

Research Article

Mechanism of Coal Seam Permeability Enhancement and Gas Outburst Prevention under Hydraulic Fracturing Technology

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In view of the high gas pressure and low permeability of deep coal seam, it is difficult to control gas, which affects the safety production of coal mine. The technical scheme of hydraulic fracturing to improve the permeability of coal seam is put forward, and the gas drainage technology is used to control the gas emission of coal seam. The fracturing effect under different water pressure, different gradient fracturing times, and in situ stress is analyzed by using 3DEC (3-Dimensional Distinct Element Code) discrete element software. The simulation analysis and field verification results show that the coal seam gas pressure increases linearly with the buried depth. In situ stress characteristics and hydraulic strength are the key factors affecting the effect of hydraulic fracturing. The fracturing radius increases with the increase of flow. When the construction pressure of hydraulic fracturing test is 18 MPa, the distance between fracturing hole and drainage hole is 8.5 m. The actual measurement shows that after hydraulic fracturing and gas drainage, the maximum gas emission is reduced by 51%, and the average gas emission is reduced by 58%.

1. Introduction

China's coal reserves rank high in the world, and most of the coal seams are buried underground. As one of the main hazard sources in underground coal face mining, gas seriously threatens the production safety of fully mechanized coal face and the personal safety of operators and then restricts the coal mining efficiency. With the deep mining of coal mines in China, the in situ stress, gas pressure, and gas content increase, the coal seam is soft, and the air permeability decreases, which leads to the difficulty of gas drainage and the increase of outburst risk.

For coal mine gas control and related rock mechanic problems, many experts have carried out relevant research. For example, Li et al. [1] use pulse hydraulic fracturing technology to prevent coal mine gas disasters. The results show that the pressure change in the process of pulse hydraulic fracturing reflects the expansion of fractures and conducive to the expansion of fractures under the action of pulse pressure. The initial pressure during pulse hydraulic fracturing is negatively correlated with water volume and fracturing time. Li et al. [2] proposed the combination of surface and underground natural gas exploitation methods to realize joint exploitation; second, joint mining is realized by drilling up and down coal seams and along coal seams; third, the goal of joint mining of coal and coalbed methane. Wang et al. [3] established a three-dimensional gas drainage project and studied and verified the effect of soft rock protective layer in mining technology practice. You et al. [4] proposed an innovative and practical coal



(c) Lithologic histogram

FIGURE 1: Research target location and project overview.

mine gas risk assessment method to provide help for the prevention and control of coal mine gas accidents. Si et al. [5] established a constitutive equation of coal considering the closed pore effect. On this basis, the gas migration model of closed pore coal seam is established, including gas diffusion model between closed pore and open pore and fracture gas seepage model. Jun et al. [6] used high-pressure water jet slotting to release the gas pressure in the coal seam, increase the permeability of the coal body, improve the gas drainage efficiency, and eliminate the risk of outburst. Aguado and Nicieza [7] proposed that high-pressure water injection and mining protective coal seam methods can improve safety.

Song et al. [8] summarized and analyzed the latest technologies for controlling gas explosion. Guo et al. [9] analyzed the influence of faults on gas occurrence, and the research shows that the complexity of faults increases the difficulty of mine gas prevention and control and seriously threatens mine safety. Gao et al. [10] analyzed the influence of mining rate on in situ stress, which is also an important factor affecting gas emission. Lin et al. [11]



FIGURE 2: Regression trend line between gas content and coal seam buried depth.

proposed a cross hole hydraulic slotting technology for preventing and controlling coal and gas outburst disasters in coal roadway excavation. Zhou et al. [12] combined the stress balance equation and gas transport equation and simulated and calculated the distribution laws of displacement, stress, and gas pressure in solid on the basis of numerical simulation. Huang et al. [13] proposed measures to prevent and control gas explosion accidents by using fault tree analysis method. Mingzhong et al. [14] evaluated the deep buried in situ stress evaluation method. Gao et al. [15] studied the spatial propagation law of gas explosion in goaf of coal mine. Li and Hua [16] considered that gas release can also release rock mass strain energy. Cui et al. [17, 18] analyzed the influencing factors of hydraulic fracturing.

In recent years, gas casualties have occurred frequently. For example, 44 people died in the gas explosion accident in Xiaojiawan coal mine; gas outburst accident in Dengfeng coal mine killed 5 people; gas explosion in Dashan coal mine killed 12 people. According to the current research status and the actual engineering geological characteristics of the target mine, this paper plans to use the method of hydraulic fracturing for gas drainage. Through numerical simulation, DFN is used to model the fracture field, and the effects of fracturing time, water pressure, and in situ stress on the fracturing effect are analyzed. Finally, the appropriate construction method is selected for engineering test research.

2. Engineering Background

2.1. Engineering Geology. Donggou coal mine is located in China, Xinjiang, and 56 km south of Hutubi County, as shown Figure 1. The administrative division is under the jurisdiction of Shiti Township, Hutubi County. The minable coal seams in Donggou coal mine are B₁, B₂, B₃, B_4^{1} , and B_4^{2} , and the fault structure in the mining area is relatively developed. Controlled by the regional monoclinal structure, the mine field is generally a monoclinal structure gently inclined to the north, with a dip of 10°-25° and inclination of 10°-15°. The strata in the mining area from old to new are Qianxia Formation (c2qx) of Middle Carboniferous, Xiaoquangou group (T2~3xq) of Middle Upper Triassic, Badaowan Formation (j1b) and Sangonghe Formation (j1s) of Lower Jurassic, Xishanyao Formation (J2x) and Toutunhe Formation (j2t) of Middle Jurassic, Qigu Formation (J3q) and Kalaza Formation (J3k) of Upper Jurassic, and the first subgroup of Tugulu Formation of Lower Cretaceous (k1tga). Xishanyao Formation of Middle Jurassic is the main coal bearing formation in the mining area.

The target working face studied in this paper is located in B4² coal seam, with buried depth of $136.38 \sim 50.24$ m, thickness of $1.67 \sim 5.23$ m, and average of 3.13 m. The recoverable thickness is $1.67 \sim 3.77$ m, the average recoverable thickness is 2.95 m, the standard deviation of thickness is 0.93, and the coefficient of variation is 29%. The lithology of the roof is fine sandstone, siltstone, argillaceous siltstone, and mudstone, and the lithology of the floor is coarse sandstone, fine sandstone, siltstone, argillaceous siltstone, and carbonaceous mudstone.



FIGURE 3: Regression trend line between gas pressure and coal seam buried depth.



FIGURE 4: Mechanical model of crack initiation under hydraulic fracturing.

2.2. Gas Distribution and Emission Characteristics. The roof and floor of $B4^2$ coal seam are mudstone and carbonaceous mudstone with poor permeability, which is beneficial to the preservation of coal seam gas. In addition, the fractures within the mine range are not very developed, so the gas connectivity of each coal seam is relatively poor. The measured results show that with the increase of coal seam burial depth, the proportion of methane increases and the gas content increases. As shown in Figure 2, it shows the gas content under different burial depths. The results show that the gas content is about 1.2 m³/t when the burial depth is 190 m. Under the burial depth of 270 m, the gas content is as high as 4 m^3 /t, the burial depth increases by 1.42 times, and the gas content increases by 3.33 times.

According to the results in Figure 3, the gas pressure gradient of B_4^2 coal seam with buried depth is $0.34 \text{ m}^3/\text{t/km}$. Based on the analysis of gas emission law of transportation roadway, return air roadway, and working face, the measured value of gas emission from transportation roadway of working face is $5.9 \text{ m}^3/\text{min}$. The measured value of gas emission from transportation roadway is $4.28 \text{ m}^3/\text{min}$. During the mining of the working face, the gas emission reaches $15 \text{ m}^3/\text{min}$.



FIGURE 5: Numerical calculation discrete element model.

TABLE 1: Basic physical and mechanical parameters of coal and rock.

Compressive strength/	Tensile strength/	Elastic modulus/	Poisson's	Internal friction angle/	Friction coefficient	Density/
MPa	MPa	GPa	ratio	(°)		(kg/m ³)
10.12	2.18	2.49	0.28	35.22	0.734	1289

3. Hydraulic Fracturing Mechanism and Numerical Calculation Model

3.1. Mechanism of Increasing Coal Seam Permeability under Hydraulic Fracturing. Hydraulic fracturing started from oil and gas exploitation and is gradually applied to coal seam gas drainage. There are primary microfractures and pore structures in the coal body, but these structures are closed under the action of high ground stress, and the permeability channel is not fully open, resulting in internal gas accumulation. After high-pressure water is injected into the borehole, the stress on the borehole wall is concentrated and the primary fractures begin to expand and open. With the continuous fracturing, the fracture further expands around, thus increasing the permeability of gas flow. Figure 4 shows the schematic diagram of hydraulic fracturing. Formula (1) represents the stress at any point around the borehole [19, 20].

$$\begin{bmatrix} \sigma_t = \frac{\sigma_v + \sigma_H}{2} \left(1 - \frac{R^2}{r^2} \right) + \frac{\sigma_v - \sigma_H}{2} \left(1 + \frac{3R^4}{r^4} - \frac{4R^2}{r^2} \right) \cos 2\theta \\ \sigma_\theta = \frac{\sigma_v + \sigma_H}{2} \left(1 + \frac{R^2}{r^2} \right) - \frac{\sigma_v - \sigma_H}{2} \left(1 + \frac{3R^4}{r^4} \right) \cos 2\theta \\ \tau_{r\theta} = -\frac{\sigma_v - \sigma_H}{2} \left(1 - \frac{3R^4}{r^4} + \frac{2R^2}{r^2} \right) \sin 2\theta \end{bmatrix}.$$

$$(1)$$

Assuming that the water pressure is *p*, the stress load will be caused to the unit body around the hole wall. The stress caused by the water pressure is shown in

$$\sigma_r^{\ p} = p, \tag{2}$$

$$\sigma_{\theta}{}^{p} = -p. \tag{3}$$

When the stress $\sigma_{\theta}{}^{p}$ caused by water pressure is greater than or equal to σ_{θ} , cracks will occur around the hole wall. In conclusion, the characteristics of in situ stress and hydraulic strength are the key factors affecting the effect of hydraulic fracturing.

3.2. Numerical Calculation Model and Results. The threedimensional discrete element numerical simulation software 3DEC is used to establish the numerical calculation model. The size of the model is set as 40 * 40 * 60 m, the vertical stress is the weight of the overburden, and the lateral pressure coefficient is 1.3. The model uses DFN (discrete fracture network) for initial fracture division [21, 22], as shown in Figure 5. Assuming that the model medium has elastic brittle mechanical properties, its failure process belongs to elastic damage theory, and the physical and mechanical parameters of coal are shown in Table 1. The damage of the medium element of the model conforms to the maximum tensile strength and Mohr Coulomb criterion. In the numerical calculation, the model block adopts Mohr Coulomb criterion, and the joint adopts Coulomb slip criterion. Based on the coupling theory of pore and seepage, the coupling equation of stress joint seepage is introduced.

In the process of seepage flowing in the fracture grid, the seepage affects the rock mass stress distribution through the normal seepage force and tangential drag applied to the fracture wall, and the damage caused by stress redistribution reacts on the fracture seepage. The effect



(a) Hydraulic fracturing time 250 s



(b) Hydraulic fracturing time 350 s



(c) Hydraulic fracturing time 450 s

FIGURE 6: Continued.



(d) Hydraulic fracturing time 650 s

FIGURE 6: Characteristics of fracturing radius under different fracturing time (10 m³/h).



FIGURE 7: Relationship between effective fracturing radius and fracturing time.

of stress on seepage can be expressed by cubic law, such as formulas (4)-(5).

$$q_f = \frac{\gamma (b_0 + \Delta b)^3}{12\mu} J, \tag{4}$$

$$\Delta b = f(\sigma). \tag{5}$$

The influence of seepage on stress can be determined by the equivalent load of seepage force on the fracture surface at the node, as shown in

$$F_{i} = \frac{l}{6} \left(2p_{i} + p_{j} \right); F_{j} = \frac{l}{6} \left(p_{i} + 2p_{j} \right); T_{i}$$

$$= \frac{b_{0}}{4} \left(p_{i} - p_{j} \right); T_{j} = \frac{b_{0}}{4} \left(p_{j} - p_{i} \right).$$
(6)

In the formula, γ , μ represents the unit weight and dynamic viscosity coefficient of water, respectively. b_0 is the initial opening of the crack. Δb is the variable of crack opening under stress. p_i, p_j is the seepage hydrostatic pressure at both ends of the fracture. l is fracture aperture. F_i , F_j is the normal equivalent nodal force. T_i, T_j is the tangential equivalent nodal force. Fracturing time is the key factor affecting the effective radius of hydraulic fracturing, as shown in Figure 6, which shows that the joint fissure opening increases with the increase of water injection time.

Fracturing time is the key factor affecting the effective radius of hydraulic fracturing, as shown in Figure 6, which shows that the joint fissure opening increases with the increase of water injection time. When the grouting flow is 10 m^3 /h, the grouting duration is 250 s, 350 s, 450 s, and 650 s, respectively, and the effective radius of fracturing is 6.9 m, 10.3 m, 11.8 m, and 12.7 m, respectively.

As shown in Figure 7, it shows the relationship between effective fracturing radius and fracturing time under different flow. According to the data, the fracturing radius increases with the increase of flow. At the same time, the fracturing radius is greatly affected by the fracturing time in the early stage and then slows down.

Initial in situ stress field is also an important factor affecting hydraulic fracturing. In order to better analyze the initiation pressure under different stress levels, numerical calculation is carried out. Fix the maximum horizontal principal stress as 11.5 MPa and the vertical stress as 11.5 MPa, 13.0 MPa, 14.4 MPa, and 17.3 MPa. The ratio of vertical stress to horizontal stress is 1.0, 1.1, 1.25, and 1.5, respectively.

As shown in Figure 8, when the vertical stress is 11.5 MPa, the cracking pressure is 15.8 MPa, and the instability pressure of tunnel wall is 22.1 MPa. When the vertical stress is 13 MPa, the cracking pressure is 14.3 MPa, and the instability pressure of tunnel wall is 19.6 MPa. When the vertical stress is 14.4 MPa, the cracking pressure is 13.2 MPa, and the instability pressure of tunnel wall is 18.2 MPa.

When the vertical stress is 17.3 MPa, the cracking pressure is 9.9 MPa, and the instability pressure of tunnel wall is 17.7 MPa. The increase of vertical stress leads to the increase of tensile stress at the top of the borehole, which makes the crack easier to expand.

4. Application of Hydraulic Fracturing Technology

The technical equipment of hydraulic fracturing is mainly composed of power supply system, water supply system, and fracturing system. The fracturing system is mainly composed of high-pressure water injection pump, water tank, high-pressure fracturing pipe, special hole sealer for hydraulic fracturing, and monitoring system. XRB2B emulsion pump is selected as the core equipment water injection pump, with rated pressure of 20 MPa and flow of 80 L/min. The hole sealer is selected, with applicable hole diameter of 40~50 mm, maximum expansion diameter of 70 mm, and



FIGURE 8: Effect of vertical stress on hydraulic fracturing.

pressure resistance of 30 MPa under working state. The gas extraction pump station is equipped with two sets of high and low negative pressure systems. The model of high negative pressure extraction pump is 2BE4620-2BY4. The model of low negative pressure extraction pump is 2BE4520-2BY4, one for use and one for standby.

According to the gas occurrence of the coal seam and the roadway layout of the working face, hydraulic fracturing boreholes and gas drainage boreholes are, respectively, arranged in the return air roadway. The spacing between the fracturing hole and the pumping hole is 8.5 m. The pumping hole is 18 m longer than the fracturing hole. It takes 65 min from the start of water injection to the maximum water pressure, and the total water injection time is about 260 min. The construction pressure of this hydraulic fracturing test is determined to be 18 MPa. The drilling arrangement is shown in Figure 9.

After 12 hours of fracturing, drain water from each fracturing hole and extraction hole. When the water flow is small and there is high concentration gas, connect the extraction hole and fracturing hole into the underground gas extraction system at the same time. In order to record the gas emission parameters of the hydraulic fracturing effect, the gas emission of adjacent working faces without fracturing is compared.

Figure 10 shows the change trend of gas emission in the roadway with time during the mining process of the working face after gas drainage. The black curve indicates that gas drainage is carried out directly without hydraulic fracturing and the gas emission characteristics in the mining process of the working face.

The red curve indicates the gas emission characteristics in the mining process of the working face after hydraulic fracturing and gas drainage. Without hydraulic fracturing, the maximum gas emission is $10.5 \text{ m}^3/\text{min}$, and the average value is $9.2 \text{ m}^3/\text{min}$. After hydraulic fracturing, the maximum gas emission is $5.1 \text{ m}^3/\text{min}$, and the average value is $3.8 \text{ m}^3/\text{min}$. The maximum value is reduced by 51%, and the average value is reduced by 58%.



Mining roadway

FIGURE 9: Layout of pumping and pressure relief boreholes in working face.



FIGURE 10: Effect of hydraulic fracturing on gas emission from coal face.

5. Conclusion

Based on the severe situation of coal mine gas outburst, this paper carried out the research on hydraulic fracturing gas discharge. Through engineering investigation, numerical calculation, and field application, the influence of key parameters such as in situ stress, liquid injection pressure, and pressure injection time on fracture effect is analyzed, which is finally applied to engineering practice.

- (1) The variation gradient of gas pressure in B_4^2 coal seam with buried depth is 0.34 m³/t/km. The characteristics of in situ stress and hydraulic strength are the key factors affecting the effect of hydraulic fracturing
- (2) Use DFN (discrete fracture network) for initial fracture division; based on the pore seepage coupling theory, the stress joint seepage coupling equation is introduced. The results show that under the working condition of 10 m³/h, the grouting duration is 250 s, 350 s, 450 s, and 650 s, respectively, and the effective fracturing radius is 6.9 m, 10.3 m, 11.8 m, and 12.7 m, respectively. The fracturing radius is greatly affected by the fracturing time in the early stage, which varies with the fracturing time slow down after. The increase of vertical stress leads to the increase of tensile stress at the top of the borehole, which makes the crack easier to expand

(3) According to the field measurement, the construction pressure of hydraulic fracturing test is 18 MPa, the spacing between fracturing hole and extraction hole is 8.5 m, and the extraction hole is 18 m longer than the fracturing hole, which can meet the needs of field engineering. After hydraulic fracturing and gas drainage, the maximum gas emission is reduced by 51% and the average value is reduced by 58%.

Data Availability

The data used to support the findings of the study are available within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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