

Research Article

Evaluation Method of Coal-Bed Methane Fracturing in the Qinshui Basin

Zhengrong Chen¹ and Tengfei Sun² 

¹China National Offshore Oil Corporation Research Institute, Beijing 100028, China

²College of Mechanical and Electrical Engineering, Beijing University of Chemical Technology, Beijing 100029, China

Correspondence should be addressed to Tengfei Sun; suntengfei7@sina.com

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In order to evaluate the productivity effects of coal-bed methane well fracturing, the relationship between the five factors of horizontal in situ stress difference is analyzed: fracturing friction, net pressure, fracture morphology, fracturing curve shape, and fracturing effect, taking the coal-bed methane wells in the Qinshui Basin as the research target. The results show that the smaller the horizontal in situ stress difference, the larger the fracture stimulation volume; the smaller the fracturing friction and the net pressure, the higher the productivity of the coal-bed methane well; the greater the proportion of coal-bed methane wells with complex fractures in the form of fracturing fractures, the greater the productivity; the fractures formed by descending and mixed fracture curves are ideal, and the effect after fracturing is better. Based on support vector machine for the above five factors, a fracturing effect classification and evaluation model is established using the fractured wells in the target block as training samples, and the effect prediction of nearby coal-bed methane wells is performed. The results show that the prediction results are in excellent agreement, comparing the prediction classification results of support vector machine with the average daily gas production. This theoretical method realizes the classification of the complex effects of coal-bed methane fracturing and provides a theoretical basis for the design of coal-bed methane well production stimulation and effect prediction.

1. Introduction

Qinshui Basin is located in the southeast of Shanxi Province, China. Coal-bed is mainly the Upper Carboniferous Taiyuan Formation and the Lower Permian Shanxi Formation. It is a set of offshore and continental interactive coal-bearing deposits developed above the paleoweathering crust of the Ordovician. There can be more than 10 coal seams; the total thickness of the coal seam is between 1 and 24 m. The main coal seams for coal-bed methane development are No. 3 and No. 15, which belong to high rank coal. The coal body structure is mainly a native structure and contains a certain proportion of fragmented coal and mylonite coal. Coal seams have higher lateral heterogeneity and their gas content is generally high. Therefore, Qinshui Basin is rich in coal-bed methane resources and is an important natural gas production base. However, the main coal seams in this area are

all low permeability reservoirs. Based on the above geological background and coal reservoir conditions, coal seams need hydraulic fracturing to have economic value.

Hydraulic fracturing is an important stimulation measure for coal-bed methane due to its low porosity and permeability [1–5]. However, coal develops a large number of microfractures and cleats, and the heterogeneity is strong, resulting in more complex fracture extension morphology [6, 7], which makes it difficult to accurately predict and evaluate the effect of coal fracturing. The fracturing project is a systematic project, and there are many factors influencing its effect. The indicators for evaluating the fracturing effect of coal seam are mostly qualitative parameters, which have greater ambiguity [8, 9]. Coal-bed methane fracturing effect is often simulated by physical model experiments, and numerical simulation techniques are used to establish fracturing models to simulate and evaluate the effects of

fractures. However, this method is more dependent on the accuracy of the fracturing model. It is difficult for conventional classic fracturing models to simulate the complexity of fracture propagation in coal seams [10–17]. As a method of indirect evaluation of fracturing effects, well testing technology cannot directly evaluate fracturing effects and it is difficult to explain complex coal seam fractures [18–20]. Although fracture monitoring can directly grasp the characteristics of fracture morphology, it is limited to the current monitoring technology, and there is a large error between the actual fracture and the monitoring result [21–23]. Therefore, the above methods have certain limitations in application.

Based on the above problems, the coal fracture propagation law is analyzed, and the relationship between five indexes (the horizontal in situ stress difference, fracturing friction, net pressure, fracture morphology, and fracturing curve shape of coal seam) and fracturing effect is deeply discussed. The support vector machine method (SVM) in statistics is used to predict and analyze coal-bed methane wells, and a method for classifying and evaluating the effect of coal-bed gas fracturing is obtained by comprehensively integrating 5 indexes. This method has important reference for the productivity risk prediction of coal-bed methane wells and the selection of wells and layers.

2. Fracturing Evaluation Index

There are many factors that affect coal-bed methane well fracturing. Field operations show that it is difficult to accurately evaluate coal fracturing morphology and production increment effects through operation parameters such as displacement, sand ratio, and liquid injection volume. In a specific coal-bed methane blocks, the fracturing operation technology and scheme are unchanged, the fracturing effect is mainly related to the fracturing operation difficulty and the final fracture morphology. The morphology of fractures under hydraulic fracturing is mainly determined by in situ stress and operation pressure. At the same time, the characteristics of the coal-bed methane fracturing curve reflect the ease of fracturing operation. Therefore, the fracturing prediction index of coal-bed methane wells can be determined from in situ stress, fracturing curve characteristics, and fracture morphology etc.

2.1. Horizontal In Situ Stress Difference. In situ stress is an important data basis for guiding fracturing operation. It determines the fracture extension and final morphology of coal fracturing. It is mainly composed of overburden in situ pressure and the horizontal maximum and minimum in situ stress. Rich cleats and microfractures are developed in the coal seam. Weak surfaces such as microfractures and cleats during fracture extension are likely to form more complex fracture morphology, increasing the volume of fracture. The stimulated volume of fractures in extension is mainly controlled by the horizontal maximum and minimum in situ stress. The horizontal in situ stress difference can indicate the difficulty of forming a fracture network through coal

fracturing. The larger the in situ stress difference is, the more likely the fracture is to form a flat double-wing fracture, and the smaller the stimulated volume is. The smaller the horizontal in situ stress difference is, the more likely the fracture is to form a multibranched fracture network, and the larger the stimulated volume is.

Therefore, the horizontal stress difference can represent the degree of influence of horizontal in situ stress difference on the fracture network [24], namely,

$$D = \sigma_H - \sigma_h, \quad (1)$$

where D is the horizontal in situ stress difference, MPa; σ_H is the horizontal maximum in situ stress, MPa; and σ_h is the horizontal minimum in situ stress, MPa. According to field experience, coal seams with relatively complete coal structures have complex fractures and multiple fractures when the horizontal in situ stress difference is less than 3 MPa, and single fractures are more likely to occur when it is greater than 3 MPa.

2.2. Fracturing Friction. Fracturing friction is a reaction force that prevents fracture propagation. Good fracture propagation requires less fracturing friction. However, due to the development of microfractures and cuttings in the coal seam, local sand plugs are often formed, making it difficult to further expand the fractures and reducing the fracturing effect. At the same time, coal-bed methane also forms irregular fractures or curved fractures, which also results in greater fracturing friction during the fracturing fluid injection process, which limits the propagation of fractures and affects the ultimate fracturing effect.

A large number of fracturing friction statistics of coal-bed methane wells in block A of Qinshui Basin are shown in Figure 1. The higher the fracturing friction, the lower its production capacity, indicating that the higher the fracturing friction, the greater the effect of the fracturing friction on the fracturing fluid injection, and so the lower the injection energy and the worse the fracturing effect. Figure 1 shows that when the fracturing friction is less than 4 MPa, the production capacity is relatively high and the fracturing effect is better. When the fracturing friction is greater than 4 MPa, the production capacity is relatively low.

Fracturing friction can be expressed by the ground pressure difference before and after the pump stops during the fracturing operation curve [25, 26]:

$$P_{fri} = P_e - ISIP, \quad (2)$$

where P_{fri} is the fracturing friction, MPa; P_e is the ground pump pressure before shutting pump, MPa; and ISIP is the instantaneous shut-in pressure, MPa. Therefore, the fracturing friction can be obtained by the above formula, and the fracturing effect can be evaluated.

2.3. Net Pressure. The net pressure of shut-in fracturing is the difference between the fluid flow pressure in the hydraulic fracture and the formation closure pressure. Generally, when the fractures formed by fracturing are more

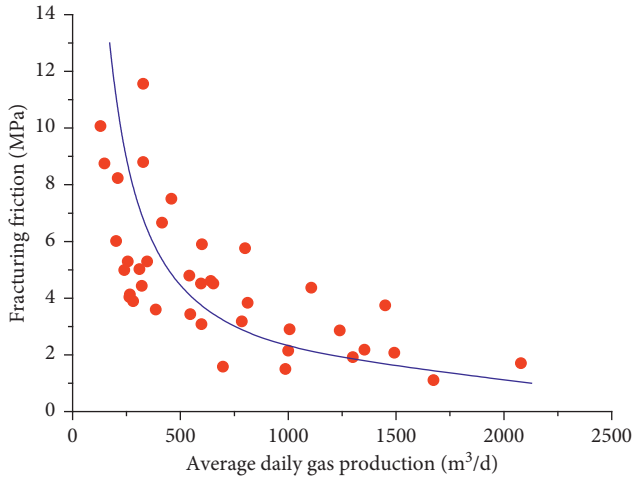


FIGURE 1: Relationship between fracturing friction and productivity.

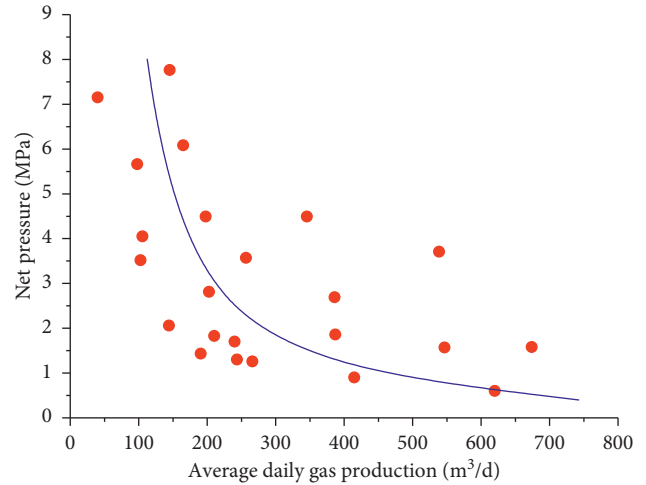


FIGURE 2: Relationship between net pressure and productivity.

regular or single fractures, the force required to open the formation during fracturing is smaller, and the pressure at which the fracturing pressure is greater than the formation closure stress is smaller; that is, the required net pressure is smaller. If fracturing forms multiple fractures or irregular fractures, the fracturing pressure will act on multiple fractures, so the net pressure will be greater. At the same time, the ability of fracture propagation is reduced, so fracture extension is more difficult and the fracturing effect is worse. The net pressure of shut-in fracturing reflects the final morphological type and the complexity of the fracture extension, that is, the difficulty degree of forming the fracture.

Through statistical analysis, the net pressure of various coal-bed methane wells during fracturing with consistent fracturing schemes in block A of Qinshui Basin is shown in Figure 2. It can be known that the higher the net pressure, the lower the production capacity. This is because the higher the net pressure, the more severe the overpressure inside the fracture, which makes it more difficult for the fracture to propagate, so it is difficult to form an effective fracture, and the fracturing effect will be worse.

According to the above analysis, the fracturing effect can be described by the net pressure data, and the productivity of the coal-bed methane after fracturing can be evaluated. Figure 2 shows that when the net pressure is less than 3 MPa, the production capacity is relatively high and the fracturing effect is better. When the net pressure is greater than 3 MPa, the production capacity is relatively low.

The net pressure of shut-in pump can be expressed by the following formula [25, 26]:

$$P_n = ISIP - P_C + P_w, \quad (3)$$

where P_n is the net pressure of shut-in pump, MPa; P_w is the hydrostatic pressure, MPa; and P_C is the closure pressure, MPa. Therefore, the net pressure can be obtained by the above formula and the fracturing effect can be evaluated.

As shown in Figure 3, the net pressure of the fracturing wells in block A of Qinshui Basin and the nearby block B is statistically analyzed. The comparison shows that the net

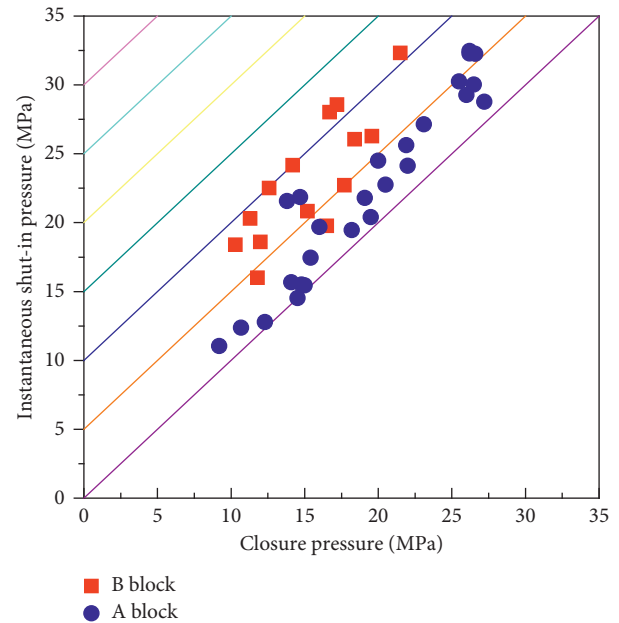


FIGURE 3: Contrast of net pressure in blocks A and B of Qinshui Basin.

pressure of wells in block A of Qinshui Basin is generally lower than that of block B. The average daily gas production of coal-bed methane wells in block A is 968.3 m³/d, and the average daily gas production of coal-bed methane wells in block B is 323.5 m³/d. The productivity of wells in block A is generally higher than that in block B. It shows that the coal-bed methane well in block B is more difficult to form fracture than that in block A, and the fracturing effect is even worse, resulting in relatively low gas production.

2.4. Fracture Morphology. Fracture morphology directly reflects the final effect of fracturing construction, but underground fractures are currently difficult to monitor or have poor monitoring accuracy, especially for coal-bed

methane. Therefore, reasonable prediction of the fracture morphology of coal-bed methane fracturing is one of the important methods to predict the fracturing effect.

In theory, the fracture extension direction during fracturing is mainly perpendicular to the direction of the minimum in situ stress and parallel to the direction of maximum in situ stress. The vertical action of the overburden in situ stress and the horizontal maximum and minimum in situ stress determines the main morphology of the fracture extension. By analyzing the formation in situ stress, the extension direction of fractures can be judged, and the fracture morphology can be studied. The fracture morphology is evaluated by the initiation pressure and the closure pressure according to the morphology characteristics of the coal initiation and closure [27].

2.4.1. Initiation Morphology Characteristics. When the fracture of the coal-bed methane well begins, the vertical fracture and horizontal fracture need to overcome different fracture initiation restrictions, and the corresponding initiation pressure is also different.

Among them, the initiation pressure when the fracture is vertically fractured is [28]

$$P_{fv} = \frac{3\sigma_h - \sigma_H - \alpha((1 - 2\mu)/(1 - \mu))P_p + S_t}{1 - \alpha((1 - 2\mu)/(1 - \mu))}. \quad (4)$$

The initiation pressure when a horizontal fracture occurs is

$$P_{fh} = \frac{\sigma_v - \alpha P_p + S_t}{1 - \alpha((1 - 2\mu)/(1 - \mu))} + \alpha P_p, \quad (5)$$

where P_f is the formation initiation pressure, MPa; S_t is the tensile strength, MPa; σ_H is the horizontal maximum in situ stress, MPa; σ_h is the horizontal minimum in situ stress, MPa; σ_v is the overburden in situ stress; μ is the Poisson's ratio; P_p is the formation pressure, MPa; and α is the effective stress coefficient.

According to the difference between the vertical and horizontal initiation pressure model above, when the horizontal initiation pressure is less than the vertical initiation pressure, the fracture initiate horizontally and form a horizontal fracture ($P_{fh} < P_{fv}$); when the vertical initiation pressure is less than the horizontal initiation pressure, the fracture initiate vertically and form a vertical fracture ($P_{fv} < P_{fh}$). Comparing the relationship between the two models above, we can judge the morphology of the coal initiation fracture.

2.4.2. Closure Morphology Characteristics. Fracture will propagate along the natural fractures and the weak surface of the coal seam owing to the natural fractures and cleats in the coal seam. Therefore, the fracture extension morphology may be inconsistent with the initiation morphology. By analyzing fracture closure, the fracture gradually closes after the pump is stopped at the end of the fracturing. If the closure pressure is equal to the pressure of the overburden in situ stress, the formation is horizontally

closed, and the fracture is horizontal in the process of the fracture propagation. If the closure pressure is equal to the horizontal minimum in situ stress, the formation is vertically closed, and the fracture is vertical in the process of the fracture propagation. Therefore, the fracture propagation morphology can be judged by the fracture closure pressure.

The fracture is horizontal when the fracture closure pressure is equal to overburden in situ stress:

$$P_C = \sigma_v. \quad (6)$$

The fracture is vertical when the fracture closure pressure is equal to horizontal minimum in situ stress:

$$P_C = \sigma_h, \quad (7)$$

where P_C is the closure pressure, MPa.

Combining the fracture initiation morphology and the fracture closure morphology shows that if the fracture is a vertical fracture when the fracture is broken and a horizontal fracture when it is closed, or a horizontal fracture when the fracture is broken and a vertical fracture when closed, the fracture forms a complex fracture morphology that is not a single fracture.

Through the comprehensive use of the above fracture morphology evaluation methods, it can be judged that the vertical, the horizontal, or the complex fracture is formed during fracture initiation to extension process, so as to grasp the morphology characteristics of the coal fracturing.

The fracture morphology of coal fractures in block S of Qinshui Basin is analyzed. The proportion of complex fractures in coal seam is the largest, accounting for 75%, and the average daily gas production is 545.2 m³/d. However the proportions of vertical seam and horizontal seam are small, accounting for 13% and 12%, respectively, and the average daily gas production is 385.6 m³/d and 489.3 m³/d, respectively. This shows that the fracture in coal seams usually forms complex fracture morphology, but the proportion of single-form fracture is small. Due to the larger stimulated volume of complex fracture, the productivity of coal-bed methane wells with complex fracture is relatively high.

2.5. Fracturing Curve Shape. Fracturing operation curve is a comprehensive reflection of fracturing technology system and rock mechanical characteristics. Changes in fracturing operation curve can reflect the process of hydraulic fracture initiation, extension, and closure. In addition, fracturing initiation pressure, extension pressure, closure pressure, and formation characteristic parameters can be obtained by analyzing the fracturing curve. At the same time, the fracturing operation curve comprehensively reflects the interaction between the fracturing pressure and the formation rock. The change of the fracturing pressure can indicate the fracture morphology. The fracture morphology can be predicted by analyzing the characteristics of the coal fracturing curve. The change of the fracturing curve is of great significance for the evaluation of the fracturing effect and the division of the fracturing curve type.

According to the characteristics of the coal fracturing curve, it can be classified into four types: ascending shape, descending shape, stationary shape, and mixed shape [29].

2.5.1. Ascending Fracturing Curve Shape. Ascending fracturing curve indicates the increase of the net pressure in the fracture, as shown in Figure 4(a). The pressure gradually increases, indicating that overpressure occurs in the fracture, the fracture growth is hindered, and the extension area is limited. If there is a sharp increase in pressure, it means that sand blockage or barrier occlusion occurs.

2.5.2. Descending Fracturing Curve Shape. Descending fracturing curve indicates the decrease of the net pressure in the fracture, as shown in Figure 4(b). The fracture extends to connect natural fractures, cleats, and low stress formations or faults, which cause the pressure to decrease. It indicates that the fractures gradually extend deeper into the formation.

2.5.3. Stationary Fracturing Curve Shape. Stationary fracturing curve indicates that the change in net pressure in the fracture is relatively stable, as shown in Figure 4(c). The injected liquid and the loss liquid in the formation reach a dynamic equilibrium state, and the fracture morphology remains stable. Fracture extension encounters microfractures or cleats in the coal seam to make the injection loss equalize.

2.5.4. Mixed Fracturing Curve Shape. Mixed fracturing curve contains the morphology characteristics of various curves, as shown in Figure 4(d). The net pressure in the fracture fluctuates greatly, and the energy acting on the fracture changes greatly. Fractures encounter natural fractures, cleats, and low stress formations or faults, leading to reduced pressure. Sand blockage or shielding barriers will increase the pressure. The coal seam has strong nonuniformity, and the fracturing pressure fluctuation is serious, which can easily cause the coal seam to form T-shaped, I-shaped, and other complex asymmetric fractures.

The relationship between the type of fracturing curve in block S for Qinshui Basin and the average daily gas production of single is counted. The average daily gas production from high to low is as follows: descending curve ($460.9 \text{ m}^3/\text{d}$) > mixed curve ($448.3 \text{ m}^3/\text{d}$) > ascending curve ($332.6 \text{ m}^3/\text{d}$) > stationary curve ($308.4 \text{ m}^3/\text{d}$), as shown in Figure 5.

The descending curve indicates that the microfractures or cleats are connected throughout the fracture extension process to increase the drainage area of the formation as much as possible, and the volume of the reservoir stimulation increases the single-well production capacity. The ascending curve indicates that the fracture extends in the initial stage of fracturing. However the later pressure is increased, and the fracture extension is limited, which results in a decrease in productivity. The stationary curve indicates that the fracturing fluid injection and loss reach

equilibrium during most of the fracture and even the entire fracturing process, and the fracture does not have a wide range of extension. The stimulation volume is the lowest, and the postpressing capacity is also the smallest. The mixed curve indicates that the fracture has been extended and blocked several times during the fracturing process. The fracture extension is between the descending type and the ascending type, and the average productivity is lower than the descending type and higher than the ascending type.

2.6. Relationship of Indexes. In the coal-bed methane block of the Qinshui Basin, coal seams with poor coal structures have more microfractures and cleats, and the fracturing curve is unstable, which is prone to mixed and ascending curves. At this time, fracturing is more difficult, and fracture friction and net pressure are both high. The fracture forms are mainly complex and multiple fractures, and even I-shaped and T-shaped fractures are formed.

However, the coal seam with a better coal structure has fewer microfractures and cleats, so the fracturing curve is simpler, which is prone to stationary and descending curves. At this time the fracture extends as a relatively flat single fracture, such as a vertical or horizontal fracture. Then fracture friction and net pressure are both lower.

In deep coal seams, the greater the depth of the coal seam, the greater the horizontal in situ stress difference, with vertical and complex fracture being prone to occur. Fractures are more difficult to extend, fracturing curves are more prone to mixed and ascending curves, and fracture friction and net pressure are relatively higher.

Correspondingly, in shallow formations, the horizontal in situ stress difference will be small, and it is easier to form a horizontal or complex fracture. Fractures are easier to extend, fracturing curves are more prone to stationary and descending curves, and fracture friction and net pressure are relatively lower.

Because the mechanical properties of coal seams are relatively soft, the heterogeneity is strong, and microfractures and weak interfaces develop more, so the relationship between the above factors is not absolutely consistent. Therefore, this paper explores a mathematical model that integrates the five factors to evaluate fracturing effects.

3. Support Vector Machine Classification

The support vector machine is a statistical method for the classification problem of finite samples. It has a stronger theoretical basis and better generalization performance than the neural network learning algorithm [30]. The core is to classify the two types of data. Through training, the data is placed on both sides of the two-dimensional plane or the multidimensional hyperplane to achieve the best classification of the data.

The classification of a large amount of two-dimensional data is as follows: (x_i, y_i) , $i = 1, \dots, n$, $y_i \in \{+1, -1\}$. Through the plane $wx + b = 0$, the above data is classified

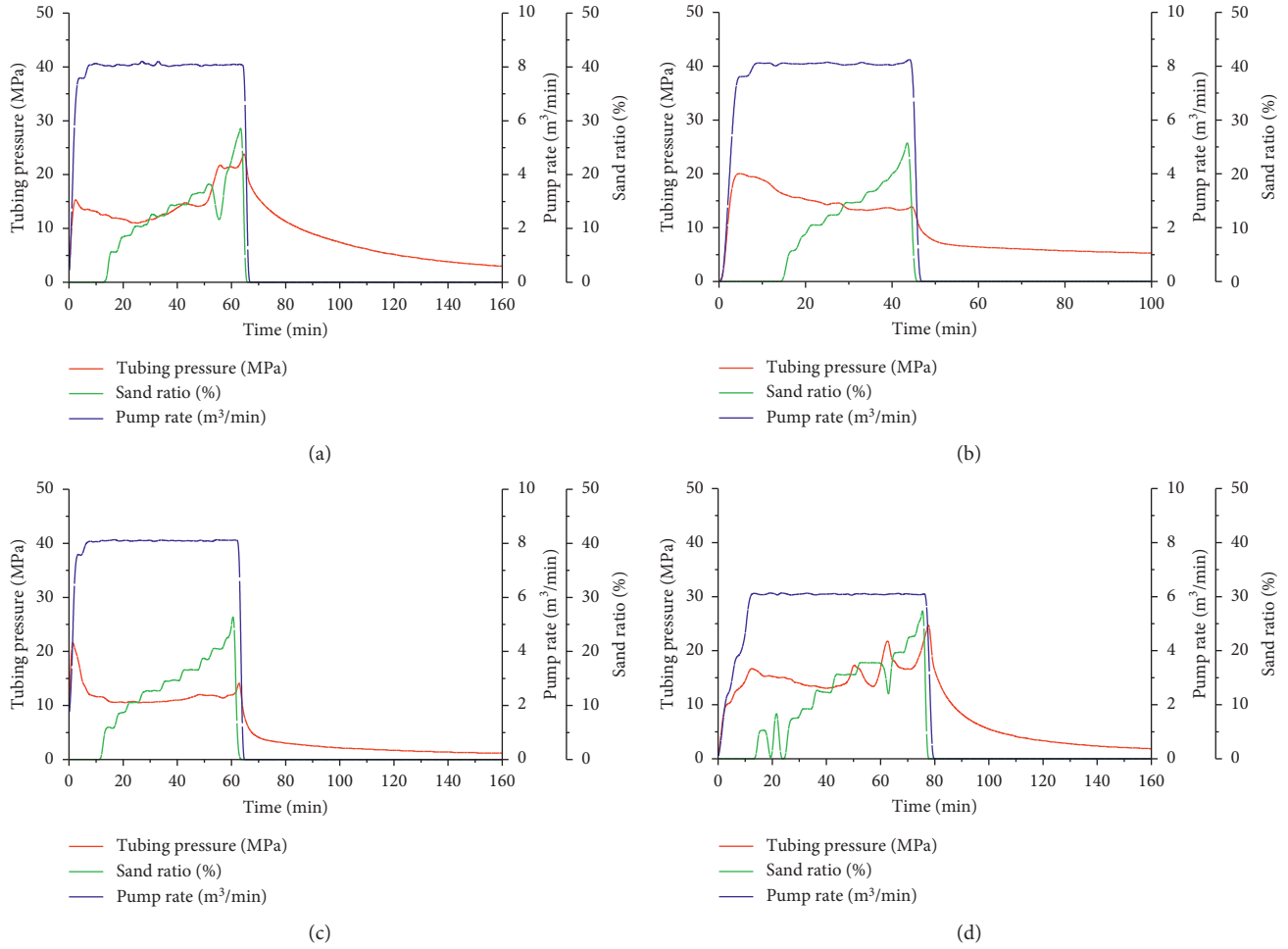


FIGURE 4: Four types of fracture operation curve: (a) ascending fracturing curve shape, (b) descending fracturing curve shape, (c) stationary fracturing curve shape, (d) mixed fracturing curve shape.

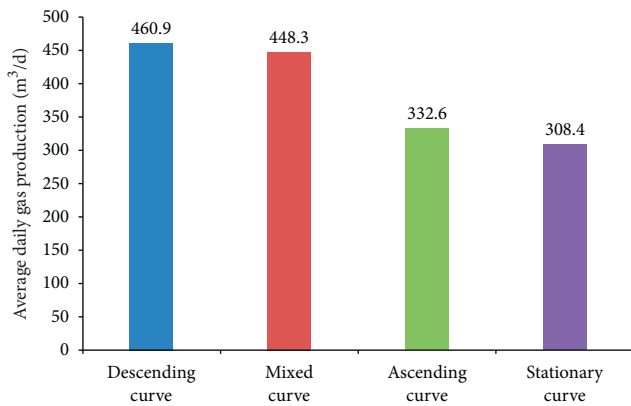


FIGURE 5: Comparison of average daily gas production for different fracturing curve shapes.

into two dimensions, and the sum of the minimum distances from data to the plane is maximized.

$$\min = \left\| \frac{1}{2} \|w\|^2 \right\|. \quad (8)$$

Introducing the slack variable at the same time, the above formula can be expressed as

$$\min = \left\| \frac{1}{2} \|w\|^2 + C \sum_{i=1}^n \xi_i \right\|. \quad (9)$$

This two-class problem is transformed into a constrained minimum problem. The Lagrange function is introduced to solve the above problems, and the optimal classification function is obtained:

$$f(x) = \text{sgn} \left\{ \left[\sum_{i=1}^n \alpha_i y_i (x_i \cdot x_j) \right] + b \right\}. \quad (10)$$

For the problem of nonlinear classification, the support vector machine maps the sample data to a high-dimensional feature space and then seeks the optimal classification surface from the high-dimensional feature space, as shown in Figure 6. The optimal classification function can be obtained by solving

$$f(x) = \text{sgn} \left\{ \left[\sum_{i=1}^n \alpha_i y_i \Phi(x_i) \cdot \Phi(x) \right] + b \right\}. \quad (11)$$

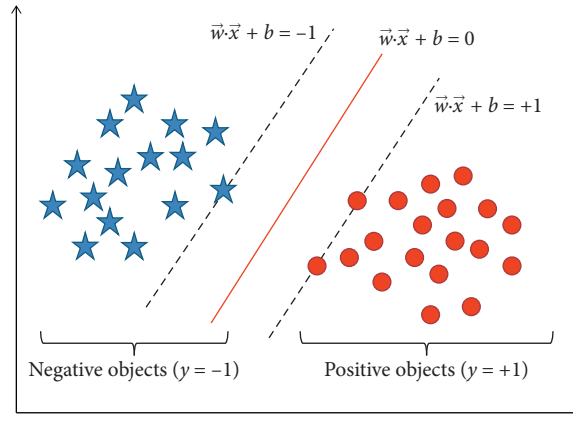


FIGURE 6: Schematic of support vector machine.

TABLE 1: Fracturing performance classification of coal-bed methane wells.

Well	Horizontal in situ stress difference (MPa)	Fracturing friction (MPa)	Net pressure (MPa)	Fracture morphology	Fracturing curve shape	Average daily gas production (m^3/d)	Predicted classification results
1	2.55	2.18	0.47	Complex morphology	Descending shape	674.19	I
2	2.39	2.92	1.26	Complex morphology	Mixed shape	546.59	I
3	2.94	2.86	0.7	Complex morphology	Descending shape	538.66	I
4	3.12	2.25	0.5	Horizontal morphology	Mixed shape	387.31	II
5	3.18	3.43	1.57	Complex morphology	Mixed shape	386.09	II
6	3.52	3.6	2.69	Horizontal morphology	Ascending shape	353.33	III
7	3.29	3.54	1.58	Complex morphology	Mixed shape	310.77	III
8	3.39	4.13	3.71	Complex morphology	Ascending shape	276.92	III
9	3.67	6.92	5.66	Horizontal morphology	Mixed shape	266.01	III
10	3.94	5.02	4.49	Vertical morphology	Stationary shape	243.72	III

Input vector of known sample feature parameters is as follows: $x = (x_1, x_2, \dots, x_n)$, where x_i is the selected parameter. Normalize x by $x = (x - x_{\min}) / (x_{\max} - x_{\min})$. The output vector $y = (y_1, y_2, \dots, y_m)$ is classified based on fracturing effect. The classification function is calculated by programming, and a model is established by test data. Finally classification result is performed based on the target well data.

The fracturing effect is mainly related to the final fracture morphology of fracturing operation. Therefore, the above five indexes for evaluating the fracture morphology and the difficulty of fracture propagation of the coal-bed methane fracturing operation are combined, and the fracturing effect of the fracture is predicted by the support vector machine method.

4. Application

Through the support vector machine modeling, the above five indexes, namely, horizontal in situ stress difference, fracturing friction, net pressure, fracture morphology, and fracturing curve shape, are selected to be input parameters and output parameters and are fracturing effect levels. The evaluation of the fracturing effect levels is based on the average daily gas production after fracturing, which can be divided into three grades: I, II, and III.

The fracturing wells in the block S of Qinshui Basin are used as training samples. 10 target wells are predicted, and the fracturing classification of each well can be obtained, as shown in Table 1. The prediction results show that the predicted classification results of the SVM model have a

good correlation with the average daily gas production of each well, and the error is small, which indicates the correctness of the SVM model.

5. Conclusion

- (1) Five evaluation indexes are established to evaluate the fracturing effect of coal-bed methane wells, namely, horizontal in situ stress difference, fracturing friction, net pressure, fracture morphology, and fracturing curve shape.
- (2) The research shows that the smaller the horizontal in situ stress difference, the fracturing friction, and the net pressure of shut-in pump are, the better the fracturing effect is. Complex fracture morphology and the descending and mixed type of the fracturing curve have better fracturing effect.
- (3) Based on the five fracturing evaluation indexes, a model for evaluating the classification of fracturing effect is established by the support vector machine. The fracturing effect can be divided into three grades: I, II, and III. The field application results of the model indicate that the fracturing classification evaluation error is small and satisfy the requirements of actual prediction. The model has important guiding role in the prediction of fracturing effect and capacity risk assessment of coal-bed methane wells.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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