration system. The air supply duct should be sized so that the duct velocity does not exceed 460–610 m/min to prevent excessive pressure drop in the duct (Brooker et al. 1992). In-bin control systems should be employed to control aeration cooling and natural air/low temperature grain drying (Moreira and Bakker-Arkema 1992). A controller decides if, when, and for how long fan operation is needed.

Figure 8 shows typical aeration supply systems. The air is distributed into the grain via aeration ducts or a perforated floor. Ducts do not distribute the air evenly through the grain. The location and spacing of the aeration ducts are critical because they determine the uniformity of airflow through the grain. If a grain silo is equipped with a fully perforated floor, distribution is more even, provided the grain surface is level and the fines in the grain are either removed by cleaning or coring of the grain, or evenly distributed throughout the grain mass with the help of a good spreader.

In flat storages more than one aeration duct is generally required. The optimal spacing of the ducts is based on the ratio of the shortest to the longest path of the air from the duct to the grain surface. The ratio should be approximately 1.5. Figure 9 illustrates the concept of proper spacing of aeration ducts in flat grain storages. The reader is referred to aeration system design handbooks for more information.

Aeration Controllers

The use of automatic aeration controllers to optimise aeration time should be a widely adopted stored-grain management technology. Simple aeration controllers with hour meters that operate fans based on a thermostat set-point have shown to provide precise grain temperature management. Some managers choose to control both high and low temperatures to keep potential temperature differences between the grain and the outside to within 5–10°C. Automatic fan controllers should control grain temperatures to within 2°C of the controller's thermostat set points. Two to three aeration cycles may be needed to accomplish a desired grain temperature reduction using manually operated fans. With suitable cold air ambient temperatures, automatic systems can reduce grain temperatures by intermittently operating the fan whenever suitable weather conditions prevail. Simple aeration controllers usually pay for themselves in less than one year.

Aeration based on the Seed Wet-Bulb Temperature (SWBT) as defined by Wilson and Desmarchelier (1994) is a strategy that has particular benefit in warm temperate climates for dry grains. The SWBT is determined as a function of the moisture content and temperature of the grain. Fan controllers are set to select ambient conditions to achieve the target SWBT based on meteorological data, or actual local conditions by measuring ambient air temperature and relative humidity. Low temperatures at night can be used to cool the grain, and warm conditions during the day enable the grain to be harvested at low moisture. When low moisture grain is cooled to the SWBT, its dry-bulb temperature is near the mean ambient air dry-bulb temperature. Consequently, the grain will not tend to rewarm when the aeration system is turned off, thereby limiting the temperature difference that drives moisture migration.

Aeration based on the equilibrium moisture content (EMC) of grain is another fan control strategy. However, it has been mostly utilised for conditioning moist grain in a bin to the target moisture content. The EMC strategy involves several possible modifications, such as operating the fan based on a self-adjusting minimum number of hours of daily fan operation that depends on the calendar date, the maximum moisture content of the binned grain, a 3–5% EMC window initially and a smaller one near the end of the drying cycle, or in addition to the EMC window a 5–10°C temperature window with limits on the maximum and minimum allowable temperatures (Moreira and Bakker-Arkema 1992).

Humidistat controls add to the cost of controllers and are not necessary for most bulk storage aeration except possibly in the humid tropics, and where more precise control over grain conditions is required.

Humidistats are difficult to maintain, limit the amount of usable cooling time, and if not properly understood can cause more problems than they solve.

More sophisticated control strategies require not only reliable sensors that are regularly calibrated but also programmable microprocessors that are well understood by the user. Several commercial systems have been available for years. Today's state-of-the-art systems are PC-based and tie control strategies into predictive aeration and storage modeling software (Wilson 1990; Maier et al. 1996).

Aeration of Wet Grains

Aeration is also used to maintain the condition of recently harvested, wet grain before it can be dried. The objective of maintenance aeration is different from that of aeration cooling. Because wet, warm grain heats up and moulds quickly, it can be maintained in reasonable condition in temperate climates for 3–7 days depending on the initial grain moisture and temperature if it is aerated at relatively high airflow rates of 0.50–1.0 m^3/min/t. The practice of

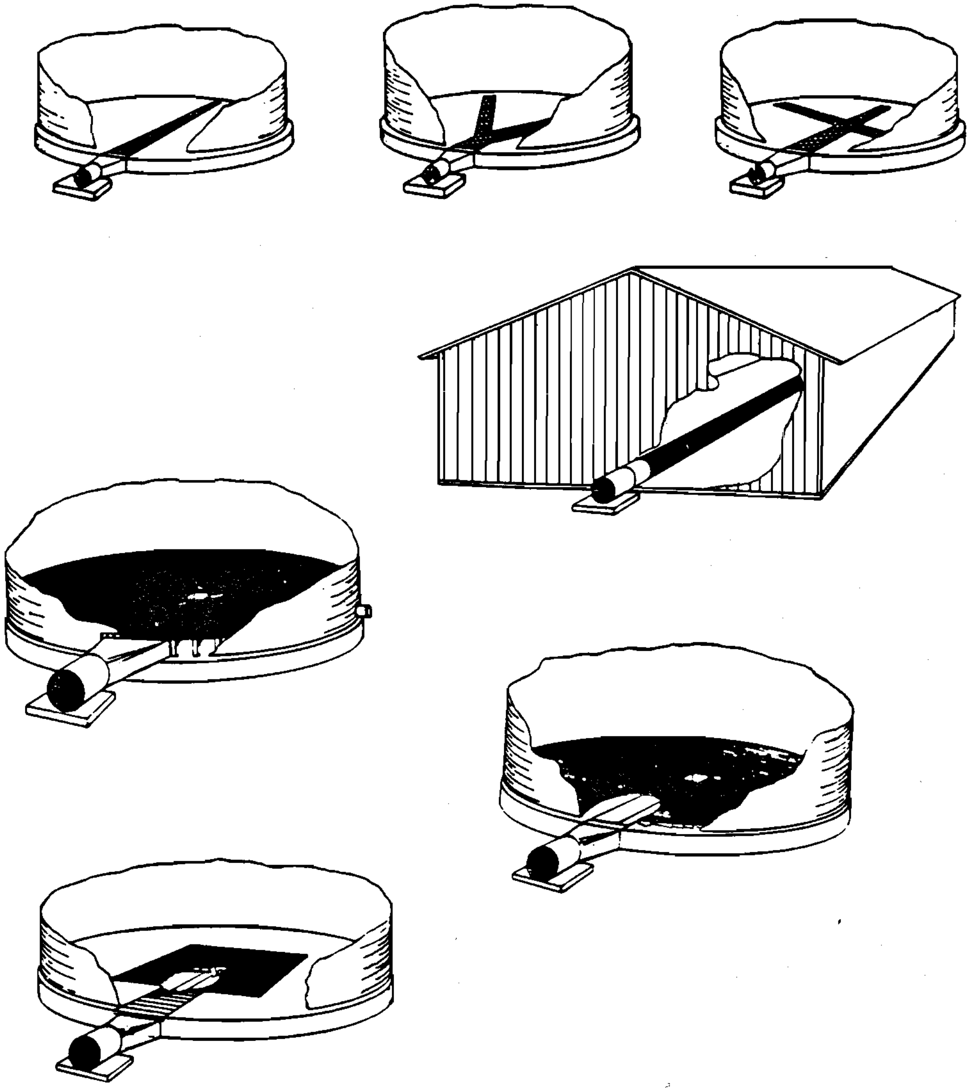

Figure 8. Typical grain aeration systems in circular storage structures (from Brooker et al. 1992).

maintaining the quality of 16–20% moisture content (w.b.) grain by aeration with ambient air decreases the storability of the grain and should be employed with caution (Brooker et al. 1992). Farmers and elevator operators are generally better off expanding drying capacity in order to keep wet holding to the shortest practical time.

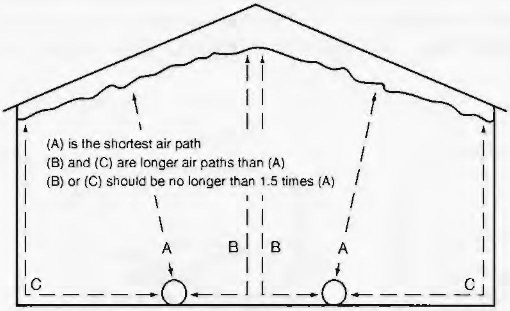

Figure 9. Guidelines for duct spacing in a flat storage (from Brooker et al. 1992).

Chilled Grain Aeration

Chilled grain aeration is defined as the cooling of grain independent of the ambient conditions using a mechanical refrigeration system. In a grain chilling system ambient air is ducted over a bank of refrigeration coils in order to decrease its temperature (Fig. 10). In this process the relative humidity of the air is increased. The chilled air is reheated slightly to match the equilibrium relative humidity of the stored grain. After the initial cool-down, a rechilling cycle is run periodically in order to maintain the grain at the desired temperature. The specifications of a typical grain chiller are given in Table 3. The operation of a typical grain chiller is shown in Figure 11 during a 5-day early-summer period in the midwestern United States. The ambient temperature varied between 10 and 28°C while the chilled-air temperature was maintained between 6 and 7°C. Likewise, the relative humidity of the chilled air remained practically constant at 90±2% although the ambient air humidity ranged from 25 to 98%.

The ability to control the bin inlet air temperature and relative humidity is especially desirable for food grain storages, such as breakfast cereals, snack food grains, milling grains, etc., where product value is higher. Grain chilling is currently used for storing wheat, maize, popcorn, and rice in several U.S. commercial food processing facilities (Maier 1994). Potential benefits include less liability and improved worker safety due to reduced or eliminated chemical handling; less shrinkage; less spoilage potential; reduced insect damage; and lower drying costs. Recommended grain temperatures for chilled grain storage depend on the grain moisture content, type and end use (Burrell 1982). However, grain temperatures below 15–17°C are usually sufficient to significantly

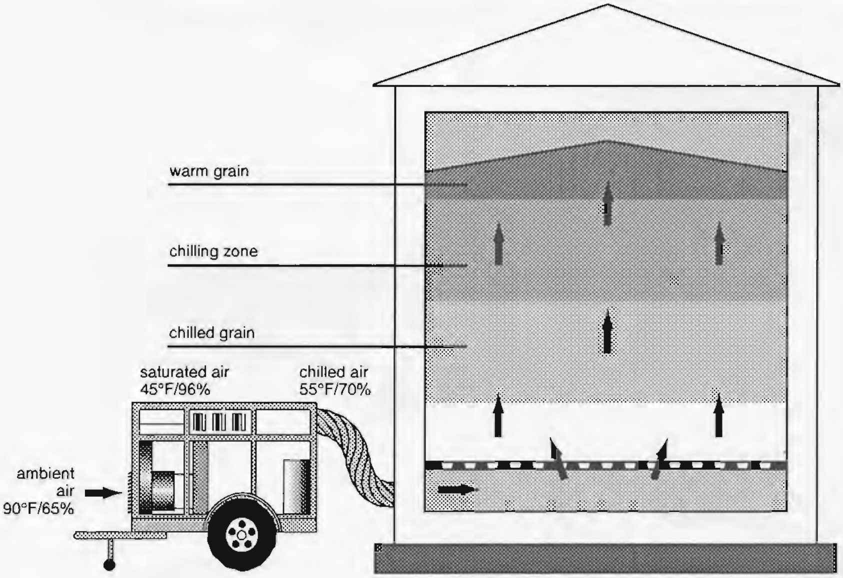

Figure 10. Chilled aeration and conditioning process utilising a mobile grain chiller, which utilises a refrigeration system to control the temperature and relative humidity of the air into the storage bin (55°F ≈ 13°C; 90°F ≈ 32°C).

slow most insect development. Maier (1992, 1994) extensively reviewed the utilisation of chilled grain aeration in the U.S. and around the world. Rulon (1996) investigated the annual operating costs and amortised net present costs of chilled aeration versus ambient aeration plus fumigation for pest management for U.S. conditions. Chilling has generally lower annual operating costs, and given the current price of commercial chillers in the U.S. can be justified despite the large capital investment required.

Storage Management Using S.L.A.M.

Aeration of stored grain has to be part of an overall preventive postharvest management system involving sanitation, loading, aeration and monitoring (S.L.A.M.) (Maier et al. 1994). Elevator operators and producers must adjust these grain storage management strategies depending on their location, facility, stored product, harvest time, and storage period.

- *Sanitation* before loading grain into a storage requires cleaning bin aeration ducts, floors, and unload auger trenches, where insects thrive on grain dust and fine material; cleaning out insect harbouring locations, such as weeds, trash, and mouldy grain in and around storages; spraying an approved postharvest insecticide around the perimeter of the bin, 1–1.5 m up the outside wall, and fumigating empty storages; sealing tank, bin and silo base openings including fans to provide barrier protection against insect entry at all locations below the roof eaves [Note: Roof blowers and vents should be left open except when fumigating.]
- *Loading* storages properly involves cleaning, coring, and leveling. Cleaning (screening) removes grain dust and fines that insects and moulds thrive on, and improves aeration. Coring grain bins and silos means operating each storage unload conveyor to pull the peak down at least half way and remove the central core of fines, trash, and foreign material accumulated under the loading spout to make aeration more effective and to remove a major insect attractant. Leveling clean grain using a spreader or removing the peak by coring makes it easier to manage and assures more uniform airflow.
- *Aeration* to maintain grain temperatures as uniform as possible and as low as practical by managing aeration fans using automatic control. Grain temperatures should be kept below the optimum insect feeding and breeding range of 21 to 32°C.
- *Monitoring* grain in storage using temperature cable thermocouple readouts; scheduled grain and insect sampling; protectant top dressing as needed; fumigation as needed based on economic threshold; and aeration or grain turning when hot spots are detected.

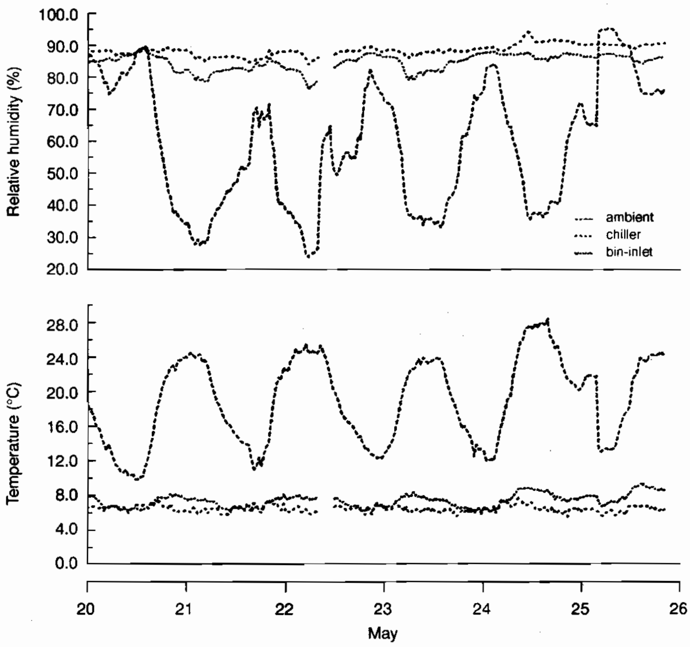

Figure 11. Temperature and relative humidity of the ambient, chilled and bin-inlet air in May 1989 under Midwestern USA conditions (from Maier et al. 1993).

When coordinated, S.L.A.M. management strategies will help to maintain grain quality, minimise marketable moisture weight loss, reduce operating costs, and preserve stored product quality.

Table 3. Design and operating specifications of a commercial[a] grain chiller in a temperate climate.

Cooling capacity	
max. capacity under favourable conditions:	500 t/day
average capacity:	330–340 t/day
Flow volume of the cold air	
at a static pressure of 100 mm W.G.:	14200 m^3/h
300 mm W.G.:	18000 m^3/h
Compressor cooling capacity (nominal)	
at 30°C condensing temperature and 0°C evaporating temperature:	115 kW
Connected load	
compressor:	25 kW
cold air fan:	30 kW
connected load at nominal cooling capacity:	55 kW

[a] GTC3500 manufactured by AAG Manufacturing, Milwaukee, Wisconsin, USA.

Aeration Modeling

Simulation programs can be used to accurately determine the time required to cool a mass of grain. An in-depth analysis of grain aeration can be made with a fixed-bed drying model (Bakker-Arkema 1984). The aeration simulation model chosen in the subsequent case studies assumes steady-state between the grain and air temperatures and humidities. The model is called AERATE, and was developed by Michl (1983); significant modifications to the Michl model were made by Maier (1992) and Maier et al. (1996). The Michl model is similar to the Thompson (1972) fixed-bed grain drying model.

The AERATE program requires information about the desired aeration strategy, the ambient conditions, the bin configuration, and the grain being dried/cooled. The simulation of conventional aeration is accomplished using historic weather data. The hourly temperature and relative humidity values are needed, along with the local barometric pressure. The other moist air parameters are calculated with the help of the built-in psychrometric subroutines. In the chilled aeration operation, it was assumed that the inlet air temperature and relative humidity were supplied by a commercial grain chiller independent of the ambient conditions. The cooling air temperature and relative humidity to the grain pile were constant at the bin inlet and depended on the desired storage temperature and moisture content of the grain. To prevent insect development a threshold of 15°C grain temperature was chosen (Baur 1984).

The effectiveness of preserving grain quality utilising both ambient and chilled aeration will be illustrated for Thai, Brazilian and U.S. conditions, for both maize and paddy rice.

Case Studies

Case 1: Thailand

Input data for Thailand

In order to assess the potential use of grain chillers in Southeast Asia, the storage of paddy in central Thailand was previously considered by Maier et al. (1993). Simulation was employed to analyse ambient versus chilled aeration of a 15 m diameter and 10 m high steel silo filled with 1000 t of paddy initially at 27–29°C. The silo was assumed to be equipped with a fully perforated floor for uniform airflow through the paddy. Airflow rates in the range of 0.05–0.5 m^3/min/t were considered as recommended for the bulk storage of grains by Brooker et al. (1992). Weather data for the central region of Thailand were used. The data were collected by the Rice Research Center in Pathumtani Province for 1988 and 1989 (AIT 1990), and analysed as described by Maier et al. (1993). For the 1000-t bin of paddy, the static pressure drop was determined for rough rice according to ASAE Data D272.2 (Anon. 1992). The calculated value was increased by 10% to account for additional pressure losses due to the perforated bin floor, the connecting duct, the velocity pressure in the duct, and fines accumulation in the grain mass.

In order to maintain the 13% moisture content of the paddy at 15°C, an equilibrium relative humidity of the chilled bin inlet air of 65% was required according to ASAE Data D245.4 (Anon. 1992). The heat loss in the connecting duct was assumed to be 1°C. Thus, the required chilled air temperature was 14°C with a relative humidity of 69%. A summary of the input parameters used in the AERATE grain cooling simulation model is found in Table 4. Simulation results were determined for the wet and dry seasons of 1988 and 1989 for the central region of Thailand.

Results and discussion for Thailand

Ambient aeration. The ambient air temperature and relative humidity ranges and averages are summarised in Table 5. Average temperatures and relative humidities were lower for the dry than the wet seasons. The 1988 dry season was slightly cooler and wetter than the 1989 season, while the 1988 and 1989 wet seasons were similar in temperature but with 1988 slightly wetter than 1989.

Table 4. Input parameters of the AERATE simulation model for ambient and chilled aeration of 1000 t of paddy under typical Thai conditions (from Maier et al. 1993).

Parameter	Values	
Bin diameter, m	15.0	
Bin height, m	10.0	
Bulk density, kg/m^3	566.0	
	Dry season	*Wet season*
Initial paddy temperature, °C	27.0	29.0
	Ambient	*Chilled*
Air temperature	see Table 5	14°C
Air relative humidity	see Table 5	69%
Airflow, m^3/min/t	0.150	0.148–0150
Initial paddy moisture, % wb	13.0	13.5

The ranges and final average temperatures and moisture contents of the paddy for both seasons and years are summarised in Table 6 for continuous ambient aeration. The temperature range was wider during the dry than the wet seasons (up to 11.5°C during the 1989 dry season), and the shrink loss was greater during the dry than the wet seasons. The average shrink losses of the paddy reached 0.9–1.2 percentage points of moisture by the end of the wet season aeration periods, and 1.1–1.4 points by the end of the dry seasons.

The temperature and moisture content of the paddy during four months of continuous aeration between July and October 1988 are shown in Figure 12 (the other three seasons showed similar patterns). The average paddy temperature remained above 25°C at all times, a range (up to 31°C) in which insect development is usually optimum; this verifies the results found by Nour at al. (1988). The repeated adsorption and desorption cycles as evidenced in the bottom layers of the paddy bin during the 1988 wet season tend to increase fissuring of the kernels and decrease head yield. Thus, continuous ambient aeration appears to reduce the quality of the paddy.

To reduce the adsorption and desorption cycles of the paddy, a humidistat set to operate the aeration fan when the relative humidity was below 75% was evaluated. The ranges and final average paddy temperatures and moisture contents are summarised in Table 7 for both seasons and years. Paddy temperature ranges were not significantly different compared to continuous aeration. However, average temperatures at the end of each season were higher by up to 1.6°C in the 1988 dry season and 1.7°C in the 1988 wet season compared to continuous aeration. Shrink losses were increased by 0.3% at the end of the two wet seasons and by 0.7–0.8% at the end of the two dry seasons. Figure 13 shows that the average temperature of

Table 5. Ambient air temperature and relative humidity ranges and averages during the wet (1 July – 31 October) and dry (1 November 1–28 February) seasons of 1988 and 1989 for the central region of Thailand (from Maier et al. 1993).

Year	Wet season		Dry season	
	Range	Average	Range	Average
1988	20.7–36.5°C	28.6°C	15.0–35.5°C	25.6°C
	41–100%	79%	42–100%	74%
1989	19.2–36.7°C	28.5°C	14.3–36.0°C	26.3°C
	52–100%	75%	39–100%	72%

Table 6. Ranges and final average temperatures and moisture contents of paddy aerated continuously during the wet and dry seasons of 1988 and 1989 for the central region of Thailand (from Maier et al. 1993).

Year	Wet season		Dry season	
	Range	Final	Range	Final
1988	25.7–30.9°C	29.0°C	20.2–29.5°C	26.5°C
	11.9–13.3%	12.1%	11.2–13.2%	11.9%
1989	24.8–30.1°C	28.9°C	19.6–31.1°C	30.0°C
	11.6–13.0%	11.8%	10.9–13.2%	11.6%

the paddy remained above 26°C for humidistat-controlled aeration during the 1988 wet season (the other three seasons showed similar patterns). However, the daily temperature variation in the grain pile observed during continuous aeration was avoided. The temperature of the bottom layer was higher than that of the top layer during most of the aeration period. This was due to the operation of the fan during high-ambient temperature periods when the ambient relative humidity dropped below 75%.

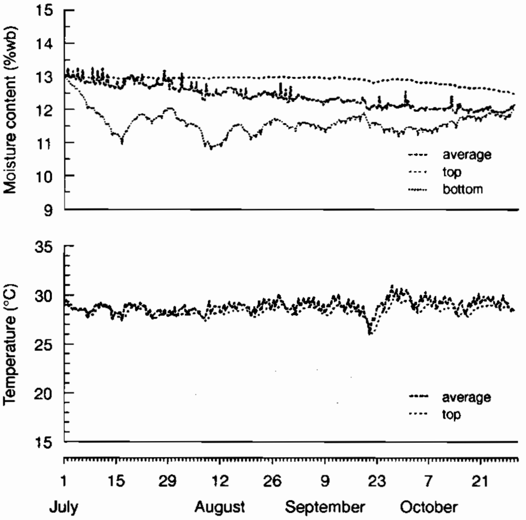

Figure 12. Temperature and moisture content of paddy rice aerated continuously under Thai conditions between July and October 1988 (from Maier et al. 1993).

On the other hand, the humidistat-controlled aeration reduced fan run-time and energy consumption. During the dry storage seasons of 1988 and 1989, 44 and 38% less energy and during the wet season of 1988 and 1989, 64 and 43% less energy were consumed, respectively, than for continuous aeration. The fan operated for 1650 and 1836 hours during the 1988 and 1989 dry seasons, respectively, and for 1062 and 1680 hours during the 1988 and 1989 wet seasons, respectively, compared with 2946 hours during the continuous four-month aeration operations. While the number of cycles of moisture adsorption and desorption during the humidistat-controlled aeration were reduced, the bottom layer reached a moisture content of as low as 9.3% during the 1989 dry season compared with 10.0% for continuous aeration (not shown). Thus, a simple humidistat does not appear to be a desirable aeration controller for use in the humid tropics.

Chilled aeration. Contrast the results in Figures 12 and 13 with those in Figure 14 in which chilled aeration with constant bin-inlet air conditions was used for the average of the two wet seasons. The paddy in the silo was completely chilled to below 20°C within 88 hours, and below 15°C within 144 hours. The moisture content of the bottom layer reached 12.5%, while the top layer was slightly below 13.0%. During the average of the two dry seasons, the chilling time was only 110 hours and yielded similar temperature and moisture profiles. Most importantly, at 15°C and 12.5–13.0% m.c., the paddy can be stored for extended periods in Southeast Asia and elsewhere with a significant reduction in the potential for insect infestation (Baur 1984). Additionally, in order to achieve the desired market moisture content of 13%, the initial paddy moisture could be as high as 13.5% due to the evaporative cooling effect of the chilled air.

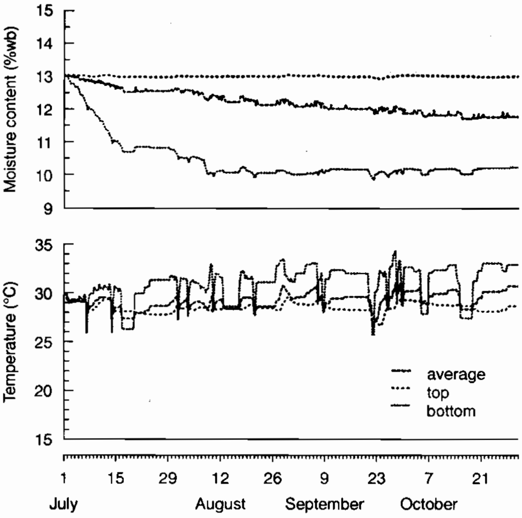

Figure 13. Temperature and moisture content of paddy rice aerated whenever the relative humidity was less than 75% under Thai conditions between July and October 1988 (from Maier et al. 1993).

The average chilling capacity of 167 t/day during the wet season in Thailand was about 50% of the rated average capacity specified by the chiller manufacturer; during the dry season, the actual capacity of 218 t/day was 35% less than the rated one. The energy requirement for chilling to 15°C during the wet season was 7.8 kWh/t compared to 5.9 kWh/t during the dry season, i.e., a decrease of 24%. These results indicate that the commercial grain chiller would not operate optimally in the central region of Thailand. Chiller manufacturers usually equip their units with larger refrigeration capacities to accommodate the higher latent cooling loads in the humid tropics.

Table 7. Ranges and final average temperatures and moisture contents of paddy aerated whenever the relative humidity of the ambient air was less than 75% during the wet and dry seasons of 1988 and 1989 for the central region of Thailand (from Maier et al. 1993).

Year	Wet season		Dry season	
	Range	Final	Range	Final
1988	26.2–30.8°C	30.7°C	20.6–28.1°C	28.1°C
	11.7–13.0%	11.8%	11.1–13.0%	11.1%
1989	24.5–29.9°C	29.8°C	19.7–30.1°C	30.1°C
	11.4–13.0%	11.5%	10.8–13.0%	10.9%

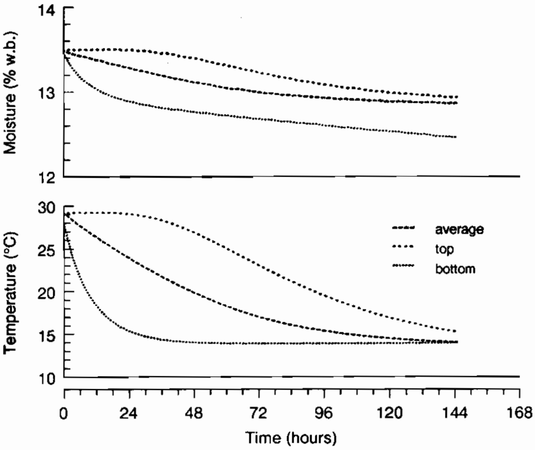

Figure 14. Temperature and moisture content of paddy rice aerated with a grain chiller during the Thai wet season (from Maier et al. 1993).

Summary for Thailand. The cooling of paddy stored under Thai conditions during the 1988 and 1989 seasons showed that ambient aeration could not reduce the average grain temperature below 25°C during either the wet or dry season. Chilled aeration moved a cooling front completely through a 1000 t bin. It lowered the paddy temperature to 15°C, which is the typical insect development threshold, in 110 to 144 hours, depending on the season. However, a commercial grain chiller originally designed for temperate climates would have to have to have its refrigeration capacity increased by 35–50% to match the fan design airflow rates desired for the humid tropics. Shrink loss due to ambient aeration was higher during the dry than the wet season, and was smallest for chilling with 0.5 percentage points compared to 0.9–1.4 points for continuous ambient, and 1.2–2.1 points for humidistat-controlled aeration. In addition, moisture gradients between the top and bottom layers were minimised by chilling. A simple on–off humidistat set to operate below 75% relative humidity ran the fan 38 to 64% less than continuous aeration. Although it reduced the effect of adsorption and desorption cycles, it removed up to 0.8 percentage points more moisture from the paddy and did not control the paddy temperature any better than continuous ambient aeration.

Case 2: Brazil

Input data for Brazil

In order to assess the advantage of the use of aeration in Brazil, the storage of maize in the Parañа region was considered by Moreira and Maier (1993). Simulation was employed to analyse conventional and chilled aeration of grain stored at a commercial grain elevator. The maize was stored in a metal silo with a holding capacity of 600 t; the silo diameter was 10.1 m and the fill depth 10.3 m. The maize was harvested on 15 March, dried (if needed) to about 14% m.c. (w.b.), and reached the silo at approximately 25°C. Different aeration schedules were used with the principle aim to cool the grain to below 15°C as rapidly as possible without excessive overdrying.

Two aeration strategies were investigated using ambient air at a flow rate of 0.11 m^3/min/t using a 5 hp fan: (1) continuous aeration, and (2) aeration whenever the relative humidity of the ambient air was below 75%. The grain temperature and moisture content in the silos were simulated for March through September in Parañа, Brazil, over a four-year period (i.e., 1989–1992) using ambient weather conditions recorded every three hours. For the chiller, the ambient air was cooled and dehumidified to a temperature of 15°C, and a relative humidity of 65% for maize. The airflow rate during chilled aeration was also 0.11 m^3/min/t.

Results and discussion for Brazil

Ambient aeration. The weather conditions for March–September 1989–1992 in the south of Brazil are summarised in Table 8. The four-year average temperature was 20°C with a range of 2.1 to 32.8°C, the four-year average relative humidity was 75.0%

with a range of 30.1 to 100%. Figure 15 shows the plot of the 1991 weather conditions for March–September.

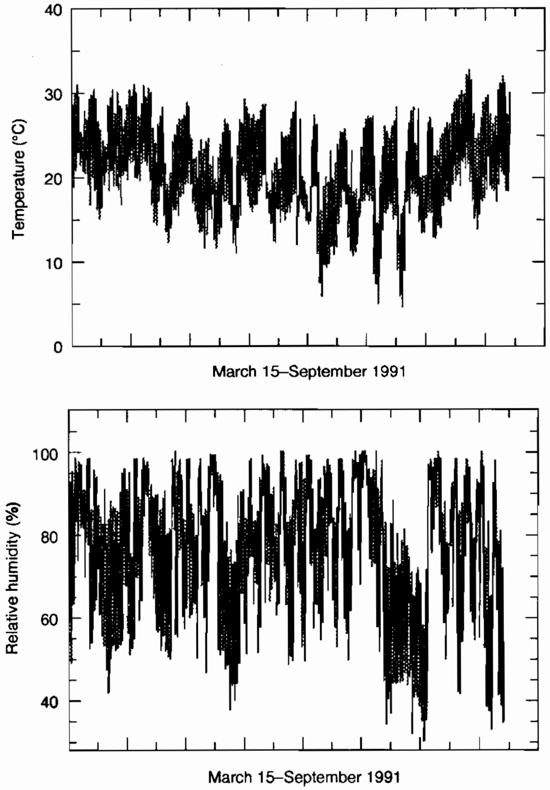

Figure 15. Ambient temperature (a) and relative humidity (b) in Parañá, Brazil between 15 March and 15 September 1991 (from Moreira and Maier 1993).

Table 8. Average, maximum and minimum ambient temperature and relative humidity in southern Brazil between March–September 1989–1992 (from Moreira and Maier 1993).

Year	Temperature (°C)			Relative humidity (%)		
1989	19.7	31.8	2.1	73.9	100	29.5
1990	19.2	32.8	2.8	76.4	100	30.1
1991	20.7	32.8	5.1	70.5	100	27.7
1992	19.5	31.3	3.1	79.1	100	31.1

Figures 16 and 17 show the average temperature and moisture content of the maize for the March 15–September 15, 1989–1992 storage periods for the continuous and humidistat-controlled ambient aeration strategies. Continuous aeration resulted in lower average grain temperatures and in less overdrying of the maize (Table 9). However, grain temperatures remained above 20°C for 1.5–3 months for continuous versus 2–4.5 months for intermittent aeration. Temperatures reached 15°C and below in two and one of the four seasons, respectively. It took longer for the maize to reach the desired storage temperature using intermittent aeration. The 1992 season was a rather humid one with the least moisture shrink for both strategies. Intermittent aeration resulted in 0.1 to 0.4 percentage points overdrying of the maize. However, the bottom grain layers shrank by as much as 1.8 percentage points compared with 1 point maximum shrink for continuous aeration. However, energy consumption was on average 40% less for intermittent aeration (Table 10).

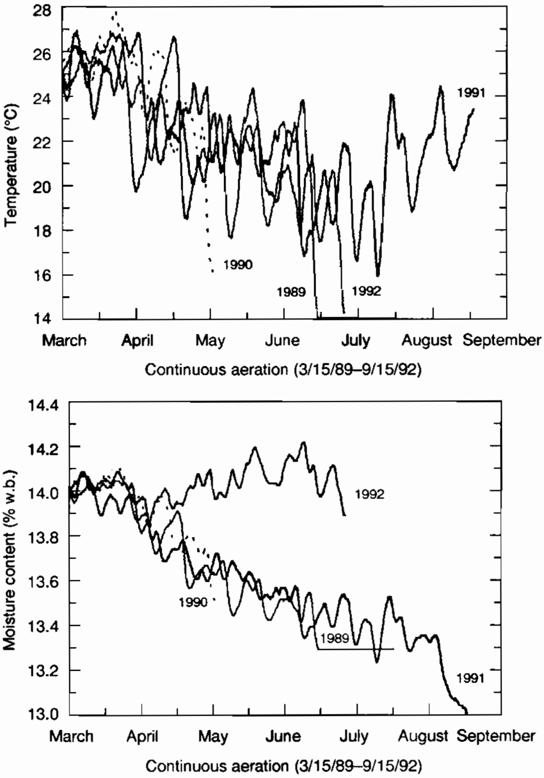

Figure 16. Temperature (a) and moisture content (b) of maize aerated continuously under Brazilian conditions between March–September 1989, 1990, 1991 and 1992 (from Moreira and Maier 1993).

Chilled aeration. Figure 18 shows a sharp contrast among the results when chilled aeration with constant air-inlet conditions is compared with the conventional aeration systems for maize (similar results were obtained for the other years). The maize in the silo cooled to below 20°C within 7 days, and below 15°C within 15 days. The final average moisture content of the maize in the silo was reduced by less than 0.3% during the cooling process.

Energy consumption was on average 4509 kW independent of the inlet temperature changes (Table 10). This was on average 19.9% more energy than for continuous aeration, and 100% more than for intermittent aeration. Nevertheless, even in warmer years the chiller was able to reduce the grain temperature from the bottom to the top of the silo uniformly to the desired value in shorter periods of time than with ambient air.

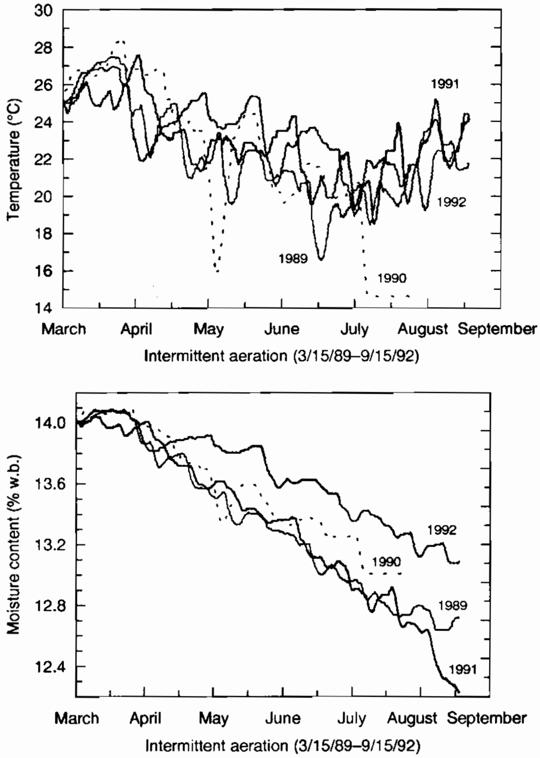

Figure 17. Temperature and moisture content of maize aerated when relative humidity was less than 75% under Brazilian conditions between March–September 1989, 1990, 1991 and 1992 (from Moreira and Maier 1993).

Summary for Brazil. The cooling of maize stored under Brazilian conditions during 1989 through 1992 mid-March to mid-September showed that ambient aeration could not reduce average grain temperatures consistently below 15°C in a predictable time. Chilled aeration cooled the 600 t steel bins within 15 days. Shrink loss was highest for intermittent ambient aeration and least for chilling. Average energy consumption for chilling of 7.5 kWh/t were only 20% higher than for continuous ambient aeration. This would appear to be acceptable given the additional savings that can accrue due to a reduction in the need for insecticides and fumigants.

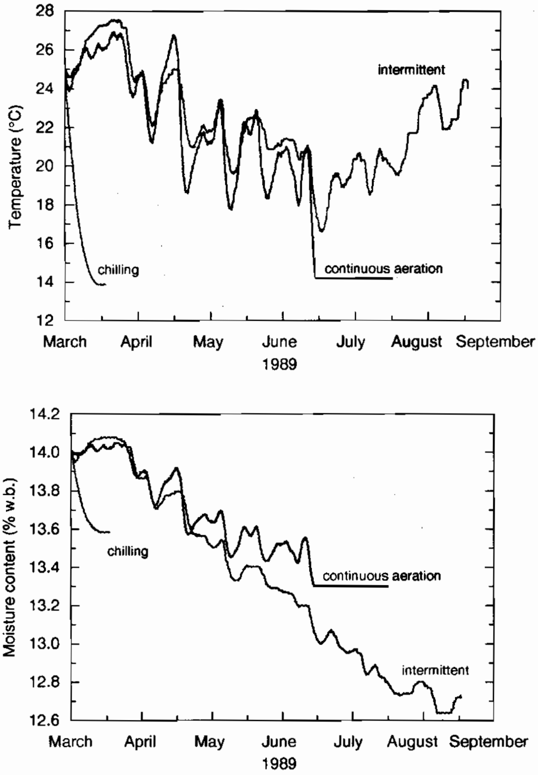

Figure 18. Temperature and moisture content of maize aerated continuously, when relative humidity was less than 75%, and using chilled aeration under Brazilian conditions between March–September of 1989 (from Moreira and Maier

Case 3: United States

Input data for the United States

In order to assess the advantage of the use of grain chillers in the United States, the storage of paddy rice and food maize in the Corpus Christi, Texas area was considered at two commercial food-grain elevators by Maier et al. (1993). The rice was stored in 60 concrete silos with a holding capacity of 91 t each; the silo diameter was 3.7 m and the fill depth 15.3 m. The maize was stored in 36 concrete silos with a holding capacity of 1200 t each; the silo diameter was 9.1 m and the fill depth 23.8 m. The rice and maize were harvested in late July, dried (if needed) to about 13% (w.b.), and reached the silos at approximately 38°C. Four aeration strategies were investigated using ambient air at a flowrate of 0.1 m^3/min/t: (1) continuous aeration, (2) aeration whenever the relative humidity of the ambient air was below 75%, (3) aeration between 10 a.m. and 4 p.m., and (4) aeration between 10 pm. and 4 a.m.

The chilling of the grain was set to provide a bin inlet air temperature of 15°C, and a relative humidity of 58% for maize and 63% for rice. The airflow rate during chilled aeration was a constant 0.1 m^3/min/t. Both ambient and chilled aeration were analysed during the warmest storage months (i.e., August, September and October) over a three-year period (i.e., 1988–1990). Weather conditions were recorded every three hours (NOAA 1988, 1989, 1990).

Results and discussion for the United States

Ambient aeration. The weather conditions for Corpus Christi, Texas, during August and October are warm and humid. The 28-year average temperatures (i.e., 1962–1989) for August were 28.6°C, for September 27.0°C, and for October 23.3°C. Ambient temperatures in 1988 ranged from 13.3 to 38.9°C, and the relative humidity from 27 to 100% during August through October.

There was little difference in the stored grain temperatures among the three seasons and between the two grains (Tables 11 and 12). The average grain moistures in the silos remained at 12.5±0.5% w.b., and the average grain temperatures for the summer were 28±2°C. Continuous aeration resulted in less overdrying of the rice and maize in the bottom layers of the silos, and in the lowest average grain temperatures (except for the 10 pm.–4 a.m. case), and has the smallest differentials in moisture content. Thus, it is the recommended strategy of aeration among the four investigated for food maize and rough rice in the warm and humid coastal region of Texas.

Table 9. Average grain temperatures and moisture contents, and ranges for the regular and chilled aeration of maize in southern Brazil between March–September 1989–1992 (from Moreira and Maier 1993).

Strategy	Year	Temperature (°C)		Moisture (% w.b.)	
Continuous	1989	20.5	26.8–14.2	13.6	14.0–13.3
Less than 75% r.h.		22.3	27.5–16.6	13.3	14.1–12.7
Chilled[a]		17.1	25.0–14.8	13.7	14.0–13.6
Continuous	1990	20.6	27.9–16.1	13.7	14.1–13.5
Less than 75% r.h.		22.1	28.5–14.6	13.6	14.1–13.0
Chilled[a]		17.4	25.0–14.8	13.7	14.0–13.6
Continuous	1991	20.6	27.8–16.1	13.6	14.1–13.0
Less than 75% r.h.		22.1	26.9–16.1	13.3	14.1–12.2
Chilled[a]		17.3	25.0–14.8	13.7	14.0–13.6
Continuous	1992	21.1	26.3–14.4	14.1	14.2–13.8
Less than 75% r.h.		23.3	26.9–18.9	13.7	14.1–13.1
Chilled[a]		17.3	25.0–14.8	13.7	14.0–13.6

[a] It was assumed that the chilled grain was maintained at these average conditions with intermittent rechilling during the 4-month storage period.

Table 10. Operating hour and power consumption of fans and chiller unit for the regular and chilled aeration of maize in southern Brazil between March–September 1989–1992 (Moreira and Maier 1993).

	Continuous		When r.h. < 75%		Chilling[a]	
Year	Operating	Power	Operating	Power	Operating	Power
1989	2778	3500	1986	2502	360	4508
1990	1659	2090	1377	1735	372	4656
1991	4440	5594	2376	2994	345	4331
1992	3066	3863	1392	1754	366	4539
Avg.	2986	3762	1783	2246	361	4509

[a] Only includes energy consumed for initial cool down of maize.

Table 11. Average grain temperatures and moisture contents, and ranges, for the regular and chilled aeration of rice in Texas between August–October 1988 (Maier et al. 1992).

Strategy	Temperature (°C)		Moisture (%, w.b.)	
	Average	Range	Average	Range
Continuous	27.8	21.1–37.8	12.8	12.2–13.2
Less than 75% r.h.	29.3	24.0–37.8	12.1	11.6–13.0
10 a.m.–4 pm.	29.3	24.7–37.8	12.3	11.9–13.0
10 pm.–4 a.m.	26.9	21.0–37.8	12.9	12.7–13.3
chilled[a]	15.2	15.0–15.5	12.9	12.8–12.9

[a] After 124 hours of chilling.

Table 12. Average grain temperatures and moisture contents, and ranges, for the regular and chilled aeration of maize in Texas between August–October 1988 (from Maier et al. 1992).

Strategy	Temperature (°C)		Moisture (% w.b.)	
	Average	Range	Average	Range
Continuous	28.3	21.9–37.8	13.0	12.4–13.6
Less than 75% r.h.	29.6	24.5–37.8	12.3	11.8–13.0
10 a.m.–4 pm.	29.8	25.2–37.8	12.5	12.0–13.0
10 pm.–4 a.m.	27.6	21.8–37.8	13.0	12.8–13.4
Chilled[a]	15.2	15.1–15.5	12.9	12.9–13.0

[a] After 154 hours of chilling.

Aeration from 10 pm. to 4 a.m. resulted in the lowest rice and maize temperatures, i.e., about 21°C in 1988 (Figure 19). However, an excessively large variation in the moisture contents developed in the silos. The bottom rice and maize layers absorb up to 1.5% of moisture over the 3-month storage season. Aeration from 10 a.m. to 4 pm., and under conditions of less than 75% relative humidity, resulted in excessive overdrying of the bottom layers of the rice and maize in the silos, i.e., by as much as 2% moisture.

Chilled aeration. The results for the various ambient aeration strategies contrast sharply with those for chilled aeration with constant air-inlet conditions for rice and maize. The rice in the silo was cooled to below 25°C within 54 hours, and below 15°C within 124 hours (Tables 11 and 12). Due to the evaporative cooling effect, the initial rice moisture content could be as high as 13.8% to achieve a desired market moisture content of 13.0% at the end of the cool-down period. The moisture content of the entire pile was within 0.1%. The final temperature gradient between the bottom and top layers was less than 0.5°C.

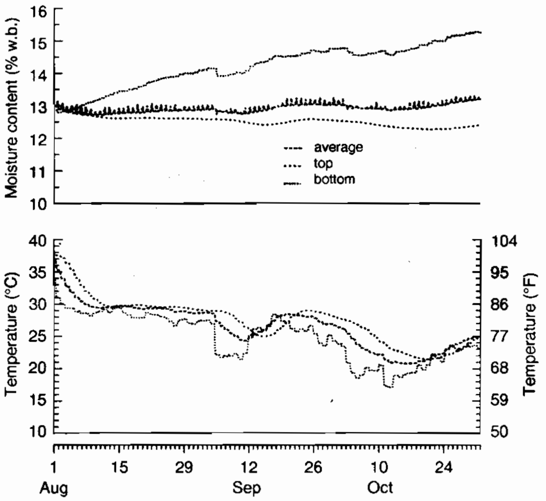

Figure 19. Temperature and moisture content of rice aerated daily from 10 pm. until 4 a.m. under Texas conditions between August and October 1988 (from Maier et al. 1993).

The cool-down of the larger-sized maize silo to below 15°C is completed in 154 hours; the maize temperature dropped below 25°C within 66 hours of chilling. The moisture content of the maize was about 13.0% at the end of the cool-down period. The moisture content differential between the bottom and top layers was less than 0.1%, and the final temperature gradient less than 0.5°C. It is noted that, depending on the capacity of the commercial grain chilling unit, multiple silos can be chilled at the same time when appropriate aeration ducting is used. Most importantly, at 15°C and 12.5–13.0% m.c., the rice and maize can be stored indefinitely in Texas, with a significant reduction in the potential for insect infestation (Baur 1984).

Summary for the United States. Ambient aeration of rough rice and food maize during the summer months (August–October), could not lower the average grain temperature below 28°C in Texas. Of the four conventional aeration strategies investigated, continuous aeration performed best since it resulted in the smallest moisture losses and gradients in the commercial rice and maize silos. Time-clock and upper-limit relative humidity control of regular aeration led to the partial overdrying or underdrying of grain in a silo. Chilled aeration with properly-sized equipment was able to lower the rice and maize temperatures in the commercial silos to below 15°C within a 120–160 hour period. Chilled aeration also prevented excessive moisture losses and maintained the moisture content of silo-stored rice and maize uniformly at 13% (w.b.).

References

AIT (Asian Institute of Technology) 1990. Thailand climate data from the weather station at the Rice Research Center, Klongloung, Pathumtani Province, Thailand. Bangkok, Thailand, AIT.

Anon. 1992. ASAE Standards. St. Joseph, Michigan, USA, ASAE.

Anon. 1995. FANS—a computer program for selecting crop drying fans and determining airflow. Minneapolis, Minnesota, USA, University of Minnesota Cooperative Extension Service.

Bakker-Arkema, F.W. 1984. Selected topics of crop processing and storage. Journal of Agricultural Engineering Research, 30, 1–22.

Baur, F.J., ed. 1984. Insect management for food storage and processing. St. Paul, Minnesota, USA, AACC.

Brooker, D.B., Bakker-Arkema, F.W., C.W. Hall, C.W. 1992. Drying and storage of cereal grains and oilseeds. New York, USA, Van Nostrand Reinhold.

Burrell, N.J. 1982. Refrigeration. In: Christensen, C.M., ed., Storage of cereal grains and their products. St. Paul, Minnesota, USA, AACC.

Hagstrum, D.W. and Flinn, P.W. 1990. Simulations comparing insect species differences in response to wheat storage conditions and management practices. Journal of Economic Entomology, 83, 2469–2475.

Maier, D.E. 1992. The chilled aeration and storage of cereal grains. Ph.D. Dissertation, Michigan State University, E. Lansing, Michigan, USA.

Maier, D.E. 1994. Chilled aeration and storage of U.S. crops—a review. In: Highley, E., Wright, E.J., Banks, H.J., and Champ, B.R., ed., Stored product protection. Proceedings of the 6th International Working Conference on Stored-product Protection, 17–23 April 1994, Canberra, Australia. Wallingford, Oxon, U.K., CAB International, 300–311.

Maier, D.E., Adams, W.H., Throne, J.E., and Mason, L.J. 1996. Temperature management of the maize weevil (Coleoptera:Curculionidae) in three locations in the United States. Journal of Stored Products Research (in press).

Maier, D.E., Bakker-Arkema, F.W., and Ilangantileke, S.G. 1993. Ambient and chilled paddy aeration under Thai conditions. Agricultural Engineering Journal, 2(1&2), 15–33.

Maier, D.E., L.J. Mason, L.J., and Woloshuk, C.P. 1994. Maximize grain quality & profits using S.L.A.M. ID-207. W. Lafayette, Indiana, USA, Purdue University Cooperative Extension Service.

Maier, D.E., Moreira, R.G., and Bakker-Arkema, F.W. 1992. Comparison of conventional and chilled aeration of grains under Texas conditions. Applied Engineering in Agriculture, 8(5), 661–667.

Michl, J. 1983. Development of a method for the calculations of the drying time required for a number of grain-aeration systems with the aid of a microcomputer (In German). M.S. Thesis, University of Hohenheim, Stuttgart, Germany.

Moreira, R.G. and Bakker-Arkema, F.W. 1992. Grain dryer controls: a review. Cereal Chemistry, 69(4), 390–396.

Moreira, R.G. and Maier, D.E. 1993. Aeration of grains using natural and chilled air. Proceedings of the 1993 FAO Technical Meeting in Grain Drying and Storage. 19–23 October 1993, Canela, Porto Alegre, Brazil.

NOAA (National Oceanic and Atmospheric Administration) 1988, 1989, 1990. NOAA Climatological Data. Washington, D.C., U.S. Department of Commerce.

Nour, D.M., Chek, T.N., and Abdullah, R. 1988. Bulk storage paddy aeration in concrete silos: a Malaysian experience. In: Champ, B.R. and Highley, E., ed., Bulk handling and storage of grain in the humid tropics. Canberra, ACIAR Proceedings No. 22, 182–188.

Noyes, R.T., Weinzierl, R., Cuperus, G.W., and Maier, D.E. 1995. Stored grain management techniques. In: Krischik, V., Cuperus, G.W., and D. Galliart, D., ed., Stored product management. E-912. Stillwater, Oklahoma, USA, Oklahoma State University Cooperative Extension Service, 71–84.

Rulon, R.A. 1996. In-bin conditioning and pest management of popcorn using chilled aeration. M.S. Thesis, Purdue University, West Lafayette, Indiana, USA.

Thompson, T.L. 1972. Temporary storage of high-moisture shelled corn using continuous aeration. Transactions of the Americal Society of Agricultural Engineers, 15, 333–337.

Wilson, S.G. 1990. User manual. AERATE: a PC program for predicting aeration system performance. Black Mountain, ACT, Australia, CSIRO Division of Entomology, Stored Grain Research Laboratory Publication.

Wilson, S.G. and Desmarchelier, J.M. 1994. Aeration according to seed wet-bulb temperature. Journal of Stored Products Research, 30(1), 45–60.

Conference Summary and Recommendations

Grain that is not dried after harvest is rapidly spoiled by moulds, heating, and insects. The longer drying is delayed, the greater will be the loss of food for humans and feed for animals. Eventually, the whole crop may be destroyed.

Grain drying is thus an important topic for all agricultural countries, and is a special problem in countries such as Thailand where at least one harvest occurs during the wet season. To satisfy the food needs of an ever-growing world population, not only must production of staple grains such as rice, maize, and wheat be increased, but also the losses that occur after harvest must be reduced.

This international conference dedicated to global sharing of knowledge on grain drying was hosted at the Food and Agriculture Organization (FAO) of the United Nations Regional Office for Asia and the Pacific in Bangkok. The conference was officially opened by Mr A.Z.M. Obaidullah Khan, Assistant Director General and FAO Regional Representative for Asia and the Pacific.

The conference, funded by the Australian Centre for International Agricultural Research (ACIAR) and FAO, and organised by the ASEAN Food Handling Bureau (AFHB), was attended by over one hundred engineers, biologists, economists, and other specialists from more than twenty countries around the world. It was organised under the banner of the Group for Assistance on Systems relating to Grain After-harvest (GASGA), an international technical advice group of which FAO is a member. The conference provided an opportunity for grain drying, handling, and storage specialists to come together and share their expertise and experience.

The problems of grain drying are technical, economic, social, and sometimes political. The technical solution to the problem of grain drying in the wet season when sun drying is often not possible is to introduce mechanical dryers—machines that burn oil or other fuels to produce heat for drying. However, those needing the dryers are often poor, small farmers who cannot afford to buy them or to pay a fee for their use. Thus, many governments and international agencies have been exploring means of overcoming this problem and extending the use of grain dryers in the farming sector.

Presentations made at this conference highlighted that much progress has been made in grain drying in the Asian region over the past ten years. The results of research have led to the design and construction of efficient dryers that match the scale of operations of farmer groups and co-operatives. Larger traders servicing export markets are adopting a two-stage drying strategy developed by collaborating teams in Australia, the Philippines, Thailand and, more recently, Vietnam, in research sponsored by ACIAR.

A breakthrough in Thailand over the past few years has been the development and commercialisation by King Mongkut's Institute of Technology Thonburi and the Rice Engineering Supply Co. Ltd of a fluidised-bed machine for rapid drying of wet paddy and maize. Units of these machines have been sold to grain traders in Thailand and many more are on order. There is also interest from other countries, and two units have already been sold in Indonesia.

In the Philippines, mobile flash dryers developed by researchers are being distributed to farmer co-operatives throughout the country as part of a government program to improve grain production.

Another aspect of grain drying that has received much attention is the use of cheaper, alternative fuels for grain drying machines. Research on the combustion of paddy husks, a material once treated as waste, has led to the development of efficient rice-husk burners producing heat for grain drying. Vietnamese researchers have built their own fluidised-bed dryers, based on the Thai design mentioned above, but using rice husks as the energy source for drying. The need to minimise emissions of greenhouse gases is also being addressed in the designs of new grain drying strategies.

International trade in staple food and feed grains—an area of considerable interest to Thailand, the world's largest rice exporter—has been a driving force for improvements in grain drying. International markets demand grain of the highest quality and appropriate drying is recognised as the crucial first step in preserving grain quality after harvest. A problem for designers of grain dryers has been lack of information on quality standards in different countries in the Asian region. Participants in the conference in Bangkok committed themselves to gathering this information for eventual publication. Also, the attention of participants was drawn to the existence of a draft international standard (ISO/DIS 11520–1) covering 'Agricultural grain dryers—determination of drying performance', published by the International Organization for Standardization. A outline of the content of the draft standard appears after this conference summary. Adoption of the testing protocols promoted by the standard could lead to further improvements in the performance of grain drying equipment.

In closing the meeting, conference chairman Dr Bruce Champ, noted that presentations and discussions during the week had highlighted that there was a general recognition and acceptance in the grain industries of Asia of the need for appropriate drying technology to maintain quality and enhance international trade in grains. In the commercial sector at least, the adoption of drying technology was self-sustaining. However, the challenge remains to bring the benefits of new knowledge in grain drying to greater numbers of the small farmers who are the main grain producers of Asia. The conference recommended that research and extension agencies continue to explore means for enhancing levels of adoption of appropriately scaled and cost effective drying systems by co-operatives and farmer groups, and that governments foster grain standards and grading systems that provide financial incentives to farmers to dry their crop.

International Standards for Agricultural Grain Dryers

The International Organization for Standardization has drafted standards for the determination of drying performance of agricultural grain dryers (ISO/DIS 11520-1). Part 1 of this protocol concerned the general issues involved and the areas covered are outlined in the following summary:

This Standard describes methods for evaluating the drying performance of continuous flow and batch grain dryers. The methods specified are for determining the evaporation rate which the machines concerned are able to achieve under the steady state conditions prevailing during the tests. Methods for correcting observed performance to other input and standard ambient conditions are described.

For continuous flow dryers the basis of the standard is to monitor the dryer during a relatively short period with steady state conditions fully established, rather than over a long period with fluctuating conditions. For batch dryers the basis is to monitor the dryer during a full cycle of operation. This approach allows the dryer to achieve an evaporation which is maximum for the test conditions, allows comparison of results between different dryers and enables the results to be corrected to specified input and standard ambient conditions.

Normative references are given to other International Standards which through reference in this text constitute provisions of this International Standard.

The text is prefaced by a series of *definitions* of drying terms and parameters by a list of the *symbols and subscripts* that identify the various quantities being measured and the *units* of measurement involved.

The performance required of test *instrumentation* is specified. This covers sensors for air properties—air temperature, air humidity, static pressure and barometric pressure; for grain properties—moisture content and mass; and for energy consumption either from electricity or fuel combusted in situ.

The *preparations* necessary for testing are outlined commencing with recognition of the nominal dryer specifications, requisition of appropriate amounts of grain, and installation of the sensors for measuring the temperature of the drying air, the cooling air, the air inlet to the heater and the exhaust air, the humidity of the inlet air for drying and cooling, the grain temperature, and air static pressure across the grain bed(s) and fan(s).

Procedures for *grain sampling* before and during tests are detailed specifying sample numbers and size, choice of sampling points, frequency of sampling for both continuous flow and batch dryers, properties to be measured and methods for their measurement, the actual conduct of sample analyses whether for temperature, moisture content, or germination, and finally for determination of grain mass and any loss in the exhaust airstream.

The sequences to be followed *during testing* are given for continuous-flow and batch dryers incorporating routines, during start up, the stabilisation period to steady state operation for continuous-flow dryers, and the test period itself.

Finally, methodology for *calculation of results* is provided. For continuous-flow dryers this involves estimation of the mass flow of the grain, its residence time in the dryer and the input moisture content in addition to the performance data common to both continuous-flow and batch dryers—evaporation rate, electrical energy consumption, thermal energy consumption from either direct or indirect heating, and thus specific thermal energy consumption and specific total energy consumption. Serial measurements are allowed for in calculation of means and their deviations.

The results are presented in a *test report* which includes a specification of the dryer on which the test is made, a description of the installation, specification of the fuel used and the input grain, and a table of results which summarises the performance of the machine (detailed in Annex E) and includes additionally measured data, graphs and other calculated data.

A series of annexes provide additional information:

ANNEX A (Normative) *Correction to standard conditions* specifically changes in air density with barometric pressure and temperature; and power, energy and fuel consumption from both electrical and direct and indirect thermal sources.

ANNEX B (Informative) *Estimation of uncertainty of derived measures of performance* by calculation of means, standard deviations, and standard errors of the means of serial measurements.

ANNEX C (Informative) *Checklist* in preparation for dryer testing covering on-site facilities, the dryer specification and capacity, measurement of fuel consumption, grain quantity and quality, sensing and measuring systems, and grain sampling.

ANNEX D (Informative) *Airflow measurement and calculations* by both direct and indirect methods, including derivation of formulae for apportioning air volume flow between drying and cooling beds, effect of standard inlets cones on airflow and estimation of humidity of exhaust air.

ANNEX E (Informative) Example format for test reports for both continuous-flow and batch dryers.

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