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Prevention and Control of Coal and Gas Outburst by Directional Hydraulic Fracturing through Seams and Its Application

Xianzhong Li,* Weilong Zhou, Shigang Hao, Tao Wu, and Jinhao Zhang

Cite This: *ACS Omega* 2023, 8, 38359–38372

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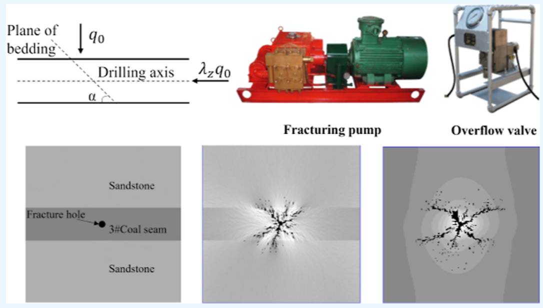
ABSTRACT: The regionalized pressure relief, permeability enhancement, and outburst prevention of "three high and one low" coal seams with high gas, high ground stress, high outburst risk, and low permeability have become important problems to be solved urgently in realizing the sustainable development of coal mines. In this study, a combination of theoretical research, RFPA^{2D}-Flow numerical simulation, and field test was used to study the initiation mechanism and propagation law of directional hydraulic fracturing fractures through the seam. The results show that fracture initiation depends on the axial and radial horizontal stress of the fracture hole, the physical and mechanical properties of coal and rock, and the inside of the weakest layer. Single-hole hydraulic fracturing can achieve a pressure relief radius of 7−8 m, but there is a stress concentration zone outside, which is not conducive to regional pressure relief and permeability enhancement. Directional hydraulic fracturing with multiple holes produces an approximate cylindrical compression and crushing ring and a penetrating fracture surface along the center line of the pressure crack hole and the directional hole, which better eliminates the phenomenon of stress concentration in nondirectional hydraulic fracturing. The technology was applied to the 2238 auxiliary roadway of Chengzhuang Mine of Jinmei Group, and the field implementation results showed that field implementation results showed that directional hydraulic fracturing through the seam reduced the gas content in the coal seam to a great extent, and the coal seam gas content was reduced by about 42.3%, indicating that the technology can effectively reduce the risk of coal and gas outbursts.



1. INTRODUCTION

The coal industry has received the attention of various countries as an important component of global energy. Gas associated with coal seriously threatens the safety of coal mines, among which gas explosions and coal and gas outburst accidents are the main manifestations of gas disasters. With the increase in mining depth in recent years, the surrounding rock stress has increased, the geological conditions of gas have become more complex, and the problem of gas outbursts has become more severe, which greatly restricts the normal performance of mine production capacity and affects mine safety production.

Research shows that the higher the gas content of the original coal seam, the more likely coal and gas outbursts will occur.[1] For "three high and one low" coal seams, pressure relief, reflection enhancement, and extraction are effective means to prevent coal and gas outbursts. The conventional method is to adopt regional outbursts prevention measures of prepumping coal seam gas and mining protective layer,[2,3] but this treatment method has certain requirements on coal seam spacing and gas content, and some coal seams do not have the conditions for mining protective layer.[4] To solve the problem of gas control in high gas and low permeability coal seams, a lot of theoretical research and engineering practice has been carried out in this field both at home and abroad. The results show that in low-permeability and high-gas mines, it is usually necessary to increase the permeability of the coal seam to improve the gas extraction effect,[5] and increasing permeability is a key means to improve the gas extraction effect.

Hydraulic fracturing technology is a more mature technology for increasing permeability and production in the petroleum industry and has been widely used in the development of low-permeability oil and gas fields. Most oil reservoirs are sandstone with good homogeneity, and new fractures will be formed and extended further when high-pressure water acts. Therefore, the current hydraulic fracturing theory is no longer applicable to coal seam fracturing, and more in-depth research must be carried out.[6] However, it has always been a difficult problem to apply hydraulic fracturing technology to relieve pressure, permeability enhancement, and

Received: July 4, 2023
Accepted: September 19, 2023
Published: October 5, 2023

https://doi.org/10.1021/acsomega.3c04737
ACS Omega 2023, 8, 38359–38372

outburst prevention in coal mines. The main reasons are the limited performance of pressurizing equipment, few studies on the fracturing mechanism of deep coal seams, and the large risks and limitations of fracturing, which is difficult to be widely promoted.[7,8]

Defining the fracture criteria of coal and rock materials in the hydraulic fracturing process is the theoretical basis for judging the initiation and propagation process of hydraulic fractures. Scholars began to explore crack cracking from the angle of linear elastic fracture mechanics and achieved a wealth of research results. Hubbert and Willis[9] used the method of elastic mechanics to connect the in situ measurement variables of hydraulic fracturing with the original in situ stress of coal strata for the first time and established the fracture initiation criteria for predicting longitudinal fractures in vertical or horizontal Wells. Later scholars studied the stress field characteristics of the crack tip under fluid pressure based on fracture mechanics theory based on the brittleness property of rocks and applied the maximum tensile stress theory in the traditional mechanical strength theory of materials to the hydraulic fracture discrimination criteria, which enriched the basic theory of rock fracture research. Based on the fracture criterion of Hubbert and Willis, Huang et al.[10] deduced the relationship between the hydraulic fracturing stress of inclined wellbore and the in situ stress of rock strata according to the maximum tensile stress theory. Based on the theory of maximum energy release rate, Li[11] established hydraulic fracture propagation criteria, analyzed the influence of natural fractures on hydraulic fracture propagation, and found that the larger the stress difference between the rock layer and the approaching Angle of hydraulic fracture, the easier the hydraulic fracture will pass through the natural fracture.

With continuous improvement of theoretical technology, scholars have found that the fractures formed by hydraulic fracturing can not only effectively improve the state of the coal seam and improve the gas permeability of the coal seam but also change the mechanical properties of coal and rock, which provides an important solution for the gas control work of a low-permeability coal seam. Studies have shown that fractures formed by hydraulic fracturing are more conducive to gas penetration and movement than natural fractures,[12,13] and scholars focus on the direction of coal seam gas exploitation. However, with the change of buried depth of the coal seam, the geological conditions of the coal seam become more and more complicated, and even coal seams with "extremely low permeability and extremely high ground stress" appear.[14−16] Aiming at CBM development under complex geological conditions, Chen et al.[17] collected well-test parameters of many Wells in the west Guizhou region and found that different ground stress distribution rules existed at different depths of strata. These different stress states have significant effects on the permeability, gas content, and gas production of coal seams. According to this law, the best CBM mining depth in the west Guizhou area is obtained. Mou et al.[18] conducted a simulation study on high-rank coal samples with hydraulic fracturing and found that hydraulic fracturing can improve the expansion of original microfractures, thus effectively increasing their permeability. The difference between strata and horizontal ground stress of the coal samples will affect the connectivity between fractures. This discovery has some implications for the development of coal-bed methane by hydraulic fracturing. To further study the influence of induced stress on fracture formation in hydraulic fracturing, Hu et al.[19] measured the hydraulic fracturing process in an oilfield and found that the induced stress increased significantly in a certain range near the borehole of hydraulic fracturing. However, with the process of hydraulic fracturing, the induced stress will also be released and begin to change, and the direction of the induced stress distribution always remains parallel to the direction of the maximum horizontal principal stress controlled by the fault. Sun et al.[20] studied the characteristics of coal orthotropic anisotropy on the role of hydraulic fracture formation and discussed the influence of several relevant factors such as pressure and fluid saturation in the coal cutting system. They concluded that a proper clamping angle can improve the gas production rate, which may become a future evaluation index of CBM development. Yang et al.[21] reported that a coal seam with a low water content after hydraulic fracturing, tended to have a high gas content, if it existed, thus proposing a uniform fracturing technique that combined blast fracture holes with control holes. They reported that the uniform fracturing method can effectively reduce the probability of gas outbursts in gas mines.

At present, for the hydraulic fracturing research of deep low-permeability coal seams, scholars focus on the numerical simulation direction of the rock fracture process analysis system (RFPA) on how to efficiently extract gas to achieve the effect of preventing coal and gas outbursts. Numerical simulation of hydraulic fracturing is an important means to study hydraulic fracturing technology and hydraulic fracture evolution. Because the fractures formed by conventional hydraulic fracturing tend to expand along the direction of the maximum principal stress,[22] this is often inconsistent with the direction required by the actual engineering. Aiming at how to achieve the effect of hydraulic fracturing to control the effective propagation of fractures, Li et al.[23] used RFPA software to simulate the problem of double fracture propagation of hydraulic fracturing, and the simulation results achieved asynchronous initiation, asymmetric propagation, and nonequal winding of the two fractures. The results are further verified by simulation of the oilfield. The results show that the fracture spacing and initial fracture height can effectively control the fracture zone morphology. Li et al.[24] used RFPA software to simulate the failure characteristics of conglomerate rocks after uniaxial compression and found that brittle rocks can generate multiple failure surfaces after uniaxial compression. This means that the development of natural fractures is more concentrated in brittle rock reservoirs, while a single shear failure often occurs in ductile rock reservoirs. The results show that hydraulic fractures are more likely to spread in brittle conglomerates than in ductile conglomerates.

How to use hydraulic fracturing technology to prevent and control mine disasters, Liu et al.[25] simulated the whole process of fracture initiation, expansion, and interaction in the progressive failure process of coal seam through RFPA software. The research results show that the abnormal stress region is similar to the fracture zone formed by microcracks, and the potential abnormal stress region obtained by numerical simulation is close to the microcrack development region monitored by the microseismic detection system. The research results can provide a reference for the instability failure law of deep roadways under complex geological conditions. Aiming at the problem of hydraulic fracture propagation in the weakening process of super thick coal seam roofs, Xia et al.[26] used RFPA software to simulate the simulation test of hydraulic fracture propagation in stope roofs. The results show that the direction

https://doi.org/10.1021/acsomega.3c04737
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of the maximum principal stress in the hydraulic fracturing process will gradually shift from the horizontal to the vertical direction and the expansion of hydraulic fracture in the hard roof will be affected by the mining width and mining depth of the coal seam. In the range of stress arch, the hydraulic crack will gradually deflect to form an "arch" shape crack, to achieve the stratification of a hard roof. The research can provide a theoretical analysis of hydraulic fracturing to weaken hard roofs. Ma et al.[27] used RFPA software to simulate the failure process of the coal seam floor during mining and carried out stress failure analysis. By combining the results of theoretical calculation, numerical simulation, and microseismic detection, the failure characteristics of the coal seam floor are analyzed, which provides help for the evaluation and prevention of water inrush disaster of the coal seam floor.

Because of the low gas extraction rate and large engineering amount of low permeability coal seam during hydraulic fracturing, Hao et al.[28] proposed a hydraulic cavitation-assisted fracturing technology based on the method of improving the gas permeability of coal seam to solve the recovery rate of coalbed methane and used RFPA numerical software to simulate the impact of this technology on fracture expansion and gas extraction in the coal seam. The simulation results show that this technology can effectively reduce the fracture initiation pressure, increase the effective radius of hydraulic fracturing, and finally realize the improvement of the gas extraction rate. Yan et al.[29] used RFPA^{2D}-Flow software to study coal crack growth during hydraulic fracturing and studied the change law of coal crack growth. The results show that the water pressure around the fracture hole is affected by the fracture grooving and that the fracture is more likely to expand along the direction of a greater hydraulic gradient after the fracture initiation. According to this law, field tests have been carried out, and the results show that the extraction efficiency of coalbed methane has been significantly improved. The expansion area of the hydraulic fracture is the key factor affecting the result of hydraulic fracturing. Building a uniform fracture network can effectively improve the permeability of coal seams, guide gas diffusion, and prevent gas outbursts. Lu et al.[30] used RFPA^{2D}-Flow software to simulate and verify the directional hydraulic fracturing experiment with joint control of prefracture and fractured borehole and found that this joint control fracturing method can expand the fracture expansion range of directional hydraulic fracturing and is more conducive to the directional hydraulic fracture expansion. Li et al.[31] combined RFPA software and embedded digital image technology to study the impact of rock brittleness on shale failure. On the surface of the study, brittle shale is easy to fracture by multiple cross-failure surfaces, while ductile shale is easy to fracture through failure surfaces. It is concluded that brittle rock is often the primary way of fracture propagation, and the hydraulic fracture formed by brittle rock is more complex, which is more conducive to the formation of a complex fracture network.

Considering that horizontal Wells are the main factors affecting the formation of hydraulic fracture propagation around the wellbore, Lu et al.[32] continued to use RFPA^{2D}-Flow to study the effects of different perforation densities and stresses on fracture initiation and propagation. The spatial morphology of complex fractures caused by perforation density and horizontal stress difference is found. Song et al.[33] used RFPA numerical software to simulate the effect of heterogeneous pore pressure on the direction of hydraulic fracture propagation in sandstone. The research results show that the greater the pore pressure, the more fluid pressure required for hydraulic fracture propagation can be effectively reduced and the hydraulic fracture can expand along the area with greater pore pressure. By studying the relationship between borehole spacing, water injection pressure, and water injection time, a method to control the propagation of hydraulic fracture is obtained.

These scholars have conducted systematic research on various aspects of hydraulic fracturing, through both experiments and simulations. Despite several significant results, these methods cannot satisfy the needs of mine production. For coal seams under the condition of "three high and one low", an effective and targeted antioutburst technology system is yet to be proposed. To guarantee an effective and safe operation and achieve the fracturing effect of the overall pressure release, it is necessary to explore and study directional hydraulic fracturing technology.

2. STUDY ON PREVENTION AND CONTROL OF COAL AND GAS OUTBURST BY DIRECTIONAL HYDRAULIC FRACTURING THROUGH STRATA

2.1. Analysis of Crack Initiation Mechanism of Drilling through Seams.

2.1.1. Stress State at Any Point in the Rock Surrounding the Borehole through the Seam. Because of the influence of the thickness and lamination changes of each coal seam and the difficulty in ensuring that the borehole is always parallel to the coal seam level during the construction drilling operation, most hydraulic fracturing boreholes are penetration boreholes, as shown in Figure 1.

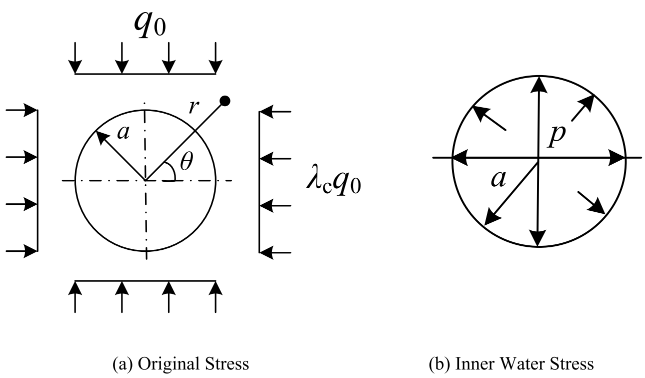

Figure 1. Stress of bore in drilling wall under original and inner water stresses.

According to Kastner's solution process, the stress at any point in the surrounding rock of the borehole before water injection fracturing is expressed as follows[34]

$$\begin{cases} \sigma_r = \dfrac{1+\lambda_c}{2}q_0\left(1-\dfrac{a^2}{r^2}\right) - \dfrac{1-\lambda_c}{2}q_0\left(1-4\dfrac{a^2}{r^2}+3\dfrac{a^4}{r^4}\right)\cos\ 2\theta \\ \sigma_\theta = \dfrac{1+\lambda_c}{2}q_0\left(1+\dfrac{a^2}{r^2}\right) + \dfrac{1-\lambda_c}{2}q_0\left(1+3\dfrac{a^4}{r^4}\right)\cos 2\theta \\ \tau_{r\theta} = \dfrac{1-\lambda_c}{2}q_0\left(1+2\dfrac{a^2}{r^2}-3\dfrac{a^4}{r^4}\right)\sin 2\theta \end{cases} \quad (1)$$

https://doi.org/10.1021/acsomega.3c04737
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where σ_r, σ_e, and $\tau_{r\theta}$ are the radial, tangential, and shear stresses at any point in the rock surrounding the borehole, respectively, λ_c is the lateral stress coefficient in the stress field of the original rock in the direction perpendicular to the horizontal axis of the borehole, a is the radius of the borehole, r is the distance from any point to the center of the borehole, θ is the orientation angle of the points, and q_0 is the self-weight stress.

The stresses under the action of only the internal water pressure are

$$\begin{cases} \sigma_r = \dfrac{a^2}{r^2}p \\ \sigma_{\theta r} = -\dfrac{a^2}{r^2}p \\ \tau_{r\theta} = 0 \end{cases} \tag{2}$$

In addition, considering the fractured hole under the dual action of the original rock stress and high-pressure water in the borehole for comparison with eqs 1 and 2, we can obtain the expression for stress at any point in the borehole surrounding the rock as follows

$$\begin{cases} \sigma_r = \dfrac{1+\lambda_c}{2}q_0\left(1-\dfrac{a^2}{r^2}\right) - \dfrac{1-\lambda_c}{2}q_0\left(1-4\dfrac{a^2}{r^2}+3\dfrac{a^4}{r^4}\right) \\ \qquad \cos\ 2\theta + \dfrac{a^2}{r^2}p \\ \sigma_\theta = \dfrac{1+\lambda_c}{2}q_0\left(1+\dfrac{a^2}{r^2}\right) + \dfrac{1-\lambda_c}{2}q_0\left(1+3\dfrac{a^4}{r^4}\right)\cos 2\theta \\ \qquad - \dfrac{a^2}{r^2}p \\ \tau_{r\theta} = \dfrac{1-\lambda_c}{2}q_0\left(1+2\dfrac{a^2}{r^2}-3\dfrac{a^4}{r^4}\right)\sin\ 2\theta \end{cases} \tag{3}$$

2.1.2. Determination of Fracture Injection Pressure and Fracture Initiation Location in the Penetration Borehole. The fracture hole is composed of multiple coal seams along the axial direction, and the surrounding rock properties of each section are different. The fracture of the pressure hole mainly overcomes the tensile strength of the weakest part of the hole in addition to factors such as crustal stress. Based on this, the aperture and axial directions of the pressure hole are discussed.

Assumptions: Along the fracture borehole axis, the surrounding rock of each section is homogeneous and isotropic; however, the nature of the surrounding rock varies from section to section.

2.1.2.1. Radial Analysis of Drill Holes through Seams. If a fracture occurs along the perimeter of a section of the borehole, the effect of the axial horizontal stress can be ignored, and only the effects of the plumb stress q_0 and horizontal radial stress $\lambda_c q_0$ can be considered, as shown in Figure 2; then:

At this point, eq 3 can still represent the tangential stress at any point within the fracture hole envelope. Further, by substituting $r = a$ into the expression for σ_r, the tangential stress on the fracture hole wall is obtained as

$$\sigma_\theta|_{r=a} = (1+\lambda_c)q_0 + 2(1-\lambda_c)q_0\cos 2\theta - p \tag{4}$$

If the hole breaks, $\sigma_\theta|_{r=a}$ must be tensile stress and

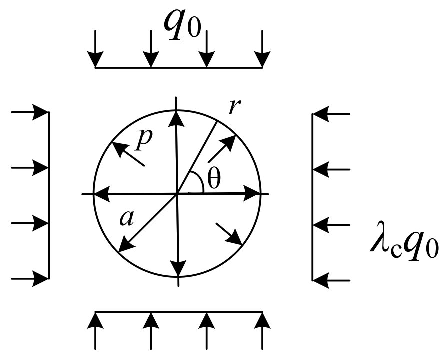

Figure 2. Stress analysis along the Bore's radial direction.

$$\sigma_\theta|_{r=a} > |R_t| \tag{5}$$

where R_t is the tensile strength of stratified coal.

Combining the above two formulas, the fracturing water injection pressure is obtained as

$$p > (1+\lambda_c)q_0 + 2(1-\lambda_c)q_0\cos 2\theta + \min\{R_{ti}\} \tag{6}$$

where R_{ti} is the tensile strength of the i stratified coal, and m is the number of strata of coal and rock passing through the pressure hole.

Therefore, at this time, the fracture injection pressure can be expressed as

$$p_{H1} = (1+\lambda_c)q_0 + 2(1-\lambda_c)q_0\cos 2\theta + \min\{R_{ti}\}(i = 1,2,\cdots,m) \tag{7}$$

2.1.2.2. Axial Analysis of Drill Holes through Seams. If a layer of the physiographic surface is ruptured along the hole axial direction in the penetration fracture borehole, the effect of radial horizontal stress can be ignored, and only the plumb stress q_0 and horizontal axial stress $\lambda_z q_0$ (λ_z is the horizontal lateral stress coefficient in the direction parallel to the borehole axis) can be considered, as shown in Figure 3.

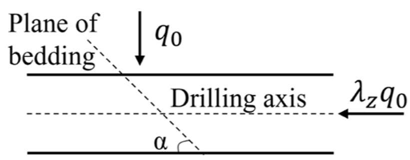

Figure 3. Stress analysis along Bore's axes.

At this point, the normal compressive stress on the laminar surface is expressed as

$$p_f = q_0\cos\ \alpha + \lambda_z q_0 \sin\alpha \tag{8}$$

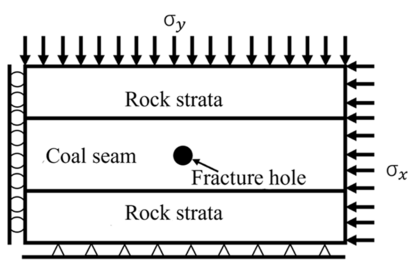

Figure 4. Numerical simulation of hydraulic fracturing solid model.

https://doi.org/10.1021/acsomega.3c04737
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where α is the angle between the laminar surface and the borehole axis.

At this point, the hydraulic fracturing pressure must overcome the normal compressive stress p_f on the laminar surface and the bonding force C on the laminar surface

$$p_{H2} = q_0\cos\ \alpha + \lambda_z q_0\sin\ \alpha + \min\{C_i\}(i = 1,2, \cdots, m) \tag{9}$$

In summary, the fracture pressure for hydraulic fracturing through seams is expressed as

$$p_H = \min\{p_{H1}, p_{H2}\} \tag{10}$$

2.1.2.3. Determination of Water Injection Pressure and Fracture Initiation Direction. When $p_H = p_{H2}$, the fracture initiation direction of the drill hole is along the normal of the seam face; the fracture initiation point is at the weakest seam face. Whereas, when $p_H = p_{H1}$, the fracture initiation direction and location of the drill hole are related to the minimum tensile strength sum of all the coal seams and λ_c.

In summary, the penetration hydraulic fracture borehole is fractured under the dual action of primary rock stress and high-pressure water, which is dependent not only on the magnitude of the axial and radial horizontal stresses in the fracture hole but also on the physical and mechanical properties of the coal rock body around the borehole before and after the construction of the borehole. In the crack initiation position, axially, it is dependent on factors related to the weakest laminae, whereas, in the radial direction, it is dependent on factors such as $\min\{R_{ti}\}$ and λ_c.

2.2. Analysis of the Mechanism of Directional Hydraulic Fracturing through Seams to Prevent the Outburst. In the process of coal tunneling, there are three stress zones in the coal body in front of the working face: pressure relief, concentrated stress, and original stress zones. Therefore, to prevent outburst during the digging process, it is necessary to change the stress distribution of the coal body in front of the working face, leave a longer pressure-relief zone, and improve the permeability of the coal seam, such that the gas in the coal seam can be released in advance.

(1) Stress transfer, extraction, and decompression effects of directional hydraulic fracturing through seams

① Concentrated stress transfer to the deep part of the coal body

The concentrated stress formed by directional hydraulic fracturing primarily promotes fracturing and deformation of the coal rock body around the fractured borehole: on the one hand, it causes the concentrated stress zone to shift to the deeper part of the coal body and reduces the crustal stress gradient in the fractured section, while the fractured and ruptured area becomes the pressure relief zone; on the other hand, the loose coal body in a high-stress state produces certain "rheology" in the direction of the nonfracture zone, so that the elastic potential in the coal body has sufficient room for release.[35] Further, the rupture zone is outside the vibration zone owing to the elastic extrusion of the blast wave and the transfer of concentrated stress to the zone, thereby prompting the elastic deformation of the coal rock in the region to become a concentrated stress zone. This ensures that a long pressure relief zone is retained to ensure the anti-outburst effect of the fractured section.

② Directional hole−directional fracture penetration

Directional hydraulic fracturing results in the formation of many interlocking fractures and fracture networks in the crushing and fracture zones, which increase the permeability of the coal body and desorb a significant portion of the adsorbed gas into free gas. Through extraction, it can achieve the purpose of discharging gas and reducing the gas pressure and gas content of the coal body in front of the working area. This facilitates the effect of unloading pressure and increasing penetration.

(2) Antioutburst effect of water

From an energy perspective, water injection into the fractured holes reduces the elastic potential and internal energy stored in the coal body.[36]

i After the fracture hole is injected with high-pressure water, the elastic modulus decreases, Poisson's coefficient increases, and the stress of the coal seam decreases. Consequently, the elastic potential of the coal seam decreases, which further reduces the energy required for the risk of outburst and effectively prevents the occurrence of coal and gas outburst. Further, water enters the fine pores of coal, rendering the coal body wet, enhancing the plasticity of coal, reducing the sudden brittle destruction of coal, reducing the ability to release gas, and reducing the internal energy of gas for the occurrence of outburst;

ii After directional fracturing, high-pressure water enters the concentrated stress zone nearer to the working face and generates fissures. Through coal seam decompression and gas extraction, the concentrated stress zone will then be transferred to the coal seam. Subsequently, high-pressure water enters the fissures and gaps inside the coal seam, rendering the original coal seam wet, changing the physical properties of coal, reducing the elastic modulus of coal, increasing the plasticity of coal, making the stress distribution more uniform, and reducing the stress concentration coefficient. This is conducive to the transfer of the concentrated stress zone to the deep part of the coal seam, effectively preventing coal and gas outburst.

(3) Directional hydraulic fracturing anti-outburst effect

Combined with the analysis of the previous unloading and permeation process, after fracturing, a first-level weak surface centered on the fracture hole up to the multilevel weak surface fracture surface running through the directional hole is produced in the coal rock body above the excavation working face. This can fully release the crustal stress and cause the stress to be redistributed evenly. In addition, the fissure face and directional hole are connected, which can facilitate the effective release of gas with high pressure in the coal seam above the working face, thereby increasing the strength of the coal seam to resist damage. The existence and development of fissure faces are key to effectively improving the coal seam permeability and preventing coal and gas outbursts.

3. HYDRAULIC FRACTURE PROPAGATION MECHANISM BASED ON RFPA

Simulations of directional hydraulic fracturing using numerical simulation enable a further in-depth study of the behavioral characteristics of fracture extension after fracturing and controlling factors. The following is a study of directional hydraulic fracturing through seams using the RFPA system.

https://doi.org/10.1021/acsomega.3c04737
ACS Omega 2023, 8, 38359−38372

In the RFPA system, RFPA^{2D}-Flow is a characteristic numerical simulation software used to analyze the hydraulic fracturing process of coal and rock with permeability and nonuniformity. In the loading process of each step, the software solves the stress distribution of a given water pressure using the finite element method and uses the strength criterion to judge the damage caused by the shear or tensile stress of the unit. The damaged unit exhibits residual strength, and the permeability increases accordingly. The water pressure is tracked and transmitted to the undamaged units around the damaged unit, and the stress calculation is then repeated. The pressure is adjusted and redistributed until the new stress is balanced.[37] Material properties of cells in RFPA^{2D}-Flow are randomly assigned according to the Weibull distribution; therefore, low-strength cells may exist in the high-pressure concentration zone away from the fracture end. Thus, microfractures may occur in the adjacent zone of the fracture region with hydraulic action.[38] Meanwhile, the maximum tensile stress (or tensile strain) criterion and the Mohr-Coulomb criterion are used as the damage threshold of this damage instantiation relationship, respectively; that is, when the stress or strain state of the unit reaches the maximum tensile stress criterion and the Moore Coulomb criterion, respectively. It is considered that the damage evolution of the unit starts to occur in tension and shear according to the elastic damage instantiation relationship to be described.[39] RFPA^{2D}-flow can effectively simulate the fracture process of rocks, including the stress distribution and crack expansion of rocks, to predict the location, shape, and size of rock fractures.

3.1. Model Building. The model is based on the 2238 auxiliary roadway of the Chengzhuang Mine of the Jinmei Group. The coal seam is approximately 4 m thick, and the mechanical parameters of the coal rock seam are given in Table 1. The material properties of the coal rock seam were assigned according to the Weibull distribution. The elastic finite element method of stress analysis was applied, and the modified Coulomb criterion (including tensile cutoff) was used for the yielding principle.

Table 1. Mechanical Properties and Seepage Parameters of Coal Strata[a]

mechanical and seepage parameters	category	
	coal seam	rock layer (top and bottom slab)
homogeneity	3	4.5
mean value of modulus of elasticity E_0/GPa	5	60
average compressive strength σ_0/MPa	35	90
Poisson's ratio μ	0.25	0.20
friction angle /deg	23	28
air transmission coefficient, $m^2/(MPa^2{\cdot}d)$	0.2	0.005
gas content coefficient A_w	2.5	0.05
strength compression to tensile ratio	20	15
strength attenuation coefficient B_s	0.2	0.25
liquid–solid coupling coefficient β	0.3	0.15

[a]To better eliminate the boundary effect, the model was built as a 40 m × 40 m two-dimensional model. Because the angle between the fracture hole and coal seam inclination varied in the range of 30–90°, a coal seam thickness of 8 m was used in the model, considering the universality and relevance of the field test. The entity model is illustrated in Figure 4.

The plane strain mechanics model was considered as a 2D problem, and the model was subjected to vertical and horizontal stresses of approximately 19 and 17 MPa, respectively. The model was divided into 400 × 400 unit blocks and the computational model is shown in Figure 5. The

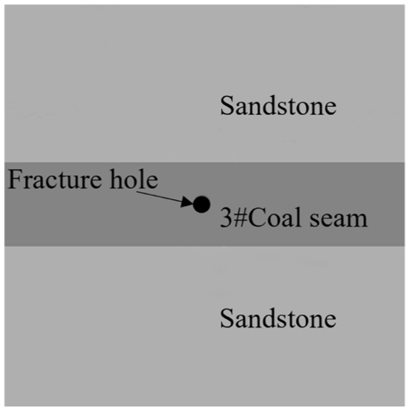

Figure 5. Hydraulic fracturing (single-hole) calculation model diagram.

initial gas pressure in the model was 2.85 MPa, and the initial injection pressure for hydraulic fracturing was 1 MPa. Each operation was incremented by 0.5 MPa, for a total of 60 operations.

3.2. Simulation Results. In the RFPA^{2D}-Flow system, a special tool, acoustic emission, can be used to quantitatively study the development of coal seam fractures under different water injection pressures. The failure of rock under the action of a load is primarily related to the formation, expansion, and fracture of cracks. When cracks form or expand, stress relaxation occurs, and a certain amount of energy appears as stress waves, leading to acoustic emission phenomena.[40] This study simulated the stress distribution of coal under different water injection pressures and the failure patterns of coal after fracturing at different gas pressures. Combined with the above analysis, the failure patterns of coal under the influence of directional holes of double-pressure cracks were analyzed.

3.2.1. Stress Variation Law Around the Fracture Hole. Figure 6 is obtained by exporting the data inside the RFPA system and processing it using excel. It is evident that there is high-frequency clutter in the graph; thus, the data can be processed using the FIR low-pass filter in MATLAB to filter out the high-frequency clutter and render the graph smoother. The processed graph is shown in Figure 7.

The same treatment was used to obtain the relevant maximum principal stress maps for injection pressures of 14 and 31 MPa, as follows in Figures 8 and 9.

Figures 7–9 show the distribution and changes in the maximum principal stress in the coal seam during hydraulic fracturing. The red line in the figure indicates the peak value of the maximum principal stress in the X direction of the pressure hole, and the part of the maximum principal stress above the red line means that stress concentration occurs in the fracturing simulation at this time. The coordinates of the horizontal axis in the figure represent the length along the model direction at the level of the fracture hole center, where the horizontal coordinate at 20 m is the position of the fracture hole center.

As evident from the figures.

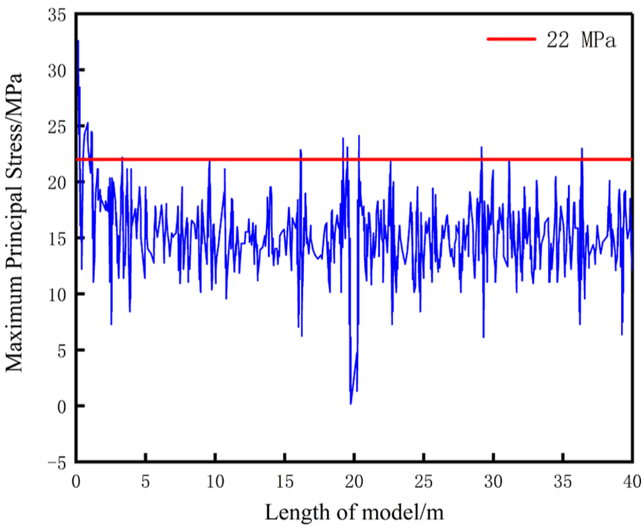

Figure 6. Maximum principal stress distribution in drilling along the *X*-direction (3 MPa).

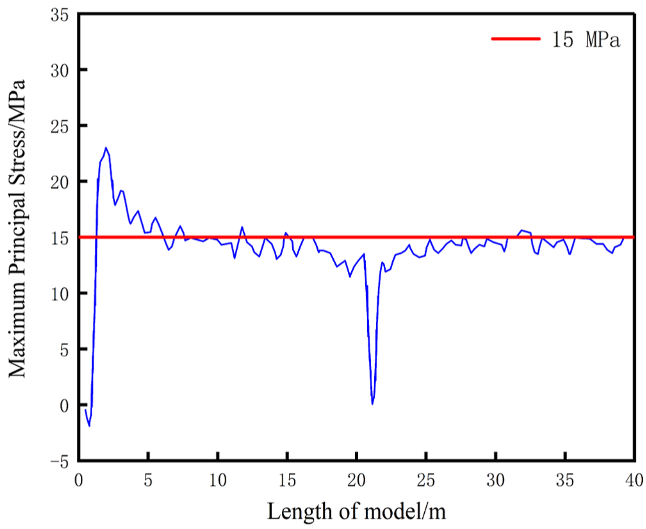

Figure 8. Maximum principal stress distribution in the drilling along the *X*-direction (14 MPa).

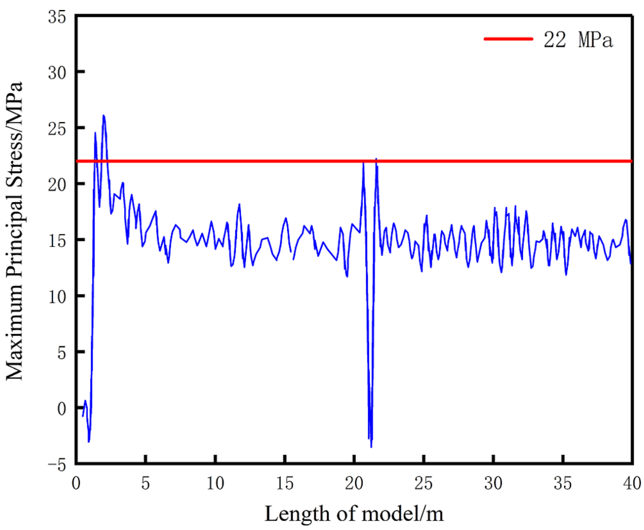

Figure 7. Maximum principal stress distribution in the drilling along the *X*-direction (3 MPa, after low-pass filter processing).

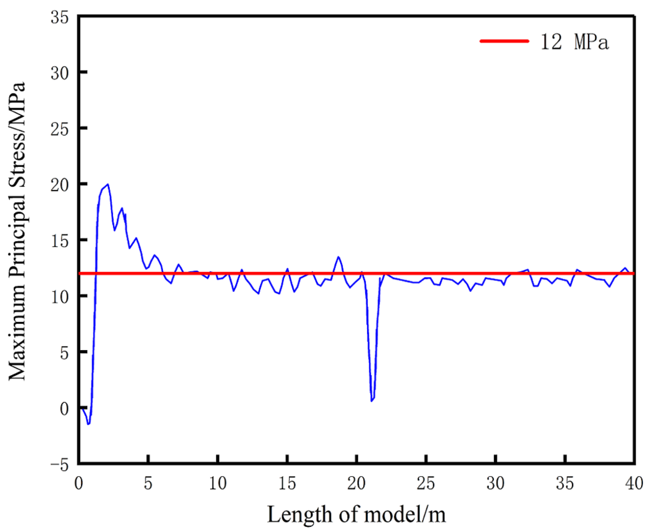

Figure 9. Maximum principal stress distribution in the drilling along the *X*-direction (31 MPa).

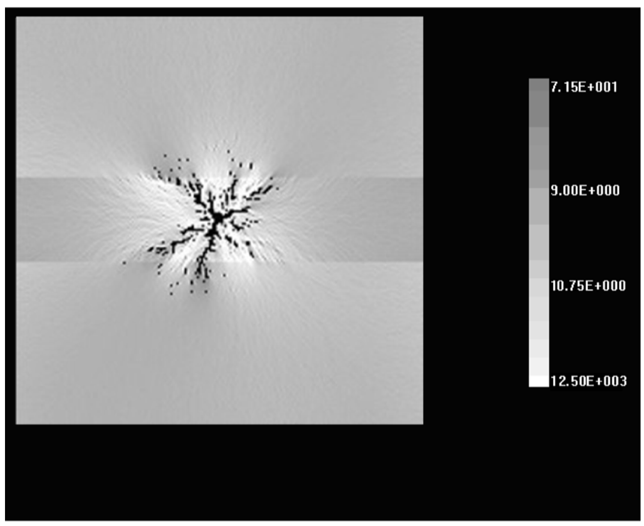

Figure 10. Single-hole hydraulic fracturing results.

1. In the construction of fracture holes and the early stage of fracturing, the crustal stress around the holes is high. Further, it also exhibits the phenomenon of stress concentration. For example, when the water injection pressure is 3 MPa, the pressure near the fracture holes is as high as 25 MPa (the maximum principal stress of the original rock is 19 MPa).
2. With an increase in the water injection pressure, the stress concentration zone within the coal seam continuously moves deeper into the coal seam on both sides of the fracture hole, and the pressure relief zone expands significantly. When the fracturing ends, most of the original rock stress decreases to below 15 MPa, and the pressure relief effect becomes more obvious. The fracturing radius is approximately 7−8 m, as shown in Figure 10. In addition, the rupture is obvious within 7−8 m, and a slight rupture occurs within a radius of 9−10 m of the water injection hole.

3.2.2. Influence of Coal Seam Gas Pressure on Coal Seam Rupture Action. To explore the influence of gas pressure on

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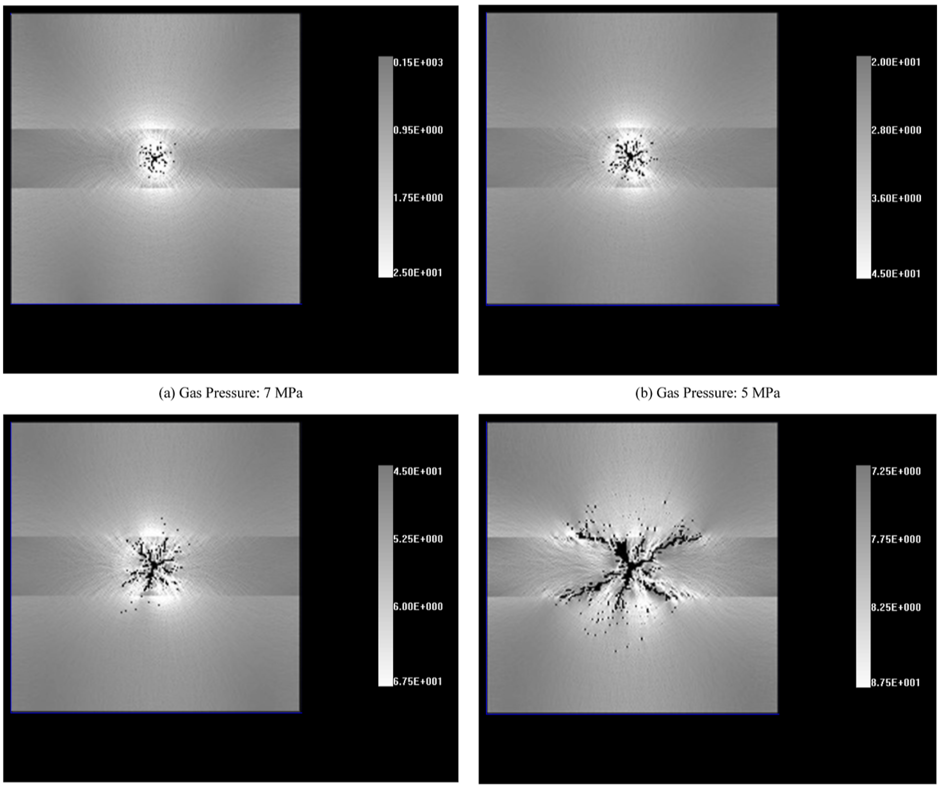

(a) Gas Pressure: 7 MPa (b) Gas Pressure: 5 MPa

(c) Gas Pressure: 3 MPa (d) Gas Pressure: 1 MPa

Figure 11. Pressure distribution of different gas pressures under the same water pressure.

hydraulic fracturing in coal seams, excluding the influence of crustal stress factors, four different calculation models with gas pressures of 1, 3, 5, and 7 MPa were established according to the parameter settings in Table 1. The models were 40 m × 40 m, with a coal seam thickness of 8 m, top and bottom plates of 16 m each, and the grid was divided into 400 × 400 pieces. All models adopted the construction of fracture holes in the center and high-pressure water emulsion to simulate the hydraulic fracturing process. For a fair comparison and analysis, the water injection pressure was set to 10 MPa to simulate the coal-seam fracture process under different gas pressures and the same fracturing conditions.

The following are the coal fracturing stress diagrams for different gas pressures (Figure 11).

3.2.3. Analysis of Hydraulic Head Isobar Graph of Fractured Holes. When the water injection pressure was 3 MPa, the coal body was unbroken and the head isobars were evenly distributed, as shown in Figure 12a.

When the water pressure increased to 14−18 MPa, hydraulic fracturing was in the stable expansion stage of the micro-fracture, a small amount of coal body rupture was developed, and the head isobar was approximately elliptical, as shown in Figure 12b,c.

When the water injection pressure was gradually increased to 24 MPa, the fractures were further developed, local fractures penetrated and developed further, the expansion rate of the main fractures and microfractures increased significantly, and the expansion process became more complicated. Moreover, the crustal stress applied to the model was greater in the vertical direction than in the horizontal direction, resulting in a larger isobaric line in the vertical direction, as shown in Figure 12d.

Coal seam gas pressure is one of the many factors that affect hydraulic fracturing. Combining the results of 3.2.2, it can be concluded that the coal seam gas pressure can offset part of the water injection pressure, resulting in a larger gas pressure, which renders it more difficult for the coal body to rupture. When hydraulic fracturing technology is implemented in the field, it is recommended that the water injection pressure be appropriately increased for hydraulic fracturing in high-gas mines to achieve the expected fracturing and abatement effects.

3.2.4. Directional Hydraulic Fracturing Simulation. The biggest disadvantage of single-hole hydraulic fracturing is that the fracturing direction is nondirectional, which easily causes stress concentration and forms a high-pressure storage area. In severe cases, coal and gas outbursts may occur due to stress concentrations. To ensure effective and safe operation and to achieve the fracturing effect of the overall pressure relief, directional hydraulic fracturing must be realized. Moreover, it is necessary to explore and study the technology of directional hydraulic fracturing.

The expansion direction of the hydraulic fracture in the rock is controlled by the stress field around the borehole. However, the actual project requires the fracture to expand in a certain direction based on which directional hydraulic fracturing technology is generated. According to the gas geology of the 2238 auxiliary roadway in the Chengzhuang mine, a simple and practical directional hole orientation technique was selected; that is, directional fracturing was performed by constructing a row of directional holes within the influence radius of the fracturing holes. A good fracturing effect was observed in the field test.

A situation when two water injection holes were arranged 15 m apart at the left and right ends was considered, wherein the four middle hydraulic fracturing directional control holes were

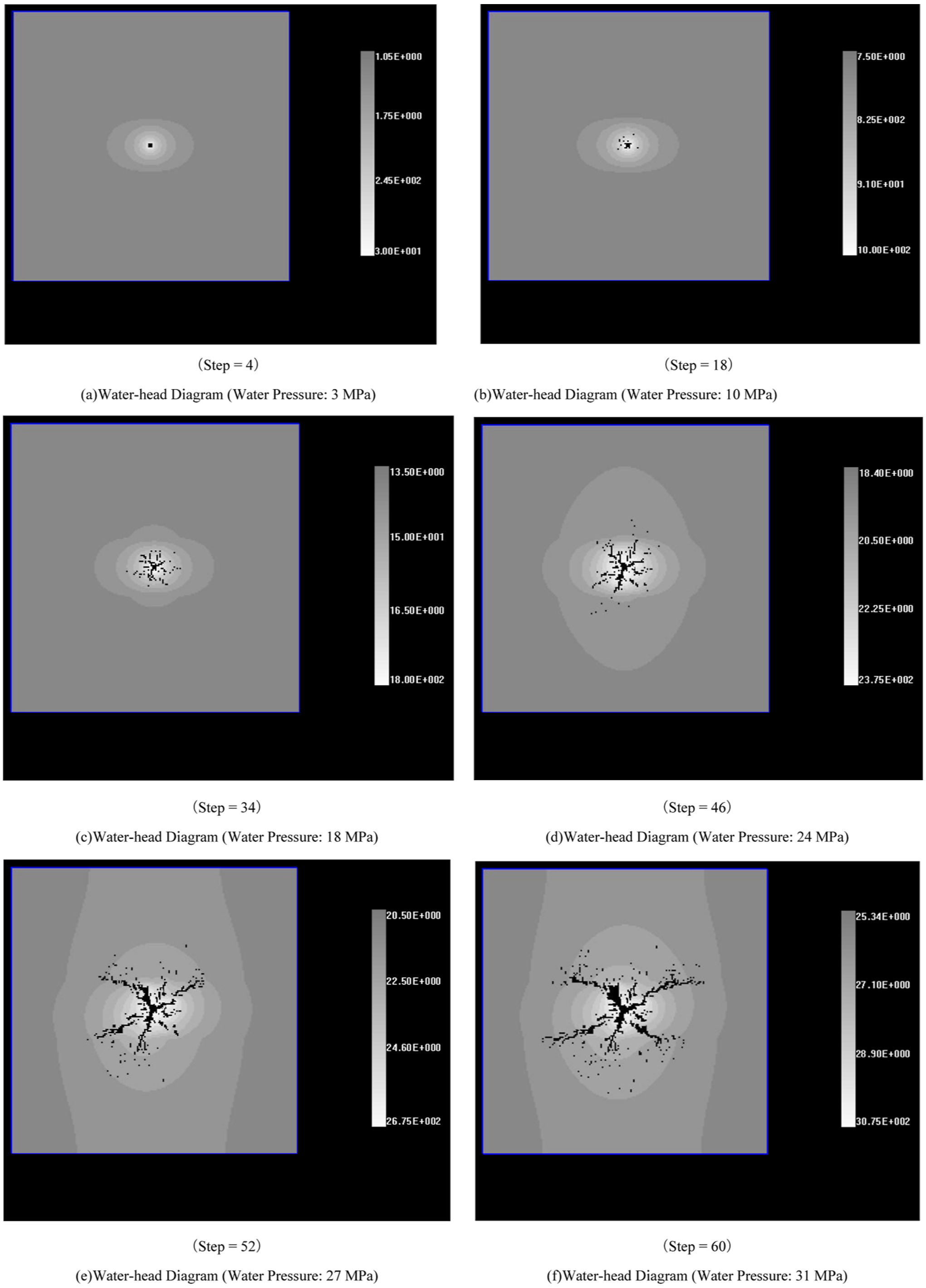

Figure 12. Water-head diagram of hydraulic fracturing drilling.

simulated. The model was 40 × 40 m, the coal seam was 8 m thick, and the top and bottom plates were 16 m. The entire model was divided into 400 × 400 units, and a two-dimensional plane strain mechanic model was established.

As can be seen from the acoustic emission results in Figure 13, the process of fracture initiation, development, and expansion of hydraulic fracturing starts from stress accumulation (Figure 13a), followed by steady growth of microcracks (Figure 13b), formation of local fracture zones (Figure 13c), and finally the result of local fracture zone expansion and penetration (Figure 13d).

Owing to the guiding effect of the directional hole, a nearly butterfly shaped compression crushing circle was formed around the fracture hole inside the coal rock body. In addition, a fracture surface ran through the fracture hole and the directional hole centerline direction to achieve the effect of controlled fracturing and avoid the phenomenon of irregular expansion of the fracture formed inside the coal body by single-hole, high-pressure water. It also eliminated safety problems such as partial decompression of nondirectional hydraulic fracturing, partial stress concentration, and the emergence of stress concentration for the hidden danger of later recovery.

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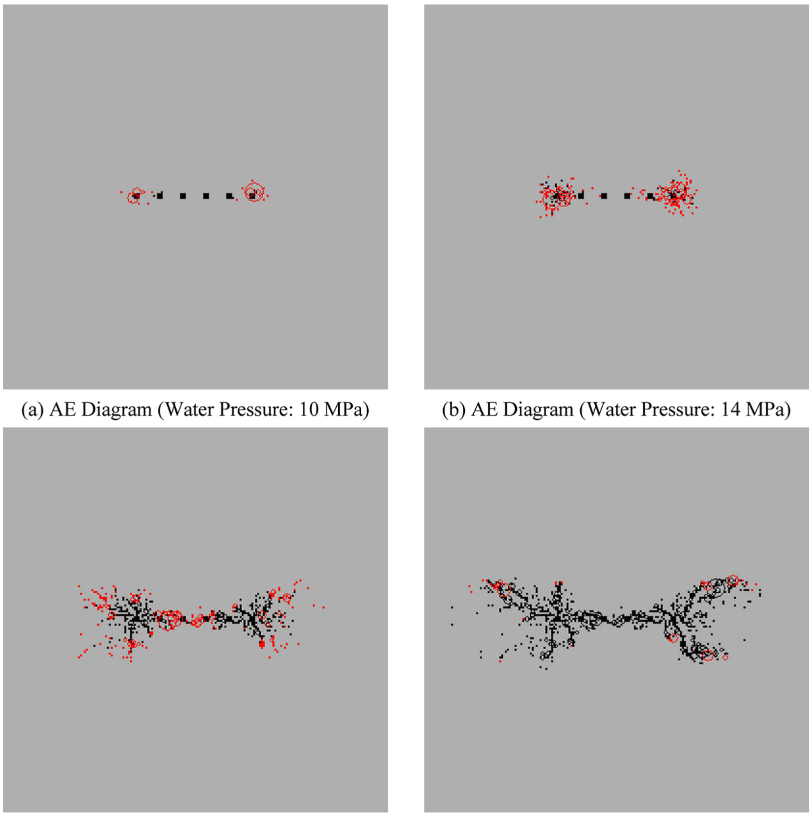

(a) AE Diagram (Water Pressure: 10 MPa) (b) AE Diagram (Water Pressure: 14 MPa)

(c) AE Diagram (Water Pressure: 21 MPa) (d) AE Diagram (Water Pressure: 25 MPa)

Figure 13. Acoustic emission map of fracture initiation and expansion during directional hydraulic fracturing.

4. EXAMPLE ANALYSIS

4.1. Site Construction Layout. Directional hydraulic fracturing technology was applied to auxiliary roadway 2238 of the Chengzhuang Mine of the Jinmei Group. Auxiliary roadway 2238 was driven to approximately 1200 m of 13# Hengchuan, the coal seam gas content was 12−14 m^3/t, and the original gas pressure was 0.52 MPa. The roof of the coal seam is sandy mudstone, with 12.02 m thick and rich plant fossils. The coal seam floor is also sandy mudstone with 0.60 m thick and rich of plant fossils. There are no geological structures exist near the construction site, as shown in Figure 14.

To improve the gas permeability of the coal body and the pumping effect, the fracturing borehole was arranged 30 m away from Hengchuan, no. 12, Auxiliary roadway 2238, to conduct directional hydraulic fracturing of the coal body without constructing boreholes in the west. During the on-site construction process, owing to serious hole collapse, the original drilling design could not satisfy the fracturing requirements. Therefore, the pressure fracture holes were modified according to the site conditions. Among the 11 holes initially identified, 2 were abandoned for different reasons, such as hole collapse and deformation, and 9 holes were completely sealed. An independent extraction hole without directional hydraulic fracturing treatment is arranged in the opposite direction of lane 2233. The gas extraction data obtained are used to compare with other directional hydraulic fracturing treatment extraction holes to test the gas extraction effect after the directional hydraulic fracturing treatment. Of the 9 boreholes, six were used as directional pressure holes and three were used as extraction holes. Figure 15 and Table 2 show the position distribution and corresponding information for each hole.

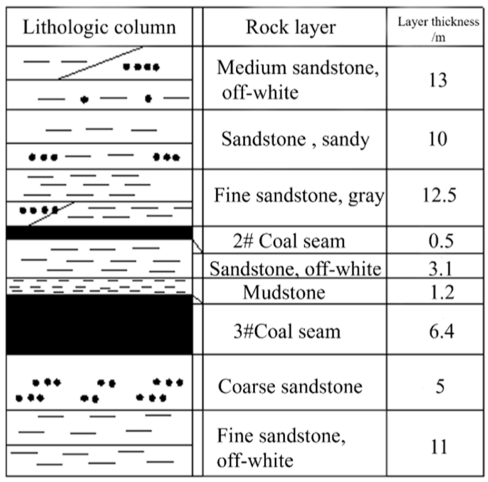

Figure 14. Local coal seam comprehensive bar chart of the Chengzhuang coal mine.

4.2. Analysis of Fracturing Results. The directional fracture holes through seams were released 2 days after the completion of fracturing and then connected to the extraction line for extraction after the pressure was removed and gas appeared. The data show that the initial extraction concentration, mixing volume, and pure volume of each hole were different because of the different degrees of pressure relief at the site.

Figure 16 shows that after using directional fracturing through the seam, the gas concentration first dropped because

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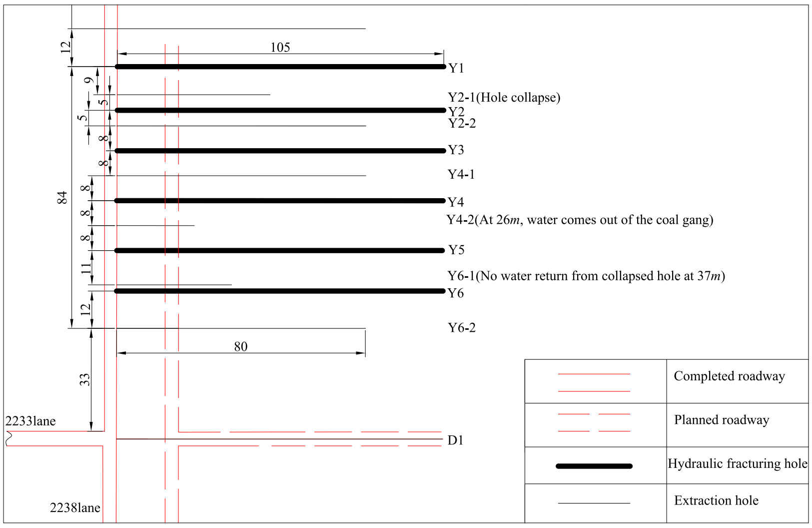

Figure 15. Fracturing borehole layout in 2238 after modification.

Table 2. Parameters of Pulsating Hydraulic Fracturing and Gas Drainage Boreholes

location	type	Aperture (mm)	hole depth (m)	inclination (°)	horizontal angle (°)
2238 auxiliary roadway	fracture hole(Y1)	94	105	2	90
2238 auxiliary roadway	fracture hole(Y2)	94	105	3	90
2238 auxiliary roadway	extraction hole(Y4−1)	94	80	2	90
2238 auxiliary roadway	extraction hole(D1)	94	105	2	90

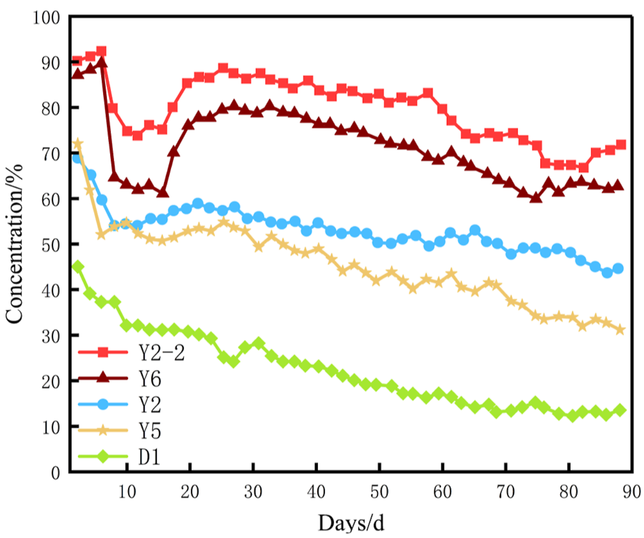

Figure 16. Gas concentration of boreholes in 2238.

the water entered the coal seam and blocked the gas flow, adding negative pressure extraction plus gas pressure and thus prompting the water to flow out. Further, the gas concentration increased and remained at a higher position, and the gas concentration remained above 50% after 91 days of extraction. Data from the independent extraction hole D1 showed that the average gas extraction concentration was low, and the gas extraction concentration after 91 days was less than 20%. From the concentration of gas extracted from the former directional extraction hole, it can be seen that the gas extraction efficiency of the extraction hole without directional hydraulic fracturing through the formation has decreased significantly, and the low gas permeability of the reservoir is the main influencing factor.

The effect of directional hydraulic fracturing through the seam on the unload pressure and the increase in permeability is mainly reflected in the reduction in gas content in the fractured area, which was measured at the end of the test, as shown in Table 3.

Table 3. Measure Results of Gas Content[a]

sampling locations	raw gas content (m^3/t)	residual gas content (m^3/t)
2238 auxiliary roadway fracturing area	12.13	7.0

[a]As evident from Table 3, the original gas content in the fractured area of the 2238 auxiliary roadway was 12.13 m^3/t, and the residual gas content of the coal seam was 7.0 m^3/t after the end of the through-seam directional hydraulic fracturing test, which reduced the gas content by 5.13 m^3/t, or 42.3%.

5. RESULTS AND DISCUSSION

In this simulation test, the initial fracturing in the pressure fracture hole was 1 MPa, and the incremental pressure was increased to 0.5 MPa per step. High-pressure water enters into the original pores and cracks of the coal body mainly through seepage. With the increase of water pressure, water begins to enter into the microcracks of the coal body, gas is compressed, and gas pressure increases. Gas pressure becomes the main factor preventing water from wetting coal bodies. As shown in Figure 12b, when the injection pressure increases to 10 MPa, an approximate annular pressure increase zone gradually forms around the hole wall, the principal stress around the hole is distributed radially, and the stress gradually accumulates. However, when the injection pressure gradually increased to 18 MPa, many microcracks appeared around the edge of the circular hole, as shown in Figure 12c. Before crack propagation, the pressure around the primary hole wall is isotropic. When one of the microcracks begins to expand deeply, the force

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direction of the crack direction gradually increases. Due to the inhomogeneity of the coal-rock medium, the microcracks are random. When the water injection pressure gradually increased to 24 MPa, the development rate of the main fracture and the microfracture near it accelerated, as shown in Figure 12d, and the expansion process became more complex, and some microfractures began to connect with the main fracture. When the pressure in the hole increases to 27 MPa, as shown in Figure 12e, the fracture can continue to expand without increasing the water injection pressure. The development of the main fracture slowed down, and the development of secondary fractures and through fracture accelerated. Fracturing instability occurs when the pressure in the hole gradually increases to 31 MPa, as shown in Figure 12f. Fracture propagation speeds up, multiple fractures occur at the tip of the main fracture, and the number of secondary fractures increases substantially. When the fracture develops to a certain extent, it will stop expanding and it is necessary to increase the water injection pressure again to make the fracture expand again. At this time, the influence radius of fracturing can reach 7−8 m.

As shown in Figure 13, with an increase in the water injection pressure in the coal seam, the stress concentration zone changed and moved deeper into the coal seam on both sides of the fracture hole and the pressure relief zone expanded significantly. When the fracturing was finished, most of the original rock stress was reduced to below 15 MPa, and the effect of reducing the coal seam pressure was more obvious. From the simulation results of directional hydraulic fracturing, the following can be concluded. Compared with nondirectional hydraulic fracturing, the fracture development between directional hydraulic fracturing is significantly greater. Moreover, owing to the guiding effect of directional holes, a nearly butterfly shaped compression crushing circle and a fracture surface running through the fracture and directional holes around the fracture holes inside the coal rock body, which better achieves the effect of controlled fracturing and eliminates the nondirectional hydraulic fracturing. The injection pressure required for directional hydraulic fracturing was low, of which the fracture pressure was approximately 21 MPa, which is lower than the fracture pressure of single-hole hydraulic fracturing. The appropriate increase in the number of injection holes is conducive to improving the effect of hydraulic pressure on increasing permeability.

The simulation results show the fracture initiation process under the dual action of raw rock stress and high-pressure water pressure. The initiation water injection pressure is not only related to the properties of the surrounding rock but also depends on the magnitude of axial and radial horizontal stress around the borehole. In general, it is affected by the weakest coal stratification in the radial direction and is controlled by the weakest stratification plane in the axial direction. Due to the existence of internal and external cracks, secondary cracks, and micropores in the coal body, high-speed water flow is generated in the cracks in the coal body during hydraulic fracturing and the water wedge into the coal body along the cracks around the borehole. The high-pressure water flow carries a huge amount of energy to further expand the original cracks and then forms a large range of cross-fracture networks around the borehole. The field practice results show that the directional hydraulic fracturing through the seam effectively plays the advantages of high energy power and hydraulic power, organically combines them, and has the advantages of changing the physical and mechanical properties of the coal, increasing and controlling the length and direction of the pressure relief belt, having strong permeability, and dust prevention.

6. CONCLUSIONS

1 The application of through-seam directional hydraulic fracturing technology for the prevention and control of coal and gas outbursts in high-gas, high-stress, and low-permeability coal seams and the determination of the form of through-seam hydraulic fracturing provide a new method of increasing the permeability and unload pressure in areas that do not have conditions for mining protective seams.

2 Among the many factors affecting hydraulic fracturing, coal seam gas pressure is an important factor. The higher the gas pressure, the more difficult it is to rupture the coal body, and the difficulty in initiating fracturing increases accordingly. When implementing hydraulic fracturing technology in the field, it is recommended that the water injection pressure be appropriately increased for hydraulic fracturing in high-gas mines to achieve the expected fracturing and abatement effects.

3 Directional hydraulic fracturing through the seam largely reduces the gas content in the coal seam, which reduces the coal seam gas content by approximately 40−50%, provides a safety guarantee for fracturing construction, and reduces the risk of coal and gas outburst. This provides theoretical support for large-scale promotion.

■ ASSOCIATED CONTENT

Data Availability Statement

The authors are unable or have chosen not to specify which data has been used.

■ AUTHOR INFORMATION

Corresponding Author

Xianzhong Li − *School of Energy Science and Engineering, Henan Polytechnic University, Jiaozuo, Henan 454000, China*; Email: lixianzhong@hpu.edu.cn

Authors

Weilong Zhou − *School of Energy Science and Engineering, Henan Polytechnic University, Jiaozuo, Henan 454000, China*; orcid.org/0009-0008-9994-9211

Shigang Hao − *School of Energy Science and Engineering, Henan Polytechnic University, Jiaozuo, Henan 454000, China*

Tao Wu − *School of Energy Science and Engineering, Henan Polytechnic University, Jiaozuo, Henan 454000, China*

Jinhao Zhang − *School of Energy Science and Engineering, Henan Polytechnic University, Jiaozuo, Henan 454000, China*

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.3c04737

Author Contributions

X.L.: conceptualization, writing-original draft, writing-review and editing, supervision, methodology. W.Z.: methodology, supervision, resources, project administration formal analysis. S.H.: formal analysis, validation, software. T.W.: investigation, methodology. J.Z.: investigation, methodology.

https://doi.org/10.1021/acsomega.3c04737
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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This research was funded by the National Natural Science Foundation of China (grant nos. 52174175, 52274078, and 52004081), Program for the Scientific and Technological Innovation Team in Universities of Henan Province (grant no. 23IRTSTHN005), and the Scientific and Technological Research Project in Henan Province (grant no. 212102310377).

■ REFERENCES

(1) Du, J.; Chen, J.; Pu, Y.; Jiang, D.; Chen, L.; Zhang, Y. Risk assessment of dynamic disasters in deep coal mines based on multi-source, multi-parameter indexes, and engineering application. *Process Saf. Environ. Prot.* **2021**, *155*, 575−586.

(2) Liu, J.; Liu, Z.; Xue, J.; Gao, K.; Zhou, W. Application of deep borehole blasting on fully mechanized hard top-coal pre-splitting and gas extraction in the special thick seam. *Int. J. Min. Sci. Technol.* **2015**, *25* (5), 755−760.

(3) Wang, L.; Lu, Z.; Chen, D.; Liu, Q.; Chu, P.; Shu, L.; Ullah, B.; Wen, Z. Safe strategy for coal and gas outburst prevention in deep-and-thick coal seams using a soft rock protective layer mining. *Saf. Sci.* **2020**, *129* (C), 104800.

(4) Cheng, X.; Zhao, G.; Li, Y.; Meng, X.; Tu, Q. Key technologies and engineering practices for soft-rock protective seam mining. *Int. J. Min. Sci. Technol.* **2020**, *30* (6), 889−899.

(5) Zhou, A.; Xu, Z.; Wang, K.; Wang, Y.; An, J.; Shi, Z. Coal mine gas migration model establishment and gas extraction technology field application research. *Fuel* **2023**, *349*, 128650.

(6) Hu, Y.; Li, W.; Chen, X.; Xu, H.; Liu, S. Temporal and spatial evolution characteristics of fracture distribution of floor strata in deep coal seam mining. *Eng. Fail. Anal.* **2022**, *132*, 105931.

(7) Wang, H.; Wang, E.; Li, Z.; Shen, R.; Liu, X. Study and application of a new gas pressure inversion model in coal seam while drilling based on directional drilling technology. *Fuel* **2021**, *306*, 121679.

(8) Li, H.; Wang, W.; Liu, Y.; Ma, J.; Gao, H. An integrated drilling, protection and sealing technology for improving the gas drainage effect in soft coal seams. *Energy Reports* **2020**, *6*, 2030−2043.

(9) Hubbert, M.; Willis, D. Mechanics Of Hydraulic Fracturing. *Trans. Am. Inst. Min. Metall. Eng.* **1957**, *210* (01), 153−168.

(10) Huang, J.; Griffiths, D.; Wong, S. Initiation pressure, location and orientation of hydraulic fracture. *Int. J. Rock Mech. Min. Sci.* **2012**, *49*, 59−67.

(11) Li, X. *Research on Fracture Propagation and Turning Based on Maximum Energy Release Rate Theory*; Northeast Petroleum University, 2019.

(12) Men, X.; Tao, S.; Liu, Z.; Tian, W.; Chen, S. Experimental study on gas mass transfer process in a heterogeneous coal reservoir. *Fuel Process. Technol.* **2021**, *216*, 106779.

(13) Xu, Z.; Zhang, J.; Shao, L.; Cao, C.; Chai, J.; Qin, Y.; Cao, J. Numerical simulation investigation on the seepage characteristics of aperture dilated rough single fracture under two-way hydro-mechanical coupling effect. *Gas Sci. Eng.* **2023**, *110*, 204865.

(14) Chen, S.; Tang, D.; Tao, S.; Xu, H.; Li, S.; Zhao, J.; Ren, P.; Fu, H. In-situ stress measurements and stress distribution characteristics of coal reservoirs in major coalfields in China: Implication for coalbed methane (CBM) development. *Int. J. Coal Geol.* **2017**, *182*, 66−84.

(15) Li, W.; Liu, J.; Zeng, J.; Leong, Y.; Elsworth, D.; Tian, J. A fully coupled multidomain and multiphysics model considering stimulation patterns and thermal effects for evaluation of coalbed methane (CBM) extraction. *J. Pet. Sci. Eng.* **2022**, *214*, 110506.

(16) Zhu, Q.; Yang, Y.; Zuo, Y.; Song, Y.; Guo, W.; Tang, F.; Ren, J.; Wang, G. On the scientific exploitation of high-rank CBM resources. *Nat. Gas Ind.* **2020**, *7* (4), 403−409.

(17) Chen, S.; Tang, D.; Tao, S.; Liu, P.; Mathews, J. Implications of the in situ stress distribution for coalbed methane zonation and hydraulic fracturing in multiple seams, western Guizhou, China. *J. Pet. Sci. Eng.* **2021**, *204*, 108755.

(18) Mou, P.; Pan, J.; Wang, K.; Wei, J.; Yang, Y.; Wang, X. Influences of hydraulic fracturing on microfractures of high-rank coal under different in-situ stress conditions. *Fuel* **2021**, *287*, 119566. , (prepublish)

(19) Hu, Q.; Jiang, Z.; Li, Q.; Wu, W.; Wang, Q.; Wang, X.; Ran, Y.; Tong, S. Induced stress evolution of hydraulic fracturing in an inclined soft coal seam gas reservoir near a fault. *J. Nat. Gas Sci. Eng.* **2021**, *88*, 103794. , (prepublish)

(20) Sun, Z.; Huang, B.; Liu, Y.; Jiang, Y.; Zhang, Z.; Hou, M.; Li, Y. Gas-phase production equation for CBM reservoirs: Interaction between hydraulic fracturing and coal orthotropic feature. *J. Pet. Sci. Eng.* **2022**, *213*, 110428.

(21) Yang, W.; Lu, C.; Si, G.; Lin, B.; Jiao, X. Coal and gas outburst control using uniform hydraulic fracturing by destress blasting and water-driven gas release. *J. Nat. Gas Sci. Eng.* **2020**, *79* (C), 103360.

(22) Pan, Z.; Wood, D. A. Coalbed methane (CBM) exploration, reservoir characterisation, production, and modelling: A collection of published research (2009−2015). *J. Nat. Gas Sci. Eng.* **2015**, *26* (C), 1472−1484.

(23) Li, T.; Li, L.; Tang, C.; Zhang, Z.; Li, M.; Zhang, L.; Li, A. A coupled hydraulic-mechanical-damage geotechnical model for simulation of fracture propagation in geological media during hydraulic fracturing. *J. Pet. Sci. Eng.* **2019**, *173* (C), 1390−1416.

(24) Li, Z.; Wang, S.; Li, L.; Zhang, J.; Li, T. Numerical simulation of brittleness effect on propagation behavior of glutenite hydraulic fractures. *Ain Shams Eng. J.* **2021**, *12* (4), 3419−3427.

(25) Liu, C.; Li, S.; Cheng, C.; Cheng, X. Identification methods for anomalous stress region in coal roadways based on microseismic information and numerical simulation. *Int. J. Min. Sci. Technol.* **2017**, *27* (3), 525−530.

(26) Xia, B.; Zhang, X.; Yu, B.; Jia, J. Weakening effects of hydraulic fracture in hard roof under the influence of stress arch. *Int. J. Min. Sci. Technol.* **2018**, *28* (6), 951−958.

(27) Ma, K.; Sun, X.; Tang, C.; Yuan, F.; Wang, S.; Chen, T. Floor water inrush analysis based on mechanical failure characters and microseismic monitoring. *Tunn. Undergr. Space Technol.* **2021**, *108*, 103698.

(28) Hao, C.; Cheng, Y.; Wang, L.; Liu, H.; Shang, Z. A novel technology for enhancing coalbed methane extraction: Hydraulic cavitating assisted fracturing. *J. Nat. Gas Sci. Eng.* **2019**, *72*, 103040.

(29) Yan, F.; Lin, B.; Zhu, C.; Shen, C.; Zou, Q.; Guo, C.; Liu, T. A novel ECBM extraction technology based on the integration of hydraulic slotting and hydraulic fracturing. *J. Nat. Gas Sci. Eng.* **2015**, *22*, 571−579.

(30) Lu, W.; He, C. Numerical simulation of the fracture propagation of linear collaborative directional hydraulic fracturing controlled by pre-slotted guide and fracturing boreholes. *Eng. Fract. Mech.* **2020**, *235*, 10712810. (prepublish)

(31) Li, Z.; Li, L.; Li, M.; Zhang, L.; Zhang, Z.; Huang, B.; Tang, C. A numerical investigation on the effects of rock brittleness on the hydraulic fractures in the shale reservoir. *J. Nat. Gas Sci. Eng.* **2018**, *50*, 22−32.

(32) Lu, W.; Bai, E.; Wei, L.; He, C.; Sun, Y.; Shi, L. Numerical simulation on spatial steering rule of directional perforation hydraulic fractures in low-permeability reservoir. *Front. Earth Sci.* **2022**, *10*, 1007218.

(33) Song, C.; Lu, Y.; Tang, H.; Jia, Y. A method for hydrofracture propagation control based on non-uniform pore pressure field. *J. Nat. Gas Sci. Eng.* **2016**, *33*, 287−295.

(34) Zhang, G.; Wei, G.; Hou, F. Theory of water injection pressure and location of fracture initiation in perforated drilling. *J. China Coal Soc.* **2007**, *01* (01), 52−55.

(35) Soleimani, F.; Si, G.; Roshan, H.; Zhang, Z. Numerical modelling of coal and gas outburst initiation using energy balance principles. *Fuel* **2023**, *334* (P1), 126687.

(36) Yang, D.; Peng, K.; Zheng, Y.; Chen, Y.; Zheng, J.; Wang, M.; Chen, S. Study on the characteristics of coal and gas outburst hazard under the influence of high formation temperature in deep mines. *Energy* **2023**, *268*, 126645.

(37) Wu, S.; Gao, K.; Feng, Y.; Huang, X. Influence of slip and permeability of bedding interface on hydraulic fracturing: A numerical study using combined finite-discrete element method. *Comput. Geotech.* **2022**, *148*, 104801.

(38) Yang, K.; Gao, D. Numerical simulation of hydraulic fracturing process with consideration of fluid−solid interaction in shale rock. *J. Nat. Gas Sci. Eng.* **2022**, *102*, 104580.

(39) Zhou, X.; Du, E.; Wang, Y. Thermo-hydro-chemo-mechanical coupling peridynamic model of fractured rock mass and its application in geothermal extraction. *Comput. Geotech.* **2022**, *148*, 104837.

(40) Wang, C.; Li, X.; Liu, L.; Tang, Z.; Xu, C. Dynamic effect of gas initial desorption in coals with different moisture contents and energy-controlling mechanism for outburst prevention of water injection in coal seams. *J. Pet. Sci. Eng.* **2023**, *220* (PB), 111270.

https://doi.org/10.1021/acsomega.3c04737
ACS Omega 2023, 8, 38359−38372