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Research Article

Investigation on the CBM Extraction Techniques in the Broken-Soft and Low-Permeability Coal Seams in Zhaozhuang Coalmine

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To enhance the coalbed methane (CBM) extraction in broken-soft coal seams, a method of drilling a horizontal well along the roof to hydraulically fracture the coal seam is studied (i.e., HWR-HFC method). We first tested the physical and mechanical properties of the broken-soft and low-permeability (BSLP) coal resourced from Zhaozhuang coalmine. Afterward, the in situ hydraulic fracturing test was conducted in the No. 3 coal seam of Zhaozhuang coalmine. The results show that (1) the top part of the coal seam is fractured coal, and the bottom is fragmented-mylonitic coal with a firmness coefficient value of less than 1.0. (2) In the hydraulic fracturing test of the layered rock-coal specimens in laboratory, the through-type vertical fractures are usually formed if the applied vertical stress is the maximum principal stress and is greater than 4 MPa compared with the maximum horizontal stress. However, horizontal fractures always developed when horizontal stress is the maximum or it is less than 4 MPa compared with vertical stress. (3) The in situ HWR-HFC hydraulic fracturing tests show that the detected maximum daily gas production is 11,000 m^3, and the average gas production is about 7000 m^3 per day. This implies that the CBM extraction using this method is increased by 50%~100% compared with traditional hydraulic fracturing in BSLP coal seams. The research result could give an indication of CBM developing in the broken-soft and low-permeability coal seams.

1. Introduction

Coalbed methane (CBM) resource is abundant in China. After decades of development, commercial CBM extraction has been achieved in Qinshui and Ordos Basin [1–3], especially in coal seams with excellent storage conditions, large gas content, and undamaged primary structure coal seams [4, 5]. However, the broken-soft and low-permeability (BSLP) coal seams are widely distributed in China, such as Jiaozuo, Huainan, and Lu'an coal fields, resulting in a relatively low CBM production [6–8].

The BSLP coal is always broken into pieces, grains, fragments, or powders, in which the original natural fracture network is destroyed or disappeared. Therefore, the BSLP coal has low mechanical strength and low permeability. When conducting drilling and hydraulic fracturing in the BSLP coal seam, problems such as difficulty in hole formation, poor cementing quality, and borehole blockage could occur.

To date, previous studies found that the pores, specific surface area, and roughness of coal increased with the broken degree of coal structures. Therefore, BSLP coal may have a high gas storage capacity [9, 10]. In primary structural coal, exogenous and endogenous discontinuities are well developed and the connected fracture/pore structures provide an effective channel for gas flow. In BSLP coal, semiclosed holes or fractures with poor permeability are often developed, which may result in short and narrow fracture networks [11, 12]. Specifically, for the mylonite coal with a large degree of fragmentation, only some microcracks exist in coal, which would further reduce the coal permeability. Therefore, it is difficult to form effective fracture networks when using hydraulic fracturing techniques in BSLP coal seams [13].
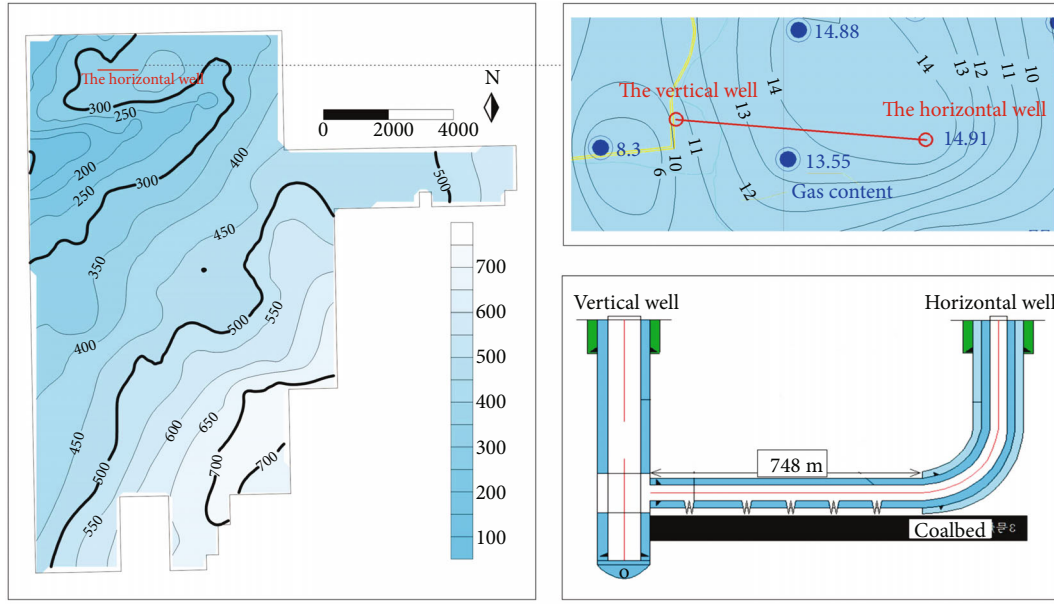
FIGURE 1: Buried depth isogram of No. 3 coal seam in Zhaozhuang coalmine and well structures.
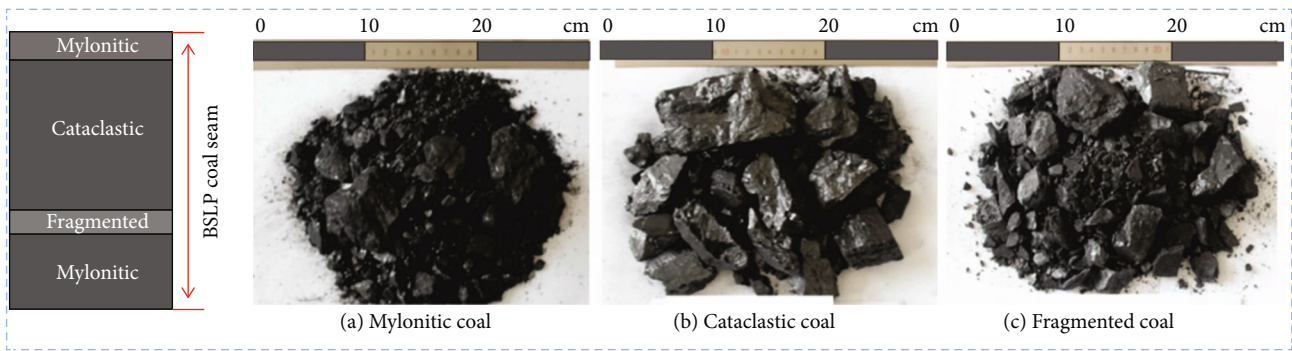

(a) Mylonitic coal   (b) Cataclastic coal   (c) Fragmented coal

FIGURE 2: Coal sample of Zhaozhuang coalmine.

TABLE 1: Coal structure characteristics and description of Zhaozhuang coalmine.

Stratum	Thickness/ m	Macrolithotype	Structure	Description
1	0.40~0.50	Semidark	Mylonitic	Mylonite, semidark coal, mainly in the form of scales, hand twist into powder, local visible
2	2.60-3.80	Semibright	Cataclastic	Mainly cataclastic coal, with thin layer of crushed coal, horizontal bedding, dip angle of 2°~3°, fissure development, fissure cut through bedding oblique crossing, a few centimeters to dozens of centimeters in length, fissure dip angle of 40° and 120°, obviously wrinkled mirror face
3	0.20~0.40	Semidark	Fragmented	Mainly fragmented coal, hand twist into granules
4	0.30~1.20	Semidark	Mylonitic	Mylonite coal, mainly in the form of scales, hand twisted into powder. At the top of the layer, there is a thin layer of carbonaceous mudstone gangue, which can be seen locally.

The virtual reservoir is a new concept considering drilling the horizontal well in the roof or floor strata but not in the coal seam [14, 15]. This technique has been successfully verified in many in situ projects [16, 17]. However, the hydraulic fracturing mechanism and fracture propagation along the coal/rock interface are not clear yet, which need to be further investigated. Therefore, in this study, we first studied the mechanical and hydraulic properties of the BSLP coal samples resourced from Zhaozhuang coalmine. Afterward, the numerical simulation was conducted to understand the HWR-HFC effect. Finally, the in situ test was done followed by some conclusions.
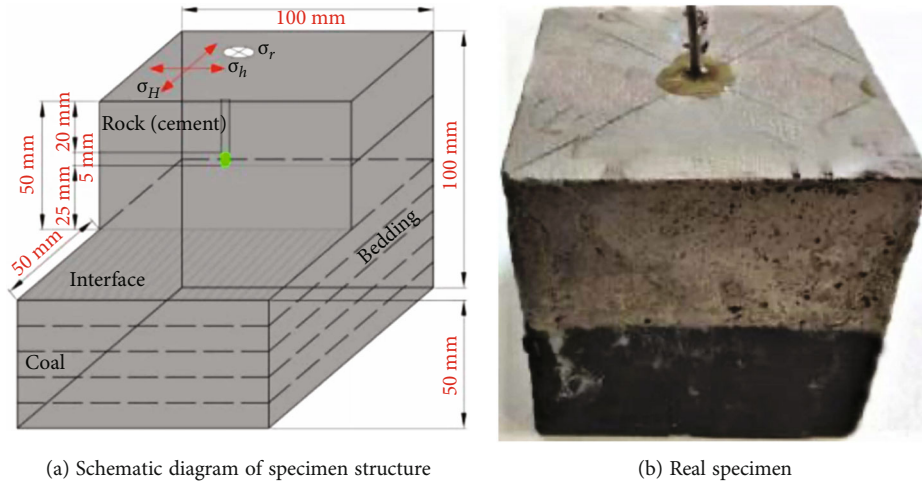
(a) Schematic diagram of specimen structure

(b) Real specimen

FIGURE 3: Schematic diagram of coal-rock assemblage.

TABLE 2: Hydraulic fracturing test parameters and results.

| Number	Stress state/MPa			Injection rate ml/min	Fracturing fluid	Fracture shape
	σ_h	σ_H	σ_V			
01#	3	5	6	20	Water	Coal seam unpenetrated
02#	3	5	7	20	Water	Coal seam unpenetrated
03#	3	5	7	20	Water	Coal seam unpenetrated
04#	3	5	8	20	Water	Coal seam unpenetrated
05#	3	5	8	20	Water	Coal seam unpenetrated
06#	3	5	9	20	Water	Coal seam penetrated
07#	3	5	9	20	Water	Coal seam penetrated
08#	3	5	9	20	Water	Coal seam penetrated
09#	3	5	15	20	Water	Coal seam penetrated
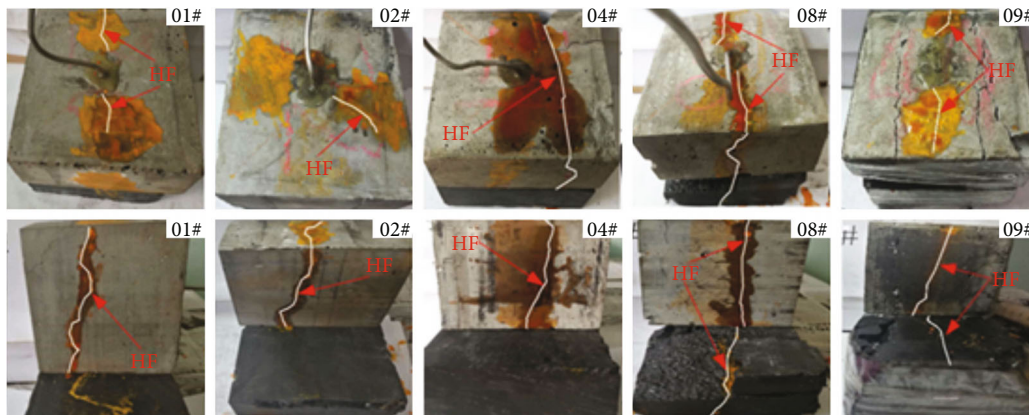
FIGURE 4: Fracture morphology distribution diagram of hydraulic fracturing in Zhaozhuang coal sample.

2. Geological Conditions of the BSLP Coal Seam

Zhaozhuang coal field is located in the Southern Qinshui Basin. Controlled by regional tectonic movement, it is a NNE regional monocline with a tendency to NE, at an angle of 5~10°. It contains faults and collapse columns, on the basis of which develop series of wide and gentle folds in the direction of NNE, formed the formation of wave ups and downs. The main faults and folds are in the direction of NNE, and the associated secondary faults are NE and NEE trending. The coal-bearing strata in the area are mainly the Taiyuan Formation (C_3t) of the Upper Carboniferous
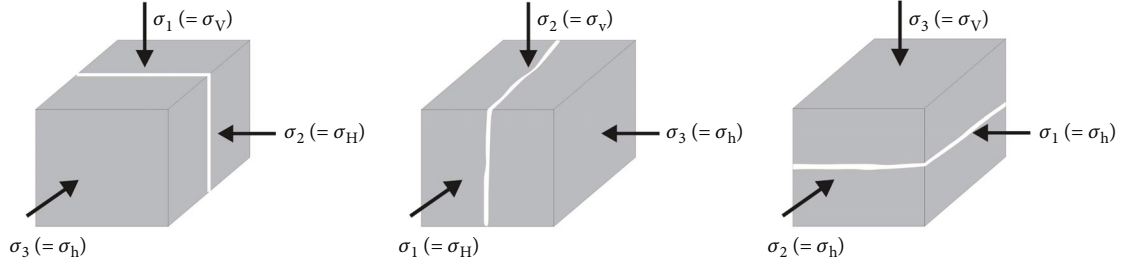
FIGURE 5: Relationship between fracture morphology and in situ stress state.

TABLE 3: Hydraulic fracturing monitoring results.

Well	Coal seam depth	Fracture shape	Area
CZ-X1	304.54-310.74	Horizontal	Adjacent area
CZ-X2	469.54-475.64	Horizontal	Adjacent area
HD-X1	490.50~496.40	Vertical	Adjacent area
ZZ-X1	594.11~598.53	Vertical	Research area
ZZ-X2	681.10~687.18	Vertical	Research area
ZZ-X03	684.78~689.4	Vertical	Research area

Series and the Shanxi Formation (P_1s) of the Lower Permian Series, with coal lines occasionally developed in the Lower Shihezi Formation and Benxi Formation. There are 15 layers of coal in Shanxi and Taiyuan Formation. Shanxi Formation contains 3 layers of coal, named No. 1, No. 2, and No. 3 from top to bottom. Taiyuan Formation contains 12 layers, named Nos. 5, 6, 7, 8_{-1}, 8_{-2}, 9, 11, 12, 13, 14, 15, and 16. The accumulated total thickness of Shanxi Formation and Taiyuan Formation is 118.19-206.86 m, generally 153.18 m. The total thickness of coal seam is 3.38-18.21 m, 12.80 m on average, and the coal coefficient is 8.33%.

The No. 3 coal seam in Zhaozhuang coalmine is a typical BSLP coal seam with a thickness of 0.50~6.60 m and a buried depth of 150~990 m. The floor elevation of the coal seam is between 120 m and 780 m (Figure 1). The ranks of coal are mainly lean and anthracite coal with a vitrinite maximum reflectivity (R_{omex}) of 2.23%-2.83%. The average Langmuir volume, pressure average, and gas saturation degree of the No. 3 coal are 32.21 cm^3/g, 2.04 MPa, and 59.6%, respectively. The in situ stress of this coal seam is 8.43~10.89 MPa with an underground stress gradient of 1.12~1.53 MPa/100 m. The reservoir gas pressure is 3.53~6.25 MPa with a gas pressure gradient of 0.46~0.86 MPa/100 m, which implies that this BSLP reservoir lacks gas pressure.

The layered characteristics of the coal seams are as follows: a layer of mylonitic coal at the top and bottom of No. 3 coal seam (Figure 2(a)), in which a thickness of about 0.45 m at the top and 0.3-1.20 m at the bottom (Table 1). Macroscopic coal is a kind of semidark coal, and the value of its hardness coefficient is less than 0.30. The upper part is mainly cataclastic coal (Figure 2(b)) with a thickness of 2.60~3.80 m, and the average hardness coefficient is about 0.60. Most of the lower part is fragmented coal (Figure 2(c)).

3. Material and Method

In the experimental test, combined rock and coal samples were employed. The sample consists of two parts: the upper part is a cement mortar sample, and the lower part is coal (Figure 3). The sizes of cement and coal samples are all $100 \times 100 \times 50$ mm. During sample preparation, the cement mortar was placed on top of the coal sample to form a whole. Therefore, the dimension of the whole sample is $100 \times 100 \times 100$ mm.

A borehole is drilled in the center of the sample with a size of $\Phi6$ mm $\times 25$ mm. Then, a steel pipe ($\Phi4 \times 150$ mm) is placed into the borehole. The sealing depth of the borehole is at the top 20 mm. The bottom 5 mm would be an open-hole section used for hydraulic fracturing. The structure diagram is shown in Figure 3 in detail. The uniaxial compressive strength, tensile strength, elastic modulus, and Poisson's ratio of the coal are 8.1 MPa, 1.26 MPa, 1.37 GPa, and 0.233, respectively. The sample was compressed by a triaxial compression test. The maximum horizontal stress and minimum horizontal stresses are 5 MPa and 3 MPa, respectively. The vertical stress varies from 6 to 15 MPa.

4. Experimental Test Results

Table 2 shows the failure modes of hydraulic fractured samples. Correspondingly, Figure 4 presents the pictures of samples after the hydraulic fracturing test. It can be seen that hydraulic fractures were only vertically developed in the cement when the vertical stress is less than 8 MPa. The fractures were extended along the interface between cement body and coal, such as samples 01#, 02#, and 04#. However, hydraulic fractures were propagated to the coal body at axial loading between 9 MPa and 15 MPa. Therefore, the hydraulic fracture shape would be changed with stress conditions. Specifically, when the difference between the vertical stress and the maximum horizontal stress increases over 4 MPa, the hydraulic fracture could punch into the coal body.

Previous studies concluded that hydraulic fractures would be developed in three forms when encounter the rock-coal interface, i.e., penetration type, crack arrest type, and deflection type [18]. When vertical stress is the maximum stress and the difference with maximum horizontal stress is over 5-6 MPa, vertical fractures would be formed. However, when the maximum stress is horizontal or it is not much different from the vertical stress, horizontal

TABLE 4: Physical mechanics test results of CBM well test.

Name	Elastic modulus/GPa	Poisson's ratio	Minimum horizontal principal stress/MPa	Maximum horizontal principal stress/MPa	Vertical stress/MPa
Coal seam roof (mudstone)	2.36	0.32	9.84	10.95	13.22
3# (upper hard layer)	0.98	0.35	7.67	8.92	13.31
3# (lower soft layer)	0.85	0.38	7.67	8.92	13.31

TABLE 5: Segmentation parameters of horizontal well.

| No.	Bridge plug location (m)	Segment length (m)	Perforation interval/length (m)	Proppant (m³) Fine sand	Medium sand	Rough sand	Fracturing fluid volume (m³)
1st	1549	92	1525-1528/3	3.08	38.53	12.94	702
2nd	1457	77	1433-1436/3	2.04	24.42	/	523
3rd	1380	119	1357-1360/3 1317-1320/3	/	75.98	/	1452
4th	1261	115	1237-1240/3 1194-1197/3	/	43.90	/	1584
5th	1146	79	1121-1124/3	/	62.03	/	2023
6th	1067	96	1044-1047/3	/	62.54	/	770
7th	971	91	947-950/3	/	56.43	10.39	814
8th	880	94	856-859/3	/	55.87	9.73	853
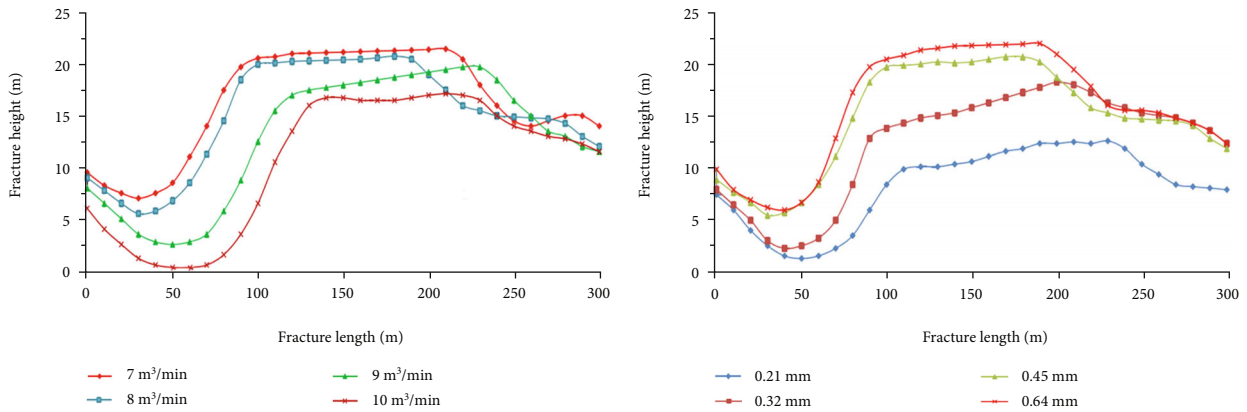
FIGURE 6: Influence of different fracturing fluid displacement and proppant particle size on the sand formation.

fractures or penetration type will be achieved [19–25]. These conclusions are consistent with our results.

5. In Situ HWR-HFC Technique Application

5.1. Well Locations. The in situ stress of coal includes vertical stress (σ_V) and horizontal stress (σ_H and σ_h). The vertical stress is mainly affected by the gravity of the overburden and can be estimated by the weight of the overburden. The characteristics of stress field are not only the key factors affecting the stability of coalmine roof, but also of great significance in the permeability prediction of coalbed methane reservoir and the morphology of fracture expansion. In general, when $\sigma_V > \sigma_H > \sigma_h$, it is normal fault stress mechanism, and hydraulic fracturing is more likely to produce vertical fractures (Figure 5). When $\sigma_H > \sigma_h > \sigma_V$ is the mechanism of reverse fault stress, hydraulic fracturing is more likely to produce horizontal fractures [26, 27].

The critical depth of in situ stress transfer in North China is about 400~1000 m. Above this critical depth, the horizontal stress would be the maximum stress. In this study, the average buried depth of the No. 3 coal seam is 667 m. Furthermore, fracturing monitoring results (Table 3) also show that the critical depth of in situ stress of No. 3 coal seam is about 500 m. Therefore, to produce vertical fracture from the roof towards coal seam, the well location should be prioritized at a buried depth deeper than 500 m.

Microseismic monitoring and fracture disclosure test results in coalmines show that hydraulic fractures extend in an elliptical shape. Furthermore, the hydraulic fracture
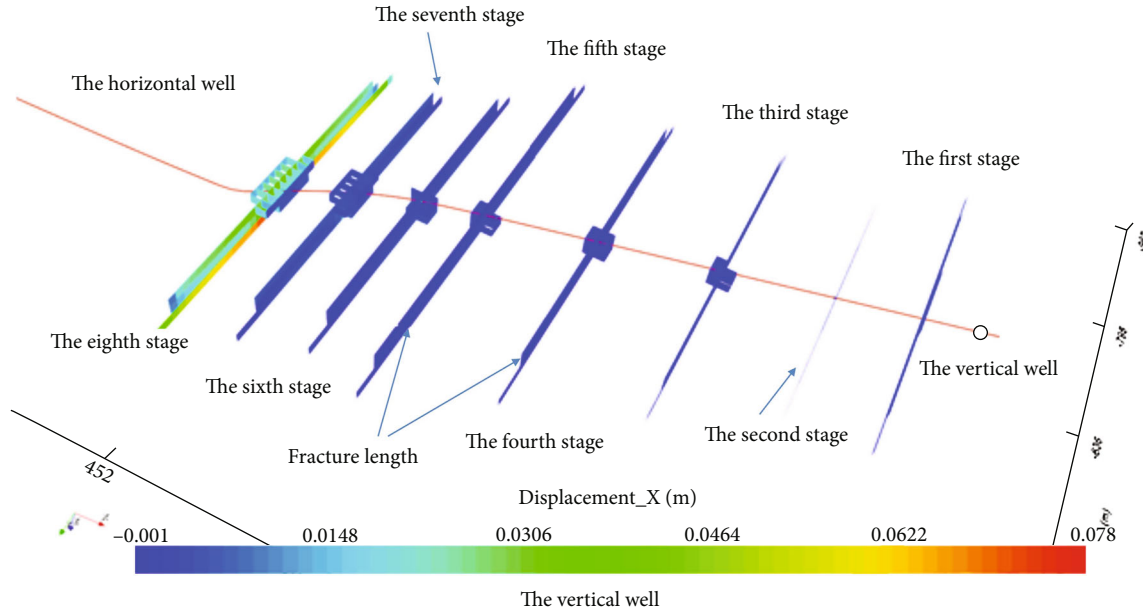
FIGURE 7: Numerical simulation results of horizontal good fracturing fractures

TABLE 6: Fracture monitoring results of horizontal well.

Fracture data		The 3rd stage (m)		The 7th stage (m)
		1357-1360	1317-1320	947-950
Length (m)	Left wing	43	46	100
	Right wing	0	68	74
	The whole wing	43	114	174
	Height (m)	11	16	12
	Direction (°)	SW70°	NE49°	NE45°
	Attitude	Vertical		Vertical

would extend along the maximum horizontal stress direction and perpendicular to the minimum horizontal stress [28, 29]. In the target area, the maximum horizontal stress direction is generally NE30-45° and the main fracture extension direction of the adjacent wells is NE42°. To ensure effective communication between the wellbore and coal seam, the horizontal wellbore trajectory should be approximately vertical or oblique to the direction of the main fracture. Ideally, the horizontal well track should be approximately perpendicular to the direction of the main fracture with an orientation of about 138°. However, considering the geological conditions, the stability of the strata, and the distance between wells, the orientation of the horizontal well is finally determined as 96°.

The final depth of the vertical well is 703 m, while the coal seam is at a depth of 643.05 m. According to the mechanical test results of the BSLP coal and well test results (Table 4), the vertical stress is greater than the horizontal stress. Therefore, vertical fractures will be formed during hydraulic fracturing. Furthermore, the maximum principal stress of the No. 3 coal seam is vertical stress, which is greater than the maximum horizontal stress (over 4 MPa).

Therefore, the hydraulic fractures will be punched from rock into the coal seam.

If the horizontal well is located along the floor, the coal particles are easy to flow into the horizontal well during drainage, which would weaken the efficiency of CBM extraction. Therefore, it is more reasonable to locate the horizontal well along the floor. Considering the roof lithology and perforation penetration ability, 0~2.0 m between the horizontal well and coal seam would be better.

5.2. Directional Perforation and Staged Fracturing Technology

(1) Horizontal well segmentation

The length of the horizontal well is about 800 m. During the segmentation designing, firstly, the horizontal segment was equally divided into several parts. Afterward, adjust the section length according to the geological conditions. The horizontal well segmentation should be the priority considering these conditions, i.e., close to the roof, easy cemented, and far away from the casing collar. Furthermore, the
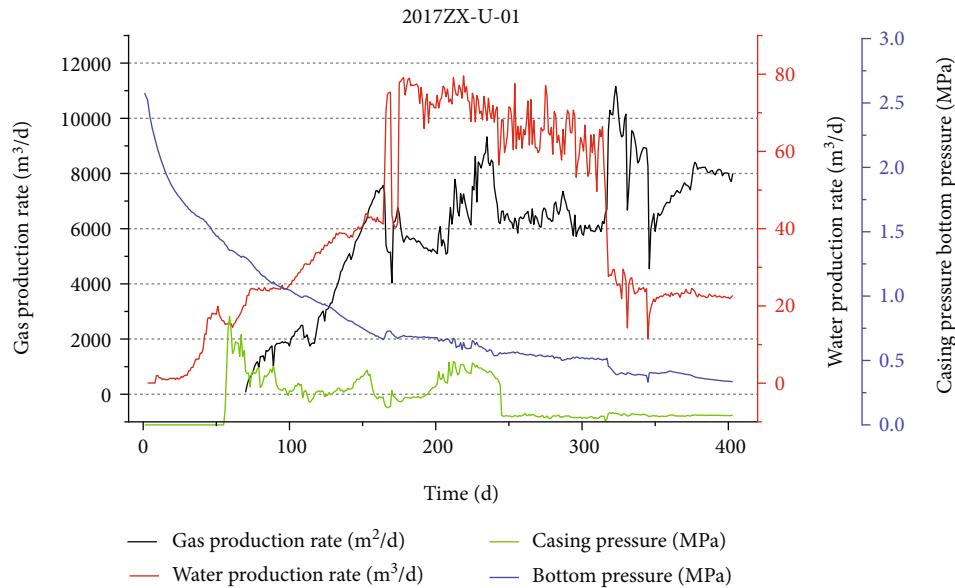
FIGURE 8: Drainage and production curve of ZX-U-01.

spacing between fractures should be controlled at about 80 m-120 m. The segmentation parameters are listed in Table 5 in detail.

(2) Deep penetration directional perforation technology

Composite deep penetration directional perforation technology was adopted to penetrate through the steel casing, cement ring, and the rock strata at the top of the coal seam, which could ensure the fracture extends to the No. 3 coal seam. This technology could create effective communication between the coal seam and wellbore and make a secondary impact on the formation by using gunpowder. This would produce multiple fracture networks in the near well zone.

The depth of deep penetration perforation channels can reach 1.2-1.5 m. The longest can reach 5 m, which greatly improves the perforating effect. According to the production casing size (φ139.7 mm), 95 mm perforating gun and 102 type perforating charges were selected. The perforating sections were divided into 8 sections and 10 clusters, each cluster was 3 m in length, and the hole density was 10 holes/m (Table 5).

(3) Fracturing technology

To solve the problems of difficulty in fracture initiation, extension, and support failure in the BSPLP coal seam, the fracturing technology of "large injection flux and high sand ratio" was employed. The comparative analysis of sand bar morphology under different fracturing fluid displacement rates (7-10 m³/min) shows (Figure 6) that the displacement rate is proportionate to the equilibrium height of the proppant bar. The proppant settlement near the fracture inlet is unconspicuous due to the high displacement rate nearby. The overall shape of the proppant bar is laid deep into the fracture. According to the comparative analysis of sand bar

morphology under different proppant particle sizes (0.21 mm-0.64 mm), the sand bar morphology of proppant moves to the depth of the fracture with the decrease of proppant particle size and tends to be laid to the fracture entrance position when the particle size is larger. Combined with the closing pressure and the length of the horizontal section, the fracturing flow rate was determined as 8-10 m³/min and the maximum sand ratio was 20%. Proppant mainly consists of medium sand and rough sand, with a small amount of fine sand.

5.3. Numerical Modeling

(1) Numerical models

A 3D numerical software named USTIM was used to conduct hydraulic fracturing numerical simulation. In the numerical modeling, clear water was used as fracturing fluid and the fluid flow was set as 10 m³/min. The amount of fracturing fluid and proppant in each section are shown in Table 5 in detail. Parameters in the numerical modeling are as follows: The bursting pressure of coal is 8.82 MPa, and the fracture gradient is 1.41 MPa/100 m. The closing pressure of fractures is 7.67 MPa. The reservoir gas pressure and pressure gradients are 1.97 MPa and 0.308 MPa/100 m, respectively. The average elastic modulus, Poisson's ratio, and the tensile strength of rock are 31.03 GPa, 0.28, and 6.98 MPa, respectively. The average elastic modulus, Poisson's ratio, and the tensile strength of coal are 39.04 GPa, 0.25, and 1.26 MPa, respectively.

(2) Fracture propagation monitoring and analysis

The lengths of induced fractures in the different sections are variable (Figure 7), which may be caused by the difference in fluid flux. For example, in the second hydraulic fracturing section, the fracture length is only 142 m under the

injection volume of 533 m^3. In the fifth section, hydraulic fracturing was conducted three times and the injection volume is about 2000 m^3. The fracture length in the fifth section was up to 252 m. Therefore, a smaller distance between the hydraulic fracturing site and well implies a better stimulating effect.

The surface microseismic monitoring device was employed to monitor the fracture propagation in the third and seventh sections. The results show that (Table 6) the fracture extends to NE. The seventh section adopts a single cluster perforation, and the total fracture length is 174 m, including 100 m on the left wing and 74 m on the right. Two clusters of perforations were used in the third stage. The first shot created 43 m fractures in the left, and the second shot created 114 m in length, in which the left fracture was 46 m and the right was 68 m.

6. In Situ CBM Extraction Results

The CBM extraction well named ZX-U-01 is the first horizontal well drilled in the roof of the Zhaozhuang coalmine. The horizontal well was divided into 8 sections, and each section was perforated by 10 clusters. Specifically, in the third and fourth sections, the single section with two cluster perforations was used to test the hydraulic fracturing efficiency. However, due to this method needed a higher injection pressure, secondary hydraulic fracturing was used. Similarly, the fifth section is far from the coal seam (over 2 m), and a third hydraulic fracturing was implemented. This well adopts the pumping method of a vertical good pumping, horizontal well, and vertical well combined producing gas.

At the initial stage of drainage (Figure 8), the bottom hole pressure was 2.408 MPa and the initial liquid level was 257 m above the roof of the No. 3 coal seam. The daily water volume gradually increased to 80 m^3/d. The maximum daily gas production reached 11,000 m^3/d. And the average gas production is about 7000 m^3/d. The cumulative water production and the cumulative gas production are 17,215.92 m^3 and 2350000 m^3, respectively. Compared with the traditional CBM extraction, gas production is increased by 50%-100%.

7. Conclusions

(1) The coal seam of the Zhaozhuang coalmine mainly consists of two layers: The top part of the coal seam is fractured coal, and the bottom is fragmented-mylonitic coal with a firmness coefficient value of less than 1.0. Specifically, a thin fragmented-mylonite layer is developed in the upper cataclastic coal layer in some areas

(2) The propagation law of hydraulic fracture in combined coal and rock samples was revealed. If the applied vertical stress is the maximum stress and greater than the maximum horizontal stress, the vertical hydraulic fractures are mostly developed, while if horizontal stress is the maximum or it is not much

different from vertical stress, the horizontal fractures are easily formed or propagated along the interface between rock and coal

(3) By using the HWR-HFC technique, a maximum daily CBM gas production of 11,000 m^3/d was achieved and the average is about 7,000 m^3/d. This gas production is increased by 50%-100% compared with other types of horizontal wells in the study area

Data Availability

The data used in this paper are obtained from the experiment of the research and its partners.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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