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Adaptability Evaluation of Coal-bed Methane Well Completion Methods Based on Multi-objective Decision-making Method

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Abstract: Coalbed methane (CBM) is an important natural gas resource, and appropriate well completion method is very important to increase productivity. At present there are many CBM well completion methods, including fractured vertical well, open-hole cavity well, U-shape well, V-shape well and pinnate horizontal well. Aim at the diversity of CBM well completion methods, multi-objective decision-making method is used to evaluate these completion methods and select the best completion to maximize economic benefit. Firstly implements production prediction and economic evaluation for each completion method, and then chooses multi-objective decision-making method to evaluate five indexes: cumulative gas production, net present value, invest recovery period, internal rate of return and risk factor, thus the most appropriate completion method can be achieved.
With this evaluation method applied to Ordos Basin, numerical simulation results show that pinnate horizontal well predominate in the beginning of exploitation compared with other completion methods, and its advantages dwindle due to limited reservoir supply capacity in the latter period. In spite of its huge investment and high risk, with high productivity, its NPV far overweighs other completion methods, so the pinnate horizontal well is the most suitable completion method. The adaptability evaluation method proposed provides favorable guidance for on-site CBM well completion method design, which has a great significance to improve China's CBM development effect.

Keywords: Well completion methods, Production prediction, Economic evaluation, Multi-objective decision-making method.

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1 Introduction

CBM is not only a kind of important natural gas resource, but also a noticeable catastrophe gas which threatens coal mine safety and may lead to climate warming. Reasonable completion method will yield a triple dividend which plays a key role in improving clean natural gas supplies, preventing gas accident fundamentally and alleviating greenhouse effect.

At present the commonest methods of CBM well completion at home and aboard include fractured vertical well, open hole cavity well, U-shape well, V-shape well and pinnate horizontal well. As we all know, it is very important to select appropriate well completion methods to improve the entire effect [Wang and Zhang (2011)].

Five evaluation indexes: cumulative gas production, net present value, dynamic payback period, internal rate of return and risk factor, combined with multi-objective decision-making method, have been considered in the process of CBM well completion evaluation in this paper. The commonest methods of multi-objective decision-making are fuzzy synthesis decision-making method, gray system theory, TOPSIS method, etc. In principle, the methods above mentioned calculate the deviation between certain well completion method and the ideal optimization scheme or the worst scheme. The more certain well completion scheme deviates from the worst scheme or approximates to the optimum scheme is considered to be the better one. While different solving processes are used in different decision-making methods, so the final evaluation results are different according to different evaluation methods. To achieve accurate evaluation results and reduce defects, this paper proposes the weighted average of normalized membership degrees (correlation degree, close degree) from different multi-objective decision-making methods in order to get the comprehensive membership degree. Higher value indicates better scheme. Different well completion methods are sorted by comprehensive membership degree value, and then the most appropriate well completion method will be optimized in Baode mining area.

2 CBM well production prediction and economic evaluation

This paper aims to select the optimum well completion method of Baode mining area in Eastern margin of Ordos Basin.

2.1 Well completion program design

To optimize the type of well in Baode mining area, 5 well completion schemes are designed separately. Casing programs and well completion parameters are shown respectively in Fig.1 and Table 1. Well pattern area is 5.76 km^2; the reservoir thickness is 10m; the horizontal permeability is 1mD; the vertical permeability is 0.5mD [Jie (2010)]. These five well completion schemes are all based on squared well pattern as their mock objects.

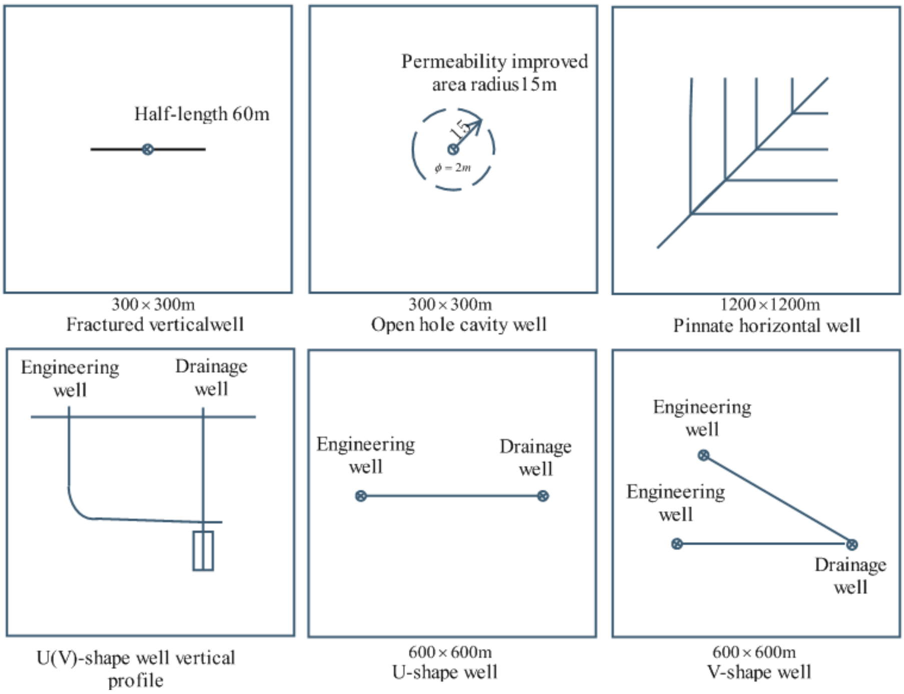

Figure 1: Five CBM well structure diagram.

2.2 Production prediction

CBM module in Eclipse software is used to simulate single well production of different well completion schemes in Baode mining area. As mock objects are all based on squared well pattern and interference between wells are ignored, productivity calculation formula of well pattern is equal to the product of single well productivity and the number of well. Uniform grid is adopted in geological model, and the grid size is 15m.

Wellbore diameter in coal seam section is 13.9mm, and the simulating time is 15 years. Geological parameters in the simulation are as follows: the thickness of coal seam is 10m; the porosity is 3%; the coal seam buried depth is 600m; the horizontal permeability is 1mD; the vertical permeability is 0.5mD; reservoir pressure is 4.8MPa; the coal-rock density is 1.4 t/m^3; the initial water saturation is 1;

Table 1: Five CBM well completion schemes.

Scheme	Control area/m	Quantity	Single well parameters	
Fractured vertical well	300×300	64	Half-length of fracture, m	60
			Fracture width, mm	6
			Fracture height, m	10
			Post-fracturing Permeability, D	30
Open hole cavity well	300×300	64	Cave diameter, m	2
			Permeability improved area radius, m	15
			Improved permeability, mD	30
U-shape well (bare hole in horizontal section)	600×600	16	Engineering well horizontal length, m	500
V-shape well (bare hole in horizontal section)	600×600	16	Engineering wells horizontal section length 500m Angle between two engineering wells is 45^0.	
Pinnate horizontal well (bare hole)	1200×1200	4	1 trunk, 8 branches, each side has 4 branches, angle is 45^0, branch spacing is 200m, symmetrical distributed, total footage, 5200m, trunk length 1200m, branches length: 800, 600, 400, 200m.	

absorption time is 10d; Langmuir volume is $30m^3/t$; Langmuir pressure is 2.9MPa. According to Fig.2 and Fig.3, pinnate horizontal well has maximized the drainage area. In this well completion method, high gas production capacity exists in the beginning of extraction, exceeding those of other well types over the first three years. Its annual production is slightly less than those of other well types in the following years as bearing volume limited and gas supply abating. After long extraction (say 15 years), the final accumulated gas production is still slightly higher compared with others. Additionally, a V-shape well is composed of 2 horizontal engineering wells and a caved well, which has larger contact area with reservoir. From annual gas production and accumulated gas production, its gas productivity is just second to pinnate horizontal well. Above all, pinnate horizontal well and V-shape well predominate in the beginning of exploitation; their advantages dwindle due to limited reservoir supply capacity in the latter period.

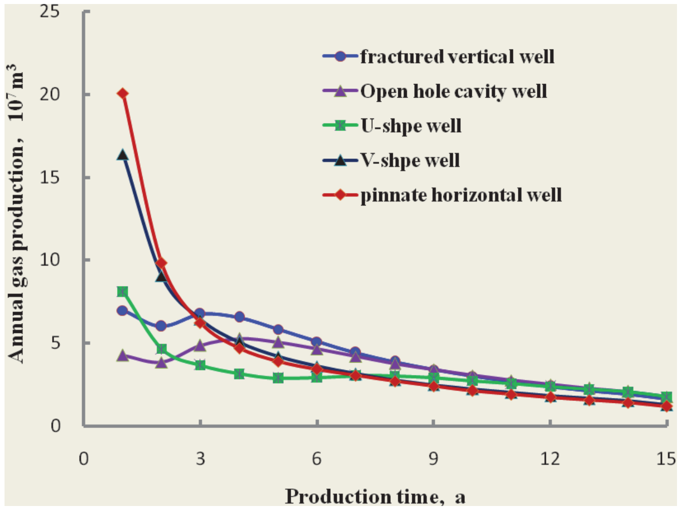

Figure 2: Annual gas production-production time.

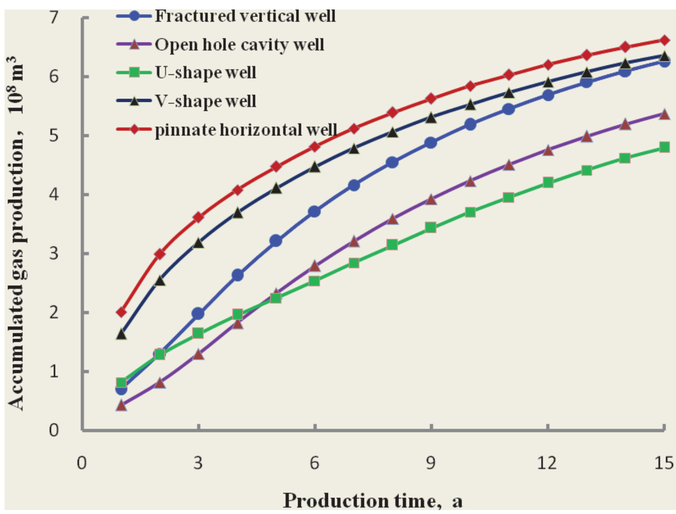

Figure 3: Accumulated gas production-production time.

2.3 Economic evaluation

Generally speaking, main economic evaluation indexes are net present value (NPV), invest recovery period (IRP) and internal rate of return (IRR) [Chen (2011)].

NPV is defined as the sum of the present values of the individual cash flows of the same entity. As a dynamic evaluation index, it mirrors a purpose to gain profit ability inside computation period, its formula is:

$$NPV = \sum_{t=0}^{n} (C_I - C_o)_t (1+i_0)^{-t} \quad (1)$$

Where C_I is cash inflow; C_O is cash outflow; I_0 is discount rate; t is the year sequence; n is the computation period.

Cash inflows of CBM target zone during the decision-making process include sales revenue and government subsidies. Cash outflows include construction investment, cost of production and operation, taxes and fees, etc. Among construction investment are mainly composed of well drilling and completion project investment, surface engineering.

t=0 indicates the investment and construction period, which takes a year; t=1 indicates to start production. According to real CBM well completion situation, equation (1) can be transformed as follows:

$$FNPV = \sum_{t=1}^{n} Q(t)Pf(1+i_0)^{-t} + \sum_{t=1}^{n} Q(t)r_b f(1+i_0)^{-t} - C_1 - \sum_{t=1}^{n} (C_2 + C_3 + T_x(t))(1+i_0)^{-t} \quad (2)$$

Where $Q(t)$ is annual production of CBM well; P is CBM price; f is the economic rate(generally, 95%); r_b is government subsidy rate; t is production period; C_0 is investment during the construction period; C_1 is working capital; C_2 is operation cost; T_x is taxes; i_0 is discount rate.

This article calculate production under the condition of different well completion methods for 15 years, and substitutes the simulated production and date in Table 2 into formula (2), then get NPV in different well completion.

Table 2 is the economic evaluation baseline date of CBM well [Luo (2010)]. Seen from Fig.4, pinnate horizontal well has maximized the drainage area. In spite of its huge investment, with high productivity, its NPV far overweighs other well types.

IRR: The internal rate of return (*IRR*) of a project is simply the interest rate that makes the NPV of the project equal to 0, which can be calculated by cash inflows. Calculating formula is as follows:

$$\sum_{t=0}^{n} (C_I - C_0)_t (1+IRR)^{-t} = 0. \quad (3)$$

Where C_I is cash inflow; C_O is cash outflow; IRR is internal rate of return; t is the year sequence; n is the computation period.

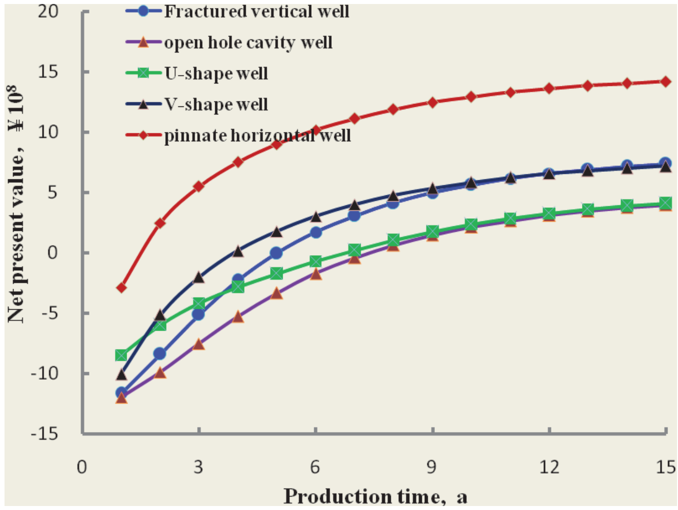

Figure 4: NPV-production time.

Table 2: Economic evaluation baseline date of CBM well.

Well drilling and completion cost, ¥10,000	Fractured vertical well	150
	Open hole cavity well completion	130
	U-shape well	450
	V-shape well	850
	Pinnate horizontal well	2200
Surface investment, ¥10,000/km^2	1008	
Working capital, ¥10,000	2% of construction investment	
Production and operation cost, ¥1/m^3	0.5	
Sale price, ¥1/m^3	1.5	
Government subsidy, ¥1/m^3	0.2	
Commodity rate	95%	
Value added tax	5% of sales revenue	
City maintenance and construction taxes, education fees, other local taxes	10% of payable Value added tax	
Income tax	25%	
Construction and production period	1a, 15a	
Benchmark yields	12%	

If *IRR* is greater than or equal to industry base yield or discount rate, the profitability satisfies the minimum requirement, and this can be accepted financially. The basic rate of return in CBM industry is 12%.

Dynamic IRP: IRP in capital budgeting refers to the period of time required for the return on an investment to "repay" the sum of the original investment. The term is also widely used in other types of investment areas, often with respect to energy efficiency technologies, maintenance, upgrades, or other changes.

$$\sum_{t=0}^{P_t}(C_I-C_0)_t(1+i_0)^{-t}=0. \tag{4}$$

$$P_t = To\text{-}1 + PV_{t\text{-}1}/PV_t \tag{5}$$

Where T_0 is year sequence number; PV_{t-1} is the accumulated net cash inflow absolute vale last year; PV_t is net cash inflow absolute vale of the year.

As IRP is generally calculated from the early year of construction, where t=0 indicates the starting time of construction, for a year, thus IPR is P_t+1.

2.4 Determining evaluation indexes

Productivity prediction and economic evaluation show that the pinnate horizontal well has obvious advantages in terms of capacity or economic, and the V-type horizontal well follows. However, coal is brittle and borehole stability is poor, in the process of drilling and completion some accidents easily occur like borehole collapse, circulation loss, resistance during tripping, slacking off, even borehole burying and other borehole problems and accidents. Because the coal bed is buried relatively shallowly and the hole curvature is bigger, and WOB (weight on bit) is hard to meet the requirements, drilling column is prone to fatigue failure while drilling horizontal branch boreholes, which results in the borehole problems. Statistics from 48 multi-branched horizontal wells in southern Qinshui Basin showed only 14 wells were successfully implemented, and 14 wells occurred collapse and buried drilling tools. The length of buried drilling tools is more than 3250m. In addition, conventional pinnate horizontal well completion process is complex, risky, and complex completion process is not conducive to the protection of coal seams, so open hole completion method is often used to reduce harm caused by the cementing operation (it is also horizontal section of U and V type well). Because collapse problem is common in completion process, collapse risk problem must be considered when evaluating CBM well completion method.

We divide the collapse risk into the following five levels, very low, low, medium, high, very high, and introduce the risk factor to evaluate the collapsed risk. Five collapse risk level corresponds to the risk factors, respectively, 0.1, 0.3, 0.5, 0.7 and 0.9. Combining with well drilling and completion experience in the field, five risk factors corresponds to fractured vertical well, open hole cavity well, U-shape well, V-shape well and pinnate horizontal well, respectively, 0.1, 0.3, 0.5, 0.7 and 0.9.

From Table 3, we can get that the well completion schemes with high productivity and economic benefits are of high risk. It is hard to choose the well completion scheme of all kinds of best index, so we need to use multi-objective decision-making method to select the best completion scheme.

Table 3: Evaluation index in 5 well completion methods.

Completion method	Accumulated gas production, ¥100 million	Net present value, ¥10 million	Dynamic invest recovery period, a	Internal rate of return	Risk coef-ficient
Fractured vertical well	6.252	5.811	6.667	20.5%	0.1
Cavity completion	5.368	2.726	9.501	15.9%	0.3
U-shape well	4.791	3.770	7.839	19.3%	0.5
V-shape well	6.353	6.193	5.230	22.8%	0.7
Pinnate horizontal well	6.617	13.883	2.408	52.6%	0.9

3 Determining the weight coefficient of evaluation index

In this paper, entropy method and deviation maximizing are used to determine the weight of each index.

3.1 Normalizing the evaluation matrix

In the evaluation system, indexes differ in content, dimension and criteria. Therefore, it is necessary to translate different indexes into unified standard, namely, standardization [Wang (2010)].

Suppose there are m evaluation schemes, n evaluation indexes, thus get a multi-objective evaluation matrix as shown in Table 3:

$$R' = \begin{bmatrix} r'_{11} & \cdots & r'_{1n} \\ \vdots & & \vdots \\ r'_{m1} & \cdots & r'_{mn} \end{bmatrix} = \begin{bmatrix} 6.252 & 7.361 & 6.020 & 0.227 & 0.1 \\ 5.368 & 3.962 & 8.399 & 0.176 & 0.3 \\ 4.791 & 4.114 & 7.759 & 0.195 & 0.5 \\ 6.353 & 7.182 & 5.920 & 0.240 & 0.7 \\ 6.617 & 14.186 & 2.537 & 0.487 & 0.9 \end{bmatrix}. \tag{6}$$

For profit index (the higher, the better), the conversation formula is:

$$r_{ij} = \frac{r'_{ij} - r'_{j\min}}{r'_{j\max} - r'_{j\min}} \tag{7}$$

For cost index (the lower, the better) the conversation formula is:

$$r_{ij} = \frac{r'_{j\max}\text{-}r'_{ij}}{r'_{j\max}\text{-}r'_{j\min}} \tag{8}$$

Where $r'_{j\min}$ is the minimum eigenvector for the j index; $r'_{j\max}$ is the maximum eigenvector for the j index. Hence the normalized matrix R:

$$R = \begin{bmatrix} r_{11} & \cdots & r_{1n} \\ \vdots & & \vdots \\ r_{m1} & \cdots & r_{mn} \end{bmatrix} = \begin{bmatrix} 0.8 & 0.333 & 0.406 & 0.165 & 1 \\ 0.316 & 0 & 0 & 0 & 0.75 \\ 0 & 0.015 & 0.109 & 0.061 & 0.5 \\ 0.856 & 0.315 & 0.423 & 0.207 & 0.25 \\ 1 & 1 & 1 & 1 & 0 \end{bmatrix} \tag{9}$$

3.2 Entropy method

Entropy is a function of matter systematic state. Entropy indicates the degree of disorder in the system. The entropy weight calculated from evaluation matrix is not an actual important coefficient, but a relative degree coefficient in the meaning of various indexes, which provides how much useful information on this issue.

On the issue of m evaluation schemes and n evaluation indexes, the entropy of the evaluation index j is:

$$H_j = \text{-}k \sum_{i=1}^{m} f_{ij} \ln f_{ij} \quad (j = 1,2...,n\ ) \tag{10}$$

Where $f_{ij} = \frac{r_{ij}}{\sum_{i=1}^{m} r_{ij}}, k = \frac{1}{\ln m}$ when $r_{ij} = 0$, setting $f_{ij}\ln f_{ij} = 0$.

The entropy weight of index j is defined as

$$w_j = \frac{1\text{-}H_j}{m\text{-} \sum_{j=1}^{n} H_j} \tag{11}$$

Thus getting the entropy weight matrix$w$:

$$w = [0.123, 0.261, 0.187, 0.291, 0.138] \tag{12}$$

3.3 Deviation maximization

On the basis of normalized matrix R, use deviation maximizing method to calculate objective weight v_j of the index j:

$$v_j = \frac{\sum_{i=1}^{m} \left| r_{ij}\text{-}r_0 \right|}{\sum_{i=1}^{m} \sum_{j=1}^{n} \left| r_{ij}\text{-}r_0 \right|} \tag{13}$$

Where r_0 is the optimum vector, $r_0 = [r_1, r_2, \cdots, r_n]$
Normalize the optimum matrix in the judgment matrix, $r_0 = [1,1, ... 1]$
Difference matrix:

$$\left|r_{ij}\text{-}r_0\right| = \begin{bmatrix} 0.2 & 0.667 & 0.594 & 0.835 & 0 \\ 0.684 & 1 & 1 & 1 & 0.25 \\ 1 & 0.985 & 0.891 & 0.939 & 0.5 \\ 0.144 & 0.685 & 0.577 & 0.793 & 0.75 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{14}$$

Utilize formula (13) to calculate the weight

$$v = [0.14, 0.23, 0.211, 0.246, 0.173] \tag{15}$$

3.4 Determine weight coefficient of evaluation index

Combining entropy method and deviation maximizing method, use weighted mean method to calculate the comprehensive weight coefficient of index j.

$$\omega = \frac{(w_j + v_j)}{2} \quad i = 1, 2, \cdots, 5 \tag{16}$$

$$\omega = [0.131, 0.246, 0.199, 0.269, 0.172] \tag{17}$$

4 Multi-objective decision-making application

In this part, three multi-objective decision-making methods are used:

4.1 Fuzzy synthesis decision-making method

Establish standard superior scheme based on membership matrix as a relative criterion of optimization and comparison. n indexes membership of superior scheme is the maximum value of index membership of all schemes, thus the superior scheme $g_i = (g_1, g_2, \cdots, g_n) = (1, 1, \cdots, 1)$, the inferior scheme $b_i = (b_1, b_2, \cdots, b_n) = (0, 0, \cdots, 0)$.
Suppose u_i is the optimum membership degree of the scheme i
$S(r_i,E) = u_i[\sum_{j=1}^{n} (\omega_j \left|r_{ij}\text{-}g_i\right|)^p]^{1/p}$, $S(r_i,E)$ is the weighed optimum distance of scheme i. $S(r_i,L) = (1\text{-}u_i)[\sum_{j=1}^{n} (\omega_j \left|r_{ij}\text{-}b_i\right|)^p]^{1/p}$, $S(r_i,L)$is the weighed optimum distance of scheme i.

Where p in the expression of $S(r_i,E)$ and $S(r_i,L)$ is the distance parameter. $p=1$ is hamming distance; $p=2$ is Euclidean distance. To calculate the optimum value of membership u_i, an objective function should be set as follows:

$$F(u_i)=\{u_i[\sum_{\text{j}=1}^{n}(\omega_j\left|r_{ij}\text{-}g_i\right|)^p]^{1/p}\}^2+\{(1\text{-}u_i)[\sum_{\text{j}=1}^{n}(\omega_j\left|r_{ij}\text{-}b_i\right|)^p]^{1/p}\}^2 \tag{18}$$

In order to calculate $\min F(u_i)$, namely, the minimum sum of squared weighed optimal distance. Suppose $\frac{\mathrm{d}F(u_i)}{\mathrm{d}u_i}=0$ to get the optimal calculating formula of u_i.

$$u_i=\frac{1}{1+\frac{\sum_{i=1}^{m}[(\mathrm{w_i}\left|r_{ij}-g_i\right|)^{\mathrm{p}}]^{2/\mathrm{p}}}{\sum_{i=1}^{m}[(\mathrm{w_i}\left|r_{ij}-b_i\right|)^{\mathrm{p}}]^{2/\mathrm{p}}}}\quad(i=1,2,\cdots,m) \tag{19}$$

Usually, by using Euclidean distance, p=2, the above formula can be simplified as:

$$u_i=\frac{1}{1+\frac{\sum_{i=1}^{m}(\mathrm{w_i}\left|r_{ij}-g_i\right|)^2}{\sum_{i=1}^{m}(\mathrm{w_i}\left|r_{ij}-b_i\right|)^2}}\quad(i=1,2,\cdots,m) \tag{20}$$

Utilize the above formula to calculate the optimal membership degree; the greater u_i indicates the better scheme. Accordingly, the membership degree of different well completion methods can be normalized as:

$$u=[0.223,\ 0.053,\ 0.036,\ 0.162,\ 0.548] \tag{21}$$

4.2 Gray system theory

Gray correlation analysis is actually a kind of method which compares closeness of geometric shape from different date. In general, the closer geometric shape indicates more similar trend and greater correlation. Therefore, during the process of correlation analysis, we firstly determine the referring series, and then compare the closeness of other referring series. By doing this can we compare and optimize other sequences [Feng (2010)].

On the base of normalized matrix R can we get referring matrix $r_0=[r_{01},\ r_{02},\ \cdots,\ r_{0n}]$, where r_{0j} refers to the optimal value in row j, thus getting a difference comparison matrix:

$$\Delta_{ij}=\begin{bmatrix} r_{11}\text{-}r_{01} & r_{12}\text{-}r_{02} & \cdots & r_{1n}\text{-}r_{0n} \\ r_{21}\text{-}r_{01} & r_{22}\text{-}r_{02} & \cdots & r_{2n}\text{-}r_{0n} \\ \vdots & \vdots & \vdots & \vdots \\ r_{m1}\text{-}r_{01} & r_{m2}\text{-}r_{02} & \cdots & r_{mn}\text{-}r_{0n} \end{bmatrix}=\begin{bmatrix} 0.2 & 0.667 & 0.594 & 0.835 & 0 \\ 0.684 & 1 & 1 & 1 & 0.25 \\ 1 & 0.985 & 0.891 & 0.939 & 0.5 \\ 0.144 & 0.689 & 0.577 & 0.793 & 0.75 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{22}$$

Calculate gray correlation coefficient

$$\varphi_{ij} = \frac{\min_i \min_j \Delta_{ij} + \rho \max_i \max_j \Delta_{ij}}{\Delta_{ij} + \rho \max_i \max_j \Delta_{ij}} \tag{23}$$

Where $\Delta_{ij} = |r_0 - r_i|$, ρ is resolution coefficient, $\rho \in [0,1]$, generally, $\rho = 0.5$.

$$\varphi = \begin{bmatrix} 0.715 & 0.428 & 0.457 & 0.375 & 1 \\ 0.422 & 0.333 & 0.333 & 0.333 & 0.667 \\ 0.333 & 0.337 & 0.360 & 0.347 & 0.5 \\ 0.776 & 0.420 & 0.464 & 0.387 & 0.4 \\ 1 & 1 & 1 & 1 & 0.333 \end{bmatrix} \tag{24}$$

In the course of calculating correlation degree, weighed gray correlation coefficient matrix is:

$$\psi_i = \sum_{j=1}^{n} \varphi_{ij} w(j) \tag{25}$$

Where ψ_i is gray correlation value, $w(j)$ is relative weighed value according to importance.

Calculate and normalize the correlation degree.

$$\psi_i\text{'} = [0.204, 0.148, 0.138, 0.174, 0.335] \tag{26}$$

4.3 TOPSIS method

Technique for Order Preference by Similarity to Ideal Solution, or TOPSIS, is raised by Hwang and Yoon in 1981. This method is applied by making a comparison and selection. By setting positive and negative ideal solution and calculating the distance between real solution and positive/negative ideal solution, the solution which is closest to the positive ideal solution and farmost from the negative optimal solution is regarded as the optimal solution [Metin Dagdeviren (2009)].

Weighing the standard matrix R (equation (9)):

$$R' = \begin{bmatrix} 0.105 & 0.082 & 0.081 & 0.044 & 0.155 \\ 0.043 & 0 & 0 & 0 & 0.116 \\ 0 & 0.004 & 0.022 & 0.016 & 0.078 \\ 0.112 & 0.077 & 0.084 & 0.056 & 0.039 \\ 0.131 & 0.246 & 0.199 & 0.269 & 0 \end{bmatrix} \tag{27}$$

Positive ideal solution: $r^+ = \max r_{ij} \quad i = 1, 2, \cdots, m$

Negative ideal solution: $r^{-} = \min r_{ij} \quad i = 1, 2, \cdots, m$

Determine the positive and negative ideal solution:

$$R^{+} = [0.131, 0.246, 0.199, 0.269, 0.155] \tag{28}$$

$$R^{-} = [0, 0, 0, 0, 0] \tag{29}$$

Calculate the Euclidean distance between target and ideal solution:

$$S_i^{+} = \sqrt{\sum_{j=1}^{n} (r_{ij}\text{-}r^{+})^2} \quad i = 1, 2, \cdots, m \tag{30}$$

$$S_i^{-} = \sqrt{\sum_{j=1}^{n} (r_{ij}\text{-}r^{-})^2} \quad i = 1, 2, \cdots, m \tag{31}$$

Calculate Euclidean distance between each well completion scheme and positive/ negative ideal solution:

$$S^{+} = [0.303, 0.426, 0.421, 0.318, 0.155] \tag{32}$$

$$S^{-} = [0.224, 0.124, 0.082, 0.174, 0.435] \tag{33}$$

Calculate the close degree of each well completion scheme:

$$C_i = \frac{S_i^{-}}{S_i^{+} + S_i^{-}} \quad i = 1, 2, \cdots, m \tag{34}$$

Normalization:

$$C = [0.223, 0.118, 0.086, 0.186, 0.387] \tag{35}$$

4.4 Comprehensive evaluation results

The above three multi-objective decision methods all work on the same principle to calculate the distance between real well schemes and the positive/negative ideal completion scheme. Different solving processes are used in different methods, which may lead to inconsistent results. In order to obtain accurate evaluation results and weaken defects, normalized membership degrees (gray correlation degree, close degree) from different methods are weighed to achieve comprehensive membership degree in this paper. Greater comprehensive membership degree indicates better scheme. In the meantime, different schemes are sorted according to their value. Comprehensive evaluation results are showed in Table 4.

Judging from the results, it may come to a conclusion that the optimal completion method is pinnate horizontal well and fractured vertical well comes second.

Table 4: Comprehensive evaluation results

Completion method	Fuzzy comprehensive evaluation	Gray system theory	TOPSIS	Comprehensive membership degree	Total sort
fractured vertical well	0.201	0.201	0.210	0.206	2
Cavity completion	0.053	0.148	0.121	0.094	4
U-shape well	0.036	0.142	0.102	0.074	5
V-shape well	0.162	0.178	0.192	0.159	3
pinnate horizontal well	0.548	0.331	0.375	0.468	1

5 Conclusions

Pinnate horizontal well and V-shape well predominate in the beginning of exploitation compared with other completion methods, and its advantages dwindle due to limited reservoir supply capacity in the latter period. In spite of its huge investment and high risk, with high productivity, its NPV far overweighs other completion methods.

This study shows that the multi-objective decision-making method is suitable to deal with the CBM well completion adaptability evaluation problem. After comprehensive evaluation of every useful index, we can get the most appropriate completion method to target CBM field. After applying this evaluation method to Baode mining of Ordos Basin, evaluating results show that the pinnate horizontal well is the most suitable completion method, followed by fractured vertical well. Adaptability evaluation method proposed in this paper provides guidance for on-site coal bed methane well completion program design, which has a great significance to improve China's CBM overall development effect.

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