Research on the Estimation Model of Soil Moisture Content Based on the Characteristics of Thermal Infrared Data

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Abstract With the portable Fourier Transform Infrared Spectroscopy (FTIR), the reflectance spectra of soil samples with different moisture content are measured in laboratory for expounding the characteristic of radiation in the thermal infrared part of the spectrum with different soil moisture content. A model of estimating the moisture content in soil is attempted to make based on Moisture Diagnostic Index (MDI). In general, the spectral characteristic of soil emissivity in laboratory includes the following aspects. Firstly, in the region of 8.0 -9.5 μm, along with the increase of soil moisture content, the emissivity of soil increases to varying degrees. The spectral curves are parallel relatively and have a tendency to become horizontal and the absorbed characteristic of reststrahlen is also weakened relatively with the increase of soil moisture in this region. Secondly, in the region of 11.0 -14.0 μm, the emissivity of soil has a tendency of increasing. There is an absorption value near about 12.7 μm. As the soil moisture content increases, the depth of absorption also increases. This phenomenon may be caused by soil moisture absorption. Methods as derivative, difference and standardized ratio transformation may weaken the background noise effectively to the spectrum data. Especially using the ratio of the emissivity to the average of 8 -14 μm may obviously enhance the correlation between soil moisture and soil emissivity. According to the result of correlation analysis, the 8.237 μm is regarded as the best detecting band for soil moisture content. Moreover, based on the Moisture Diagnostic Index (MDI) in the 8.194 -8.279 μm, the logarithmic model of estimating soil moisture is made.

Key words Thermal infrared remote sensing, Emissivity, Soil moisture content, Moisture Diagnostic Index (MDI)

Soil moisture content is an important parameter in hydrology, meteorology and agricultural scientific field, while regional soil moisture content monitoring is an important part of agricultural farmland resources management and drought monitoring and an indispensable parameter in the ground process study, which plays an essential role in improve regional and global climate mode and report result[1]. The regular soil moisture monitor is based on point measurement with a long cycle and high cost, and is not remotely meet the demand of monitoring soil moisture fast and efficient. The development of remote sensing technology makes it possible to monitor the regional soil moisture content at any time. Therefore, it is practical to further study the method to monitor soil moisture content.

Since the 1960s, scientists in many countries has managed to study soil moisture content based on thermal infrared remote sensing[1-12]. About twenty years later, Chinese scientists start to practise such technology based on the application of foreign model[11-20]. Scientists in China and abroad conducted relevant mostly studies on the thermal infrared remote sensing of soil moisture content[21-23], instead of studying the spectrum of thermal infrared emission rate of soil and the characteristics of spectrum. The measurement of emission rate spectrum of soil moisture content is subjected to external factors such as wind speed and temperature, which influences the dependability and adaptability of retrieval model. In order to explore the spectrum features of thermal infrared emission rate of soil moisture, the reflectance spectra of soil samples with different moisture contents are measured in laboratory for expounding the characteristic of radiation in the thermal infrared part of the spectrum with different soil moisture content. A model of estimating the moisture content in soil is attempted to make based on Moisture Diagnostic Index (MDI).

1 Materials and methods

1.1 Preparation of soil samples The study area is in Kunshan City in Jiangsu Province and the soil is mainly paddy soil. The soil sample is collected based on layers. The depth of sample ranges from 0 cm to 25 cm and samples are stored in a plastic pot 15 cm long and 20 cm high. Every soil sample is added with water and then is blown to dry.

Collection of data. The spectrum data of emission rate of soil sample based on the portable Fourier Transform Infrared Spectroscopy (FTIR) from American A& P Company. The equipment response spectrum is between 2 and 16 μm and the spectrum resolution rate is 4 cm^{-1}. The noise equivalent temperature difference is around 0.01 ℃ and the precision of emission rate is larger than 0.02(8 -14 μm) but lower than 0.04 (3 -5 μm). In order to avoid low temperature in soil sample, the radiation of the lower atmosphere is drowned by the radiation in the soil sample. The soil sample is heated to 30 ℃ in the thermostatic blow dry box, which is higher than the surrounding environment. Then the spectrum of emission rate of soil sample is measured. The formula of the automatic calculation of emission rate was as follow:

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$$\varepsilon_S(\lambda) = \frac{M_S(\lambda) - M_{DWR}(\lambda)}{M(\lambda, T_S) - M_{DWR}(\lambda)}$$

In the formula, $M_S(\lambda)$ represents the emission rate of radiation in the sample; $M_{DWR}(\lambda)$ represents the decreasing radiation of the plate; $M(\lambda, T_S)$ is the function of the black object at the temperature of T_S. The temperature of sample T_S is calculated through radiation model[24].

The German TRIME Data Pilot (TDR) soil moisture monitor is used to monitor the soil moisture content. This machine is based on the dielectrometric method and the soil moisture content is measured. During the process of drying the soil sample, the thermal infrared emission rate spectrum of soil sample is measured every 48 hours and meanwhile the soil moisture content is monitored.

1.3 Pre-treatment of data The measured wave band of portable Fourier Transform Infrared Spectroscopy (102F) is between 2 and 16 μm, including two atmospheric windows (3 – 5 μm and 8 – 14μm). On the one hand, the 3 – 5 μm atmospheric window is not as clean as the 8 – 14 μm atmospheric window, which would be influenced by CO_2 (4.0 – 4.4 μm), CH_4 (3.0 – 3.5 μm) and water vapor (4.4 – 5.0 μm). On the other hand, if the temperature in the field reached 30 ℃, the radiation peak was around 10 μm and it weakened as the wave band shortened. Therefore, the 3 – 5 μm atmospheric window is not applicable[23]. Therefore, the wave band of emission rate was between 8 and 14 μm. In order to eliminate the noise of spectrum radiator, the emission data is treated with five-point moving average smooth, which is helpful to analyze the radiation characteristics of emission rate in soil moisture content.

2 Result and analysis

2.1 Spectrum characteristics and analyses The characteristics of soil thermal infrared emission rate spectrum is influenced by soil moisture content, soil type, texture, roughness, organic matter and minerals, *etc*.[21]. Fig. 1 is the result of thermal infrared emission rate spectrum of four soil samples with different moisture content and one parched soil sample. Fig. 1 suggested that from 8.0 to 9.5 μm, the soil moisture content increased and the emission rate of soil thermal infrared emission rate accumulated. The spectrum curve is relatively smooth. Water has high assimilation coefficient and emission rate within the wave length range. Therefore, as the soil moisture accumulated, the soil emission rate increased, which was consistent with the study result of Salisbury *etc*.[22, 24]. During the wave length of 9.5 and 11.0 μm, the soil thermal infrared emission rate increased, but it didn't show any distinct corresponding relation to the changes of moisture content in soil. From 11.0 to 14.0 μm, with the addition of soil moisture content, the soil infrared emission rate reduced at different degrees. Besides, there was an assimilation valley around 12.7 μm and the assimilation intensified with the soil moisture addition. The assimilation valley might be produced by the absorption of soil moisture. Xiao Qin *et al*. believed that from 11 to 13 μm, along with the increase of soil moisture, the emission rate kept unchanged[24]. The reason of such difference may be the low soil moisture. The different soil types, texture, roughness, organic content and minerals result in different assimilation depth and location of absorption valley.

The spectrum curve of soil thermal infrared emission rate between 8.0 and 9.5 μm had distinct reststrahlen characteristics, namely unsymmetrical valley absorption characteristic, which is resulted from the strong absorption of SiO_2 between 8.0 and 9.5 μm[24]. Different types of soil would lead to reststrahlen absorption valley with different locations and depths. The addition of soil moisture made the spectrum curve of reflection rate (8.0 – 9.5 μm) flat and the reststrahlen absorption weakened correspondingly.

2.2 Foundation and verification of model In the process of high spectrum reflection rate data, the calculation of original high spectrum data can weaken the background information, soil roughness, sensor, and light location, *etc*.[25]. So He Junliang *et al*. proposed organic matter diagnostic index (MDI)[26]. Hence, the study introduced high spectrum data processing method and proposed moisture diagnostic index. Standardization ratio applied radiation rate value. The most sensitive wave band analysis of different moisture diagnostic index was shown in Table 1.

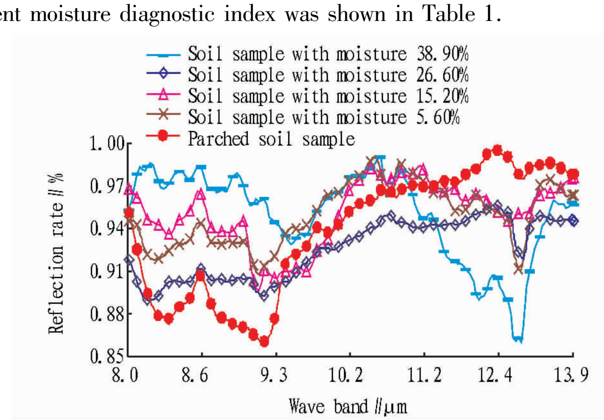

Fig. 1 Thermal infrared reflection rate spectrum curves of soil with different moisture contents

As shown in Table 1, in the moisture diagnosis index, the reflection rate ε and soil moisture content had positive relevance at the waveband of 8.194 μm and negative relevance at the waveband of 12.317 μm. Through standardized ratio treatment, such relevance can improve. Fig. 2 indicated that the changes of relevant coefficient of soil moisture content and soil moisture diagnostic index with the addition of wavelength. The soil moisture diagnosis index had distinct relevance to soil moisture content at the waveband of 8.1 – 9.1, 11.3 – 12.7, and 12.9 – 13.4 μm.

According to the comparative analysis of R^2 in Table 2, the fitting of quadratic function of moisture diagnosis index between 8.194 and 8.279 μm and soil moisture content was the best. Considering the F value, the logarithm function model was the best. The study chose logarithm function in the end, which can explain the moisture variance of 76.6%. Based on the variation analysis of the model, the maximum value of absolute error was 11.0%

and the minimum value was 0.5%, while the average relative error was 14.3%. According to the prediction evaluation in Fig. 3, the average relative error was 26.2% and the predicted precision was 73.8%. Hence, there was logarithm relation between soil moisture content and moisture diagnosis index.

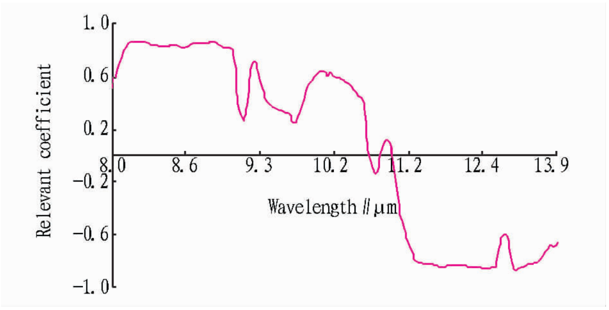

Fig. 2 Relevance of soil moisture diagnosis index and soil moisture content

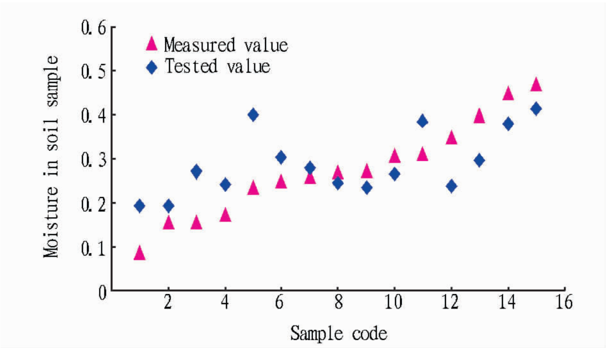

Fig. 3 Measured value and predicted value of moisture in soil sample

Table 1 The analytical result of most sensitive waveband of diagnostic index with different moistures

Moisture diagnose index	Maximum positive relevance wave band // μm	Relevant coefficient	Credibility test	Maximum negative relevant waveband // μm	Differential coefficient	Credibility test
ε	8.194	0.852	* *	12.317	-0.715	* *
ε Differential coefficient	8.683	0.598	* *	11.045	-0.628	* *
ε Difference	8.706	0.639	* *	11.083	-0.672	* *
$\varepsilon/\bar{\varepsilon}$	8.237	0.871	* *	12.964	-0.860	* *

Note: * * passed the relevance test at a credibility level of $a = 0.001$.

Table 2 Fitting model of soil moisture content and moisture diagnosis index

Moisture diagnosis index x	Model types	Fitting model equation	R^2	F value
$\varepsilon/\bar{\varepsilon}$, 8.194 - 8.279 μm	Linear	$y = 2.929\ x - 2.654$	0.764	155.593
	Logarithm function	$y = 2.952\ \ln(x) + 0.276$	0.766	156.881
	quadratic function	$y = 21.652\ x^2 - 9.292x) - 12.076$	0.769	78.441
	Power function	$y = 0.257\ x)^{11.396}$	0.643	86.325
	Exponential function	$y = 3.21E-006\ e^{11.287\ x}$	0.639	84.957
$\varepsilon/\bar{\varepsilon}$, 12.860 - 13.070 μm	Linear	$y = -3.018x + 3.249$	0.725	126.653
	Logarithm function	$y = -2.935\ \ln(x) + 0.231$	0.722	124.573
	quadratic function	$y = 29.274x^2 - 16.552x + 12.487$	0.742	67.494
	Power function	$y = 0.216x^{-11.164}$	0.588	68.511
	Exponential function	$y = 3\ 301.66\ e^{-11.498\ x}$	0.593	69.878

3 Discussion and conclusion

3.1 Discussion Watson *et al*. firstly proposed the simple mode of using daily difference of surface temperature to deduct thermal constant and applied the model successfully[2]. Price suggested ATI concept and used thermal infrared radiation temperature to calculate moisture in soil[3]. England put forward *RTI* notion and throught *RTI* had better sensitivity to moisture in soil than *ATI*[5]. The moisture in soil was applied to naked soil and low vegetation coverage soil. Under the condition of entire vegetation coverage, Idso and Jackson came up with *CWSI* concept to monitor the efficient moisture in soil[6-7]. Moran *et al*. popularized the index into partial vegetation coverage condition and proposed WDI[8]. Nemani *et al*. studied the sensitivity to changes of *Ts/NDVI*[9]. Sandholt *et al*. used simplified *Ts/NDVI* space to surveillance moisture in farmland[10]. Liu Xingwen *et al*. raised the idea of using thermal constant to monitor the surface soil humidity[11]. Zhang Renhua *et al*. brought forward the thermal constant mode the considered surface thermal constant and potential heat flux[12]. Xiao Qianguang *et al*. introduced the notion of maximum information layer of remote sensing soil moisture based on introduction equation and found comprehensive soil moisture statistic model[13]. Sui Hongzhi *et al*. used NOAA/AVHRR data to calculate thermal constant and get the singular linear relation of thermal constant and soil moisture[14]. Yu Tao improved the way to calculate the soil surface thermal constant and realized the calculation of thermal constant based on AVHRR image[15]. In order to improve the precision of soil moisture, Chen Huailiang *et al*. analyzed different types of geographic samples and soil texture under the support of GIS, eliminated the influence of soil texture and improved surveillance precision[16-17]. Zhang Renhua *et al*. established surface evaporation remote sensing information based on micro thermal constant and eliminated the disturbance of distinct heat and potential heat transportation[18]. Zhang Kehui *et al.* formulated different kinds of models like NOAA/AVHRR[19]. Yang Baogang *et al.* considered the vegetation index and modified the thermal constant value[20]. The thermal constant method and the temperature vegetation index method were based on the relation of temperature and soil moisture. There are few studies on the relation of emission rate and soil moisture, another important parameter of thermal radiation. Salisbury *et al.* discussed the relation among thermal infrared spectrum characteristics, organic content in soil, parameter of soil particles and moisture in soil. They believed the linear relation of the ratio of the tenth waveband and fourteenth waveband and moisture in soil[21]. Xiao Qin *et al.* analyzed the characteristics of thermal infrared emission rate in the field and believed that the emission rate between 8.0 and 9.5 μm with the addition of moisture in soil. The thermal infrared spectrum data reflected the moisture in soil[23]. Through study of soil emission rate and moisture, Xue Hui believed that the soil emission rate at the wavelength of 9.076 and 9.368 μm was sensitive to moisture[23].

The study proved that at the waveband from 8.0 to 9.5 μm, with the addition of moisture in soil, the emission rate of thermal infrared emission rate increased, which was consistent with previous study. The addition of moisture in soil led to flat spectrum of emission rate between 8.0 and 9.5 μm and weakened reststrahlen assimilation characteristics. Meanwhile, with the addition of moisture in soil, the thermal infrared emission rate dwindled to different degrees. There was an assimilation valley around 12.7 μm and the depth of assimilation increased with the addition of moisture in soil. The moisture in the soil and the emission rate was the most sensitive at the wavelength of 8.194 μm. The standardization of the emission rate can weaken the influence of background information, the roughness of soil, the sensor and geometric location, and can improve the precision. The study used the mean value of output to replace the emission rate of sensitive wave length, and improved the stability of model. Besides, the spectrum characteristics of thermal infrared emission rate of other physical factors of soil need further experiment to determine the practical significance of the moisture evaluation model, which lays foundation for the deduction of moisture content in soil through thermal infrared reflection rate.

3.2 Conclusion Based on the indoor experiment, the spectral characteristics of soil emissivity in laboratory were expounded. Firstly, in the region of 8.0 – 9.5 μm, along with the increase of soil moisture content, the emissivity of soil increases to varying degrees. The spectral curves are parallel relatively and have a tendency to become horizontal and the absorbed characteristic of reststrahlen is also weakened relatively with the increase of soil moisture in this region. Secondly, in the region of 11.0 – 14.0 μm, the emissivity of soil has a tendency of increasing. There is an absorption value near about 12.7 μm. As the soil moisture content increases, the depth of absorption also increases.

Through the calculation, it was deduced that the sensitive wave length to diagnose the moisture in soil was 8.237 μm and the sensitivity ranged from 8.194 to 8.279 μm. The model was $y = 2.952\ \text{In}(x) + 0.276$. The study provided scientific basis for the configuration of wave length of detector and provided new path for the fast determination of moisture in soil.

References

[1] GAO F, WANG JM, SUN CQ. advances in study on microwave remote sensing of soil moisture[J]. Remote Sensing Technology and Application, 2001, 16(2): 97 – 102. (in Chinese).

[2] WASTON K, ROWEN LC, OFFIELD TW. Application of thermal modeling in the geologic interpretation of IR images[J]. Remote Sensing of Environment, 1971, 3: 2017 – 2041.

[3] PRICE JC. The potential of remotely sensed thermal infrared data to infer-surface soil moisture and evaporation [J]. Water Resources Research, 1980, 16(4): 787 – 795.

[4] MYERS VI, HEILMAN HD. Thermal IR for soil temperature studies[J]. Photogrammetric Engineering and Remote Sensing, 1969, 35: 1024 – 1032.

[5] ENGLAND AW, GALANTOWICZ JF, SCHRETTER MS. The radiobrightness thermal inertia measure of soil moisture[J]. IEEE Trans Geosci Remote Sensing, 1992, 30(1): 132 – 139.

[6] IDSO SB, JACKSON RD, PINTER PJ, *et al.* Normalizing the stress degree-day for environmental variability[J]. Agricultural Meteorology, 1981, 24: 45 – 55.

[7] JACKSON RD, IDSO SB. Canopy temperature as a crop water stress indicator[J]. Water Resource Research, 1981, 17: 1133 – 1138.

[8] MORAN MS, CLARKE TR, INOUE Y, *et al.* Estimating crop water deficit using the relation between surface – air temperature and spectral vegetation index[J]. Remote Sensing of Environment, 1994, 4: 246 – 263.

[9] NEMANI RR, RUNNING SW, PIERCE L. Developing satellite – derived estimates of surface moisture status[J]. Journal of Applied Meteorology, 1993, 32: 548 – 557.

[10] SANDHOLT I, RASMUSSEN K, ANDERSEN J. A simple interpretation of the surface temperature/vegetation index space for assessment of surface moisture status[J]. Remote Sensing of Environment, 2002, 79: 213 – 224.

[11] LIU XW, FENG YJ. Applied thermal inertia for preparation of soil moisture map and detection effect[J]. Journal of Soil, 1987, 24(3): 272 – 280. (in Chinese).

[12] ZHANG RH. Thermal inertia model of soil moisture content and application [J]. Chinese Science Bulletin, 1991, 36(12): 924 – 927. (in Chinese).

[13] XIAO QG, CHEN WY, SHENG YW, *et al.* Monitoring soil moisture by meteorological satellite[J]. Journal of Applied Meteorological Science, 1994, 5(3): 312 – 318. (in Chinese).

[14] SUI HZ, TIAN GL, LI FQ. Double layer model of field evapotranspiration and its application in remote sensing drought monitoring[J]. Journal of Remote Sensing, 1997(3): 220 – 224. (in Chinese).

[15] YU T, TIAN GL. Applictaion of thermal inertia method in monitoring soil moisture[J]. Journal of Remote Sensing, 1997, 1(1): 24 – 31. (in Chinese).

[16] CHEN HL, FENG DY, ZOU CH. Wheat field soil moisture NOAA/AVHRR remote sensing monitoring method[J]. Remote Sensing Technology and Application, 1998, 13(4): 27 – 35. (in Chinese).

[17] LI XZ. Primary discussion on microwave remote sensing monitoring soil moisture[J]. Remote Sensing Technology and Application, 1995, 10(4): 1 – 8. (in Chinese).

[18] ZHANG RH, SUN XM. Ground evaporation remote sensing information model based on differential thermal inertia and vertification in Gansu Shapotou Region[J]. Scientia Sinica D, 2002, 32(12): 1041 – 1050. (in Chinese).

[19] ZHANG KH, LIU FY, LIU JF. Soil water remote sensing monitoring in Hebei Province[J]. Geography and Land, 2002, 18(3): 101 – 104. (in Chinese).

[20] YANG BG, DING YG, LIU JM. An experiment on soil moisture monitoring

using an improved thermal inertia method[J]. Journal of Nanjing Institute of Meteorology, 2004, 27(2): 218 –223. (in Chinese).

[21] SALISBURY JW, D'ARIA DM. Infrared(8 –14 μm) remote sensing of soil particle size[J]. Remote Sensing of Environment, 1992, 42: 157 –165.

[22] XIAO Q, LIU QH, LI XW, *et al*. A field measurement method of spectral emissivity and research on the feature of soil thermal infrared emissivity [J]. Journal of Infrared and Millimeter Waves, 2003, 22(5): 373 –378. (in Chinese).

[23] XUE H. Inversion soil moisture in Huangye Region based on thermal infrared spectrum[D]. Nanjing: Nanjing Normal University, 2006. (in Chinese).

[24] KORB AR, DYBWAD P, WADSWORTH W, *et al*. Portable fourier transform infrared spectroradiometer for field measurements of radiance and emissivity[J]. Applied Optics, 1996, 35(10): 1679 –1692.

[25] LIU WD. Remote sensing extraction of soil information and data mining research[D]. Beijing: CAS, 2002. (in Chinese).

[26] HE JL, JIANG JJ, ZHOU SL, *et al*. The hyperspectral characteristics and retrieval of soil organic matter content[J]. Scientia Agricultura Sinica, 2007, 40(3): 638 –648. (in Chinese).

[27] ZHANG ZL, YU XQ. Monitoring system for field soil water content based on the wireless sensor network[J]. Agricultural Science & Technology, 2012, 13(1): 242 –cover page 3.

[28] JIANG SW, CHEH GF, LIU Y, *et al*. Design and implementation of on –line monitoring system of soil moisture based on 3G network[J]. Journal of Anhui Agricultural Sciences, 2011, 39(25): 15815 –15816, 15819. (in Chinese).

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the development of special database on urban agriculture in our country. Upon completion of the special database, the library will strengthen the promotion and updating maintenance work for the special database to better serve the teaching research and local economic construction.

References

[1] HE JH, ZHOU JP. Research on the construction of characteristic resources integration platform of JALIS[J]. Library Science Research, 2011(10): 50 –54. (in Chinese).

[2] PENG HY. Analysis on the construction of characteristic database in art college's library[J]. Sci-Tech Information Development & Economy, 2011, 21(1): 57 –59. (in Chinese).

[3] ZHANG XL. University library characteristic database construction status and principle[J]. Library, 2011(4): 119 –121. (in Chinese).

[4] WANG BQ, ZHOU C, ZHANG Y, *et al*. Jiangsu university library digital resource construction status and sustainable development mechanism[J]. Library Science Research, 2011(11): 46 –51. (in Chinese).

[5] GUO GK. Exploration on library characteristic database construction under network environment with Liaoning library as example[J]. The Library Journal of Henan, 2011, 21(3): 154 –155. (in Chinese).

[6] CHEN CE. Practice of Jimei Library's featured database construction based on TPI system[J]. Information Research, 2011(1): 79 –81. (in Chinese).

[7] LIU D, ZHANG WD. Characteristic database construction based on metadata[J]. Information Research, 2007(6): 51 –53. (in Chinese).