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Research Article

Attribute Synthetic Evaluation Model for the CBM Recoverability and Its Application

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The coal-bed methane (CBM) recoverability is the basic premise of CBM development practice; in order to effectively evaluate the CBM recoverability, the attribute synthetic evaluation model is established based on the theory and method of attribute mathematics. Firstly, five indexes are chosen to evaluate the recoverability through analyzing the influence factors of CBM, including seam thickness, gas saturation, permeability, reservoir pressure gradient, and hydrogeological conditions. Secondly, the attribute measurement functions of each index are constructed based on the attribute mathematics theory, and the calculation methods of the single index attribute measurement and the synthetic attribute measurement also are provided. Meanwhile, the weight of each index is given with the method of similar number and similar weight; the evaluation results also are determined by the confidence criterion reliability code. At last, according to the application results of the model in some coal target area of Fuxin and Hancheng mine, the evaluation results are basically consistent with the actual situation, which proves that the evaluation model can be used in the CBM recoverability prediction, and an effective method of the CBM recoverability evaluation is also provided.

1. Introduction

The CBM reserves are the most basic material basis and the most critical geological control factor of CBM development. The CBM recoverability is the basic premise of CBM development practice, and it is also the bottleneck technology which constrains the development of China CBM. CBM, as a wealth unconventional resource, plays an important role in the national economic development. China has rich coal-bed methane resources. The total reserves in the shallow depth of 2000 m are about $30 \times 10^1 \sim 35 \times 10^{12}$ m^3 according to some incomplete statistics according to literature [1]. With the development of technology and the reduction of production cost, CBM has realized its industrialized mass production, and it has become an emerging industry. In addition, the research and development of coal-bed methane industries is an important study field to solve the energy crisis, protect the global environment, and promote coal mine safety production, and it is also supported and encouraged by the international (CDM protocol) and the state. There are broad prospects and significance according to literature [2].

There are many factors influencing the CBM recoverability; the traditional predicting or evaluating method has great limitations in the practical application due to the differences of complicated geological conditions in different regions. In order to solve the evaluation of the CBM recoverability, many researchers have conducted a lot of researches, and some advanced mathematical methods are also introduced to the CBM evaluation research work. Wang et al. [3] and Tang et al. [4] established the fuzzy prediction model of CBM recoverability by applying fuzzy mathematics theory. Zhang et al. [5] used the synthetic evaluation method combining multifactor weighed analysis and reservoir numerical simulation to study the CBM recoverability. Wang et al. [6] establish the prediction model of CBM recoverability of Fengcheng mine in the gray system theory through calculating the gray correlation degree of each index.

Attribute mathematics is a new mathematical theory put forward by Mr. Cheng Qiansheng in the 1990s; the theory of attribute synthetic evaluation focuses on discussing and solving the problem of qualitative description measure and order partition class recognition, which provides a theoretical basis

for solving such problems. Cheng [7], Cheng [8], and Wen [9] pointed out that the synthetic evaluation model system can be divided into three subsystems: the single index attribute measure system, the multi-index synthetic attribute measure system, and attribute recognition. The specific method of how to build the single index attribute measure system and the multi-index synthetic attribute measure system and how to implement the ultimate attribute recognition was given.

Taking the qualitative description measure and the order partition class recognition characteristics of CBM recoverability evaluation into account, it can been studied by attribute synthetic evaluation method. Based on analyzing the factors which influence the CBM recoverability, the synthetic evaluation model system was used to evaluate the CBM recoverability in the theory and method of attribute mathematics. At the same time, each evaluation index was objectively weighted in similar number method. Ultimately, the CBM measurement and recognition were realized. At last, according to the application results of the model in some coal target area of Fuxin and Hancheng mine, the evaluation results are basically consistent with the actual situation, which proves that the evaluation model can be used in the CBM recoverability prediction, and an effective method of the CBM recoverability evaluation is also provided.

2. The Construction of Evaluation Index System of CBM Recoverability

The CBM recoverability is the combined result of many factors. According to research results of related literature, five indexes are chosen to evaluate the CBM recoverability, including coal depth, gas saturation, permeability, reservoir pressure gradient, and hydrogeological conditions according to literature [3–6].

2.1. The Seam Thickness. The seam thickness is the place of CBM storage (reservoir), which is the premise of high yield and enrichment of CBM. The seam thickness mainly determines the contained gas in the CBM reservoir, permeability, and so forth. Under normal circumstances, the more the seams that are developed, the more the broad prospects that it has in its exploration. Therefore, seam depth should be in a reasonable range. Experience from abroad and home practice shows that the high yield would be possible if the thickness of a single seam is more than 3 m.

2.2. The Gas Saturation. Less attention has been paid to the gas saturation in the previous CBM exploration and pilot development test, but the exploration of practice and research results in recent years show that the gas saturation of the CBM reservoir is one of the main geologic factors which control the CBM recoverability. The CBM single well gas production rate is relatively low due to the low gas saturation, which restricts the commercial development of CBM in China.

2.3. The Original Seam Permeability. The original seam permeability is one of the most important parameters which can be used to evaluate CBM exploration and development potential of a region, and it is also one of the main geologic factors which control the CBM recoverability. The low original seam permeability is the major cause which leads to the low CBM single well gas production rate. Under the circumstance of same basic geological characteristics, the CBM reservoirs with medium permeability and low metamorphic grade is better than that with the high metamorphic grade. According to the CBM geological characteristics in China, the CBM reservoirs with medium metamorphic grade permeability is generally more than 1 md, and the high metamorphic grade is around 1 md. In this condition, the CBM development can be carried out.

2.4. The Seam Pressure Gradient. The seam pressure gradient or reservoirs pressure saturation is considered one of the parameters which can measure the difficulty of the CBM development. The smaller the reservoir pressure saturation, the more difficult its development. Therefore, the adsorption gas can be stripped and output only when the seam pressure is reduced to the critical desorption pressure. But, to reduce the coal reservoir pressure, higher demands on the pressure reducing measures are needed to be adopted, and it means that the longer time needs to be spent. A large quantity of field observation data show that the reservoir pressure and saturation pressure in China are obviously at a disadvantage compared with conventional oil and gas. They are generally in the undervoltage condition. So it is difficult to achieve the CBM successful development only relying on the original geological pressure. The CBM can be produced only after drainage and pressure reduction. Therefore, it has important theoretical and practical significance to the reasonable prediction of seam reservoir pressure according to literature [6].

2.5. The Hydrogeological Conditions. The hydrogeological conditions have much influence on the CBM occurrence and migration, and they are critical for CBM development. The field development practice and a large number of studies show that the hydrogeological conditions of seam have great influence on the CBM development. The hydrogeologic conditions have its duality, which could control gas or lead to the CBM dissipate, and play a role to save and gather CBM. In particular, when the seam hydrogeological condition is in a confined area and high gas content, CBM can be output easily according to literature [10].

3. The Attribute Synthetic Evaluation System and the Attribute Synthetic Evaluation Model of CBM Recoverability

Assuming X as the evaluation object space, the sample x_i ($i = 1, 2, \ldots, n$) of valuation object space has m indexes I_j ($j = 1, 2, \ldots, m$). The measure value x_{ij} of each index I_j belonging to x_i has K evaluation grades C_k ($k = 1, 2, \ldots, K$). Attribute space $F = \{C_1, C_2, \ldots, C_K\}$, and each status is called an attribute set of attribute space. The attribute synthetic evaluation includes three aspects: the single index attribute measure system, the multi-index synthetic attribute measure system, and attribute recognition.

Table 1: Grade division of single index.

Indexes	Grades				
	C_1	C_2	$\cdots$	C_{K-1}	C_K
I_1	$a_{10}-a_{11}$	$a_{11}-a_{12}$	$\cdots$	$a_{1K-2}-a_{1K-1}$	$>$ or $(<)a_{1K-1}$
I_2	$a_{20}-a_{21}$	$a_{21}-a_{22}$	$\cdots$	$a_{2K-2}-a_{2K-1}$	$>$ or $(<)a_{2K-1}$
$\vdots$			$\vdots$		
I_m	$a_{m0}-a_{m1}$	$a_{m1}-a_{m2}$	$\cdots$	$a_{mK-2}-a_{mK-1}$	$>$ or $(<)a_{mK-1}$

3.1. Single Index Attribute Measure. As to the measured values t_j of single index I_j $(j = 1, 2, \ldots, m)$, the determining method of the attribute measure $\mu_{xjk} = \mu(x_{ij} \in C_k, (1 \le k \le K))$ with the attribute C_k is to establish the attribute measure function. The change of the attribute measure $\mu_{xjk} = \mu(x_{ij} \in C_k, (1 \le k \le K))$ can be represented by the measured values t_j which belong to I_j, so the attribute measure function also can be established by the data form in Table 1.

In Table 1, a_{jk} meets the conditions of $a_{j0} < a_{j1} < \cdots < a_{jK}$ or $a_{j0} > a_{j1} > \cdots > a_{jK}$; let us assume $a_{j0} < a_{j1} < \cdots < a_{jK}$. Consider

$$\begin{aligned} b_{jk} &= \frac{a_{jk-1} + a_{jk}}{2} \quad (k = 1, 2, \ldots, K), \\ d_{jk} &= \min\left\{\left|b_{jk} - a_{jk}\right|, \left|b_{jk+1} - a_{jk}\right|\right\} \\ &\qquad (k = 1, 2, \ldots, K-1). \end{aligned} \tag{1}$$

Let x be the jst index value of x; then, the attribute measure function $\mu_{xjk}(t)$ of single index can be determined by the following formula:

$$\begin{aligned} \mu_{xj1}(t) &= \begin{cases} 1, & t < a_{j1} - d_{j1} \\ \dfrac{a_{j1} - d_{j1} - t}{2d_{j1}}, & a_{j1} - d_{j1} \le t \le a_{j1} + d_{j1} \\ 0 & t > a_{j1} + d_{j1}, \end{cases} \\ \mu_{xjK}(t) &= \begin{cases} 1, & t < a_{jK-1} - d_{jK-1} \\ \dfrac{t - a_{jK-1} + d_{jK-1}}{2d_{jK-1}}, & a_{jK-1} - d_{jK-1} \le t \le a_{jK-1} + d_{jK-1} \\ 0 & t > a_{jK-1} + d_{jK-1}, \end{cases} \\ \mu_{xjk}(t) &= \begin{cases} 0 & t < a_{jk-1} - d_{jk-1} \\ \dfrac{t - a_{jk-1} + d_{jk-1}}{2d_{jk-1}} & a_{jk-1} - d_{jk-1} t \le a_{jk-1} + d_{jk-1} \\ 1 & a_{jk-1} + d_{jk-1} < t < a_{jk} - d_{jk} \\ \dfrac{a_{jk} + d_{jk} - t}{2d_{jk}} & a_{jk} - d_{jk} \le t \le a_{jk} + d_{jk} \\ 0 & t > a_{jk} + d_{jk}. \end{cases} \end{aligned} \tag{2}$$

In the above formulas, $j = 1, 2, \ldots, m$ and $k = 1, 2, \ldots, K-1$.

3.2. Multi-Indexes Synthetic Attribute Measure. Synthetic attribute measure μ_{xk} can be calculated by the following formula:

$$\mu_{xk} = \sum_{j=1}^{m} \omega_j \mu_{xjk} \quad \left(\omega_j \ge 0, \ \sum_{j=1}^{m} \omega_j = 1\right), \tag{3}$$

where ω_j is the weight of the jst index I_j.

In this paper, the weight of each evaluation index is given by the method of using similar number to define similar weight. Firstly, assume that the weights of each index are the same; namely, the weights of each index are $1/m$. In this case, the attribute measure evaluation matrix $(\mu_{xk})_{n\times K}$ can be obtained by formula (4). At the same time, the similarity coefficients and similar weights can be calculated by formulas (5) and (6). Consider

$$\mu_{xk} = \frac{1}{m}\sum_{j=1}^{m} \mu_{xjk}, \tag{4}$$

$$\begin{aligned} r_j &= \frac{1}{n}\sum_{i=1}^{n} \left(\mu_{ij1}, \mu_{ij2}, \ldots, \mu_{ijK}\right) \cdot \left(\mu_{i1}, \mu_{i2}, \ldots, \mu_{iK}\right)^T \\ &= \frac{1}{n}\sum_{i=1}^{n}\sum_{k=1}^{K} \mu_{ijk} \cdot \mu_{ik}, \end{aligned} \tag{5}$$

$$\omega_j = \frac{r_j}{\sum_{j=1}^{m} r_j}. \tag{6}$$

3.3. Attribute Recognition. The purpose of attribute recognition is to judge which evaluation grade x belongs to by synthetic attribute measure μ_{xk}, and it can be realized by confidence criterion.

3.3.1. Confidence Criterion. Assume that the evaluation set is an ordered set of attributes space; λ is the confidence degree $(0.5 < \lambda \le 1)$, generally taken in 0.6~0.7 [7–9]. Consider

When $C_1 > C_2 > \cdots > C_K$,

$$\text{if meets } k_0 = \min\left\{k : \sum_{l=1}^{k} \mu_{xl} \ge \lambda, \ 1 \le k \le K\right\} \tag{7}$$

$$\text{or } k_0 = n - \min\left\{k : \sum_{l=0}^{k} \mu_{xn-l} \ge \lambda, \ 0 \le k \le K-1\right\}. \tag{8}$$

So, consider x belonging to C_{k_0}.

3.4. The Attribute Synthetic Evaluation Model of CBM Recoverability. The CBM recoverability evaluation is a synthetic evaluation system, it can make the recognition and prediction of CBM recoverability real by analyzing the influence factors. In this paper, attribute space F = {the grades of CBM recoverability}; the CBM recoverability can be graded as I, II, III, IV, and V, which rules C_1 = {I} = {recoverability bad}, C_2 = {II} = {recoverability comparatively bad}, C_3 = {III} = {recoverability moderate}, C_4 = {IV} = {recoverability comparatively good}, and C_5 = {V} = {recoverability good}.

Table 2: Recoverability evaluation indexes of CBM and its grades.

Evaluation indexes	Recoverability grades				
	Bad	Comparatively bad	Moderate	Comparatively good	Good
Seam thickness (m)	<4	4~5	5~6	6~8	>8
Gas saturation (m^3/t)	<8	8~10	10~15	15~20	>20
Original seam permeability (10^{-3} μm^2)	<0.3	0.3~0.5	0.5~1	1~5	>5
Reservoir pressure gradient (Mpa/100)	<0.4	0.4~0.6	0.6~0.8	0.8~1.0	>1.0
Hydrogeological conditions	1	2	3	4	5

Table 3: CBM resources mining parameters measured results.

Mine	Seam thickness (m)	Gas saturation (m^3/t)	Original seam permeability	Reservoir pressure gradient (Mpa/100)	Hydrogeological conditions
Liujia mine	8.9	9.0	1.1	0.95	5
Wangyingzi mine	6.6	9.0	0.7	0.88	5
Dongliang mine	5.1	9.6	1.8	1.08	3
Yiyou mine	7.6	9.7	3.5	1.25	3
Qinghemen mine	4.7	9.6	6.0	0.55	2
North of Hangcheng mine	3.1	11.2	0.7	0.42	3
South of Hangcheng mine	4.4	17.2	0.7	0.72	3

Based on the above grade division, firstly, set up the single index measure function of CBM recoverability. Secondly, build the multi-indexes synthetic measure function of CBM recoverability. At last, the attribute synthetic evaluation model CBM recoverability can be obtained by attribute recognition.

4. Engineering Application

The single index attribute measure function can be built by the definition of single index attribute measure function and Table 2.

On the basis of the grade standard of Table 2, the single index attribute measure function can be built according to formula (1). In the case of seam thickness, the attribute measure functions are as follows (other index attribute measure functions can be similarly established, can be limited to space, and differ a list):

$$\mu_{i11}(t) = \begin{cases} 1 & t < 3.5 \\ 4.5 - t & 3.5 \le t \le 4.5 \\ 0 & t > 4.5; \end{cases}$$

$$\mu_{i12}(t) = \begin{cases} 0 & t < 3.5 \\ t - 3.5 & 3.5 \le t \le 4.5 \\ 5.5 - t & 4.5 < t \le 5.5 \\ 0 & t > 5.5; \end{cases}$$

$$\mu_{i13}(t) = \begin{cases} 0 & t < 4.5 \\ t - 4.5 & 4.5 \le t \le 5.5 \\ 6.5 - t & 5.5 < t \le 6.5 \\ 0 & t > 6.5; \end{cases}$$

$$\mu_{i14}(t) = \begin{cases} 0 & t < 5.5 \\ t - 5.5 & 5.5 \le t \le 6.5 \\ 1 & 6.5 < t \le 7.5 \\ 7.5 - t & 7.5 < t \le 8.5 \\ 0 & t > 8.5; \end{cases}$$

$$\mu_{i15}(t) = \begin{cases} 0 & t < 7.5 \\ 7.5 - t & 7.5 \le t \le 8.5 \\ 1 & t > 8.5. \end{cases} \tag{9}$$

The CBM resources and test wells emissions mining data are chosen as evaluation parameters of seven regions which are Liujia mine, Wangyingzi mine, Dongliang mine, Yiyou mine, Qinghemen mine of Fuxin region, and north and south of Hancheng mine of China according to literature (see [3] and [11]). See Table 3.

The single index attribute measure evaluation matrices of each evaluation object can be obtained according to the measured data in Table 3 and the single index attribute measure functions which have been built in this paper.

Table 4: Results of evaluation.

Mine	Synthetic attribute measure					Actual situation	Evaluation results in this paper	Evaluation results of fuzzy synthetic evaluation
	C_1	C_2	C_3	C_4	C_5			
Liujia mine	0	0.1614	0	0.4473	0.3393	V	V	V
Wangyingzi mine	0	0.1614	0.2897	0.4448	0.0520	V	V	V
Dongliang mine	0	0.0906	0.2591	0.2655	0.2182	V	V	V
Yiyou mine	0	0	0.1085	0.4695	0.2651	V	V	V
Qinghemen mine	0	0.2339	0.1543	0.2655	0	III	IV	IV
North of Hangcheng mine	0.2266	0.1975	0.4269	0	0	III	III	IV
South of Hangcheng mine	0	0.2660	0.4847	0.2826	0	II	III	III

In the case of Liujia mine, the single index attribute measure evaluation matrix η_1 can be calculated by substituting the index value into the single index attribute measure function:

$$\eta_1 = \begin{pmatrix} 0 & 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0.75 & 0.25 \\ 0 & 0 & 0 & 0 & 0.5 \end{pmatrix}. \quad (10)$$

The single index attribute measure evaluation matrices of other mines can be similarly established.

Taking into account the status and the importance differences of each index in the evaluation process, the weights of each index need to be determined. Reasonable selection and correct determination of the index weight will directly affect the evaluation process and the evaluation effectiveness. Combining the single attribute measure function and formula (4)–(6) in this paper, the similarity coefficient can be calculated as follows:

$$r_j = \begin{pmatrix} 1.8180 & 1.2945 & 2.1300 & 1.9450 & 0.8350 \end{pmatrix} \quad (11)$$

and the similar weight $\omega_j = (0.2266 \;\; 0.1614 \;\; 0.2655 \;\; 0.2424 \;\; 0.1041)$.

The multi-indexes attribute measure evaluation vector $e = [0 \;\; 0.1614 \;\; 0 \;\; 0.4473 \;\; 0.3393]$ of Liujia mine can be calculated according to the single index evaluation matrix η_1 and formula (3).

Take $\lambda = 0.65$; the attribute synthetic evaluation results can be obtained according to formula (7), formula (8), and attribute recognition. The evaluation results, the actual situation, and the fuzzy synthetic evaluation results are compared, and the comparison results are in Table 4. It can be seen from Table 4 that attribute recognition results are consistent with actual situation and have good consistency with the results of fuzzy synthetic evaluation according to literature [3, 4].

5. Conclusions

(1) In this paper, the CBM recoverability evaluation index system is constructed, and the influence of each index on CBM recoverability is also analyzed.

(2) The attribute synthetic evaluation model and the attribute measurement functions of each index are established based on the theory and method of attribute mathematics. Five indexes are chosen to evaluate the recoverability through analyzing the influence factors of CBM, including seam thickness, gas saturation, permeability, reservoir pressure gradient, and hydrogeological conditions. The similar number method is used to determine the similar weight of each index in the evaluation process, and it overcomes the subjective factors influencing the traditional empowerment method. At last, the CBM recoverability evaluation results are obtained with confidence recognition criteria judgement.

(3) The model is verified through engineering application. At the same time, the evaluation results, the actual situation, and the fuzzy synthetic evaluation results are compared, and the comparison results show that the property evaluation results were basically consistent with the actual situation; it also has good consistency with the results of fuzzy synthetic evaluation; an effective method of the CBM recoverability evaluation is provided.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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References

[1] G. M. Zhai and W. Y. He, "Occurrence features and exploration orientation of coalbed methane gas in China," *Natural Gas Industry*, vol. 30, no. 11, pp. 1–4, 2010.

[2] J. Yun, G. J. Qin, F. Y. Xu, X. Ch. Li, N. N. Zhong, and W. T. Wu, "Development and utilization prospects of unconventional natural gas in China from a low-carbon perspective," *Acta Petrolei Sinica*, vol. 33, no. 3, pp. 526–532, 2012.

[3] Q. X. Wang, W. J. Sun, B. Liang, and H. Y. Li, "Fuzzy mathematics-based assessment of recoverability of coalbed methane in the Fuxin Basin," *Natural Gas Industry*, vol. 28, no. 7, pp. 39–42, 2008.

[4] Sh. H. Tang, W. Yue, Ch. H. Cui, and Y. Cai, "Assessment of coal bedmethane workability through fuzzy mathematics," *Geological Review*, vol. 46, supplement 1, pp. 284–287, 2000.

[5] P. H. Zhang, Q. Zhang, B. Y. Wang, B. Y. Wang, G. F. Li, and Y. Tian, "Integrated methods of CBM recover-ability evaluation: a case study from Panzhuang mine," *Coal Geology & Exploration*, vol. 34, no. 1, pp. 21–25, 2006.

[6] H. M. Wang, Y. M. Zhu, W. Li, J. Sh. Zhang, and Y. Luo, "Two major geological control factors of occurrence characteristics of CBM," *Journal of China Coal society*, vol. 36, no. 7, pp. 1129–1134, 2011.

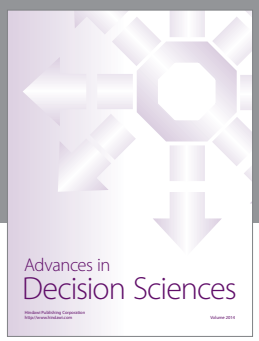
[7] Q. Sh. Cheng, "Attribute mathematics-attribute measure and attribute statistics," *Mathematics in Practice and Theory*, vol. 22, no. 2, pp. 97–107, 1998.

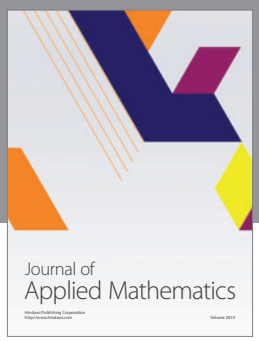
[8] Q. Sh. Cheng, "Attribute recognition theoretical model with application," *Acta Scientiarum Naturalism Universities Pekinensis*, vol. 33, no. 1, pp. 12–20, 1997.

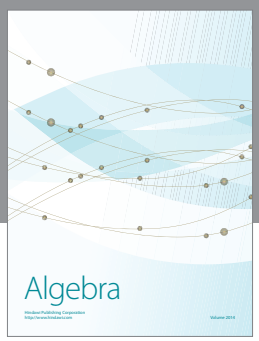
[9] Ch. P. Wen, "Application of attribute synthetic evaluation system in prediction of possibility and classification of outburst," *Engineering Mechanics*, vol. 25, no. 6, pp. 153–158, 2008.

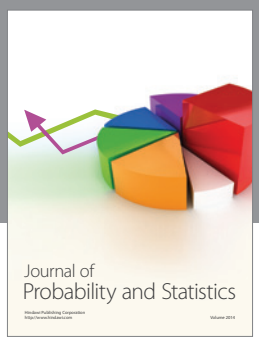
[10] J. P. Ye, Q. Wu, and Z. H. Wang, "Controlled characteristics of hydrogeological conditions on the coal bed methane migration and accumulation," *Meitan Xuebao*, vol. 26, no. 5, pp. 459–462, 2001.

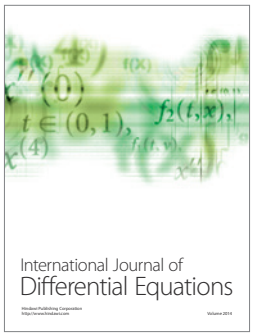
[11] D. M. Ma and Y. Ge, *Investigation and Evaluation of Coal Bed Methane in Hangcheng Mining Area*, China United Coalbed Methane Corporation, Xi'an University of Science and Technology, 2006.











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