Research Article

Optimization of Indirect Fracturing Process Parameters Based on Mechanical Properties of Fractured and Low-Permeability Coal

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Received 12 August 2021; Revised 4 December 2021; Accepted 31 December 2021; Published 7 March 2022

Academic Editor: Yingfang Zhou

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The coal-bed methane (CBM) resources in soft and low-permeability coals are assumed to be as much as $15 \times 10^{12} \text{ m}^3$ in China. Indirect fracturing technology can be an effective method to successfully extract methane within soft coals. The key to the success of this technique is to optimize the parameters, such as water injection flow rate and fracture initiation location, so that the hydraulic fracturing parameters enable the fractures to pass through the interface between coal and rock and propagate sufficiently into the coal. This paper focuses on solving the above problems by focusing on discontinuities and plastic characteristics of soft coals. Voronoi polyhedron was used to simulate the discontinuities of coal, and the constitutive relations of ductile fracture-seepage and elastoplastic damage-seepage are, respectively, given to the discontinuities and coal matrix. A numerical model was established based on the above theory to simulate the effect of stress difference $\Delta\sigma$, coal-rock interface friction coefficient $f_{c,r}$, water injection flow rate i_w , and distance between the well and the interface D_{op} on indirect fracturing fractures. The results show that the HF area in the coal is positively correlated with $\Delta\sigma$, $f_{c,r}$, and i_w , and it first increases and then decreases with the decrease of D_{op} . The above results were applied in the Zhaozhuang mine of Qinshui Basin by optimizing $D_{op} = 1 \text{ m}$ and $i_w = 8 \text{ m}^3/\text{min}$, so that CBM production has been greatly increased. The results can provide theoretical support for the efficient development of CBM in fractured and low-permeability coal seam areas.

1. Introduction

The resources of fractured low-permeability coal account for 82% of the total coal in China, and the resources of coal-bed methane (CBM) in coal is as high as $15 \times 10^{12} \text{ m}^3$ [1, 2]. The efficient exploitation of this huge reserve of clean energy will help China achieve the peak of carbon dioxide emissions in 2030 and carbon neutrality in 2060 [3]. However, the fractured coal is generally of low mechanical parameters, abundant discontinuities, and low permeability because of small crack opening, leading to the failure of traditional fracturing into coal seams, shown as short hydraulic fracture (HF) extension and borehole collapse [4, 5]. Indirect

fracturing technology can effectively avoid the disadvantages caused by the above direct fracturing coal technology. The basic step is to arrange the horizontal well in the hard roof and carry out perforation and hydraulic fracturing.

The key to the success of the technology is to optimize the indirect fracturing parameters so that HFs can be fully propagated into the coal seam. Numerical simulation is an important method to achieve the above objectives, however, its accuracy is restricted by two aspects: (1) constitutive equation and (2) coal discontinuities network model. For the first problem, the theory of linear elastic fracture mechanics was adopted by Zhang and Dontsov [6]. They found that the small stress difference and small elastic modulus difference

of adjacent rock formation would lead to the interface strongly hindering the HF propagation. Based on the theory of elastic damage mechanics, Poludasu et al. [7] and Xue et al. [8] established a two-dimensional numerical model for the problem of HF crossing the interface of the layered rock mass. They found that only when the interface strength is relatively high would HF pass through the interface. According to the CT test and the nonlinear mechanics-leakage hypothesis, Li et al. [9] developed a three-dimensional discontinuous network model and a plastic-nonlinear fracture-leakage-coupled constitutive formula. According to the numerical simulation results, Oyedere et al. [10] believe that in low-permeability media, too high a fracturing fluid injection rate will stop the propagation of hydraulic fractures. Based on the elastic damage mechanics, Guo et al. [11] studied the influence of multiple factors on the HF crossing the layered rock interface using the numerical simulation method. The results show that it is difficult for the HF to cross the interface under the conditions of low-stress difference and high material tensile strength.

For the second problem, scholars tend to simplify the fractured medium as an equivalent continuous medium (ECM) model. However, coal is naturally fractured [12]. Therefore, Vahab et al. [13] assumed that coal is a dual continuous medium. On this basis, a conclusion is obtained using the calculation of the extended finite element method, i.e., HF are easier to cross the hard medium into the soft medium. In addition, some scholars have established the discrete fracture network model (DFN) of fractured media, however, they did not deeply study its mechanical properties. For example, Ma et al. [14] simplified coal discontinuity as matchsticks, where each stick represented one coal matrix, and the space between the sticks was representative of the discontinuities. Zhao et al. [15] regarded coal as masonry structures. Karimpouli et al. [16] made statistics of the distance and distribution of coal discontinuities and developed a rectangular grid model.

The above literature shows that there are abundant discontinuities with high permeability, however, poor mechanical properties in coal and HF are easy to propagate in an adjacent rock formation in the conditions of high-stress differences, water injection flow rates, high interfacial strength, and significant differences of rock elastic modulus. However, scholars generally ignore the influence of an important parameter on indirect fracturing engineering, i.e., the distance between well and coal-rock interface (D_{op}). In addition, the elasticity theory and the simplified continuum model cannot fully reflect the characteristics of fractured and low-permeability coal, including abundant discontinuities and obvious plastic fracture behavior. Obviously, the hydraulic fracturing parameters optimized by traditional theory and model are not reliable.

Focusing on the mechanical properties of fractured and low-permeability coal, this paper studied the plastic damage-seepage features of coal matrix, ductile fracture-seepage features, and distribution law of coal discontinuities. On this basis, the fluid-solid coupling constitutive equation of coal and the geometric model for discontinuity were established. Using the numerical simulation method, the propagation

mechanism of HF under the influence of four factors was studied, including D_{op} , water injection rate, stress difference, and shear strength of coal-rock interface. The optimized parameters obtained by numerical simulation were applied to a coal mine, which greatly increases the output of CBM.

2. Geological Characteristics and Extraction Status of CBM in Zhaozhuang Mine

The proved reserves of CBM in Qinshui Basin account for more than 70% of China's CBM resources [17]. By direct fracturing coal technology, the southern Qinshui Basin has achieved average daily gas production of 1,000 m³/d per well. However, this mature technology cannot be replicated in the middle and east of the Qinshui basin because of the special geological conditions of CBM. In this paper, the Zhaozhuang mine (Figure 1) in the east of the Qinshui Basin is studied as an example.

The basic geological conditions of the CBM reservoir (No. 3 coal) in the Zhaozhuang mine are as follows: the thickness is 5 m, and the depth is 450 m. The gas content of the coal is 10 m³/t, and the reservoir pressure is 3.6–6.1 MPa. Under the influence of long-term and large-scale geological tectonic movement, 33 folds were formed in the mining area, which leads to changes in the stress state of the reservoir and the strength of the coal-rock interface. At the same time, abundant discontinuities are formed in coal under the action of strong stress, resulting in the formation of fractured and low-permeability coal. Generally, the compressive strength of coal is lower than 15 MPa, and its permeability is lesser than 1mD.

In the early engineering practice, 245 direct fracturing wells have been drilled in the Zhaozhuang mine. Only 47 wells produce gas, and the average CBM production is less than 300 m³/d, far from reaching the target of 3000 m³/d. The main reason for the failure of direct fracturing technology is that the Zhaozhuang coal has the characteristics of abundant discontinuities and obvious plastic failure so that wells are easy to collapse, and HF are difficult to extend far away, resulting in low CBM production.

However, the indirect fracturing coal technology (Figure 2) can effectively overcome the above difficulties. This new technology is strongly supported by CBM geological conditions, including vertical stress, which is the first principal stress. The rock layers gradually soften from top to bottom, which makes it possible for HF in the roof to propagate to coal. However, so far, only two of the five indirectly fractured horizontal wells in the Zhaozhuang mine have achieved the goal of 3000 m³/d.

The failure of the indirect fracturing technology is because HF do not cross the coal-rock interface. The fundamental reasons are as follows: (1) from the mechanical theory, for the layered brittle rock formation, although almost all of the hydraulic energy is used to transform into fracture surface energy (i.e., elastic energy) to promote HF propagation. The interface between the rock layers will still strongly hinder HF propagation. However, the above phenomenon will be more obvious for fractured low-permeability coal because the hydraulic energy will also be

FIGURE 1: Location of Zhaozhuang mine and CBM occurrence environment.

FIGURE 2: Schematic diagram of indirect fracturing coal technology.

consumed in the plastic work, which is not conducive to HF propagation [18]. Therefore, a new constitutive equation reflecting the toughness failure of coal needs to be established. (2) The coal discontinuities induce HFs to propagate along it [19], forming an energy-consuming mixed fracture mode. It is difficult for HFs to cross the coal-rock interface.

According to the above, the in-depth study of coal discontinuity and its fluid-solid coupling characteristics is the basis for further optimization of indirect fracturing technical parameters.

3. The Fluid-Solid Coupling Theory Model of Pore-Fractured Coal

Abundant discontinuous and significant nonlinear mechanical characteristics of plastic fracture-seepage are the

two notable features of fractured low-permeability coal. The material is a typical pore (i.e., coal matrix)-fracture (i.e., coal discontinuities) medium [20]. There are three mechanical responses in the coal process during hydraulic fracturing [21], which are as follows: plastic damage-seepage of coal matrix, ductile fracture-seepage of coal discontinuities, and the stress-seepage interaction between them.

Considering that the mechanism of coal matrix failure is plastic deformation and crack propagation [22], the two factors should be included in the constitutive model. The specific steps are as follows:

The plastic damage constitutive relation of the coal matrix is as follows [19]:

$$\sigma_s^t = (1 - d): E_0: (\varepsilon_s - \varepsilon_s^p) + \alpha p_w I, \quad (1)$$

where σ_s^t is the total stress, E_0 is elastic stiffness matrix, ε_s and ε_s^p are total strain and plastic strain, p_w is the pore water pressure, I is the unit matrix, and α is the effective stress coefficient, and its expression is as follows:

$$\alpha = 1 - \frac{K_b}{K_s}, \quad (2)$$

K_s and K_b are the effective bulk modulus of the solid constituent and drained bulk modulus of the porous medium, respectively.

The plastic strain in (2) is solved as follows:

The loading function is as follows:

$$F = \frac{1}{1-A} (q_{\text{eff}} - 3Ap_{\text{eff}} + B(\varepsilon_s^p) \cdot \langle \sigma_{\text{eff},i}^{\text{max}} \rangle - C \langle -\sigma_{\text{eff},i}^{\text{max}} \rangle) - \hat{\sigma}_{\text{eff}}(\varepsilon_s^p) = 0, \quad (3)$$

where $A = (\sigma_b/\sigma_u - 1)/(2\sigma_b/\sigma_u - 1)$, $B = \hat{\sigma}_{\text{eff}}(\hat{\varepsilon}_s^p)/\hat{\sigma}_{\text{eff}}(d) \cdot (1-A) - (1+A)$, $C = 3(1-K_c)/(2K_c - 1)$, $p_{\text{eff}} = \text{trace}(\sigma_{\text{eff}})/3$, $q_{\text{eff}} = \sqrt{2(S_{\text{eff}}: S_{\text{eff}})/3}$, $S_{\text{eff}} = \sigma - p_{\text{eff}}I$, $\sigma_{\text{eff},i}^{\text{max}}$ ($i = 1, 2, 3$) is the maximum effective principal stress, σ_b/σ_u is the ratio of biaxial strength to uniaxial strength, and $\hat{\sigma}_{\text{eff}}$ is the equivalent stress, and when $K_c = 0.667$, the shape of

loading function on the π plane is close to Mohr–Coulomb yield criterion, as shown in Figure 3.

The plastic potential function is as follows:

$$G = \sqrt{(\delta\sigma_{\text{UTS}} \tan\psi)^2 + q_{\text{eff}}^2} - p_{\text{eff}} \tan\psi, \quad (4)$$

where δ is a parameter, and $\delta = 0.1$ in numerical simulation. σ_{UTS} is the tensile strength, and ψ is the dilatancy angle.

Based on the above equations, ε_s^p can be solved by the backward Euler method [23].

The damage evolution law of $d^{(+)}$ and $d^{(-)}$ in (1) can be obtained by the experiments (Section 4).

The permeability coefficient of the coal matrix changes as the strain increases. By fitting the experimental data of full stress-strain seepage, the relationship between the permeability coefficient and strain can be obtained. The experimental procedure refers to the literature [24]. The experimental results are shown in Figure 4. As the axial strain increases, the evolution of the permeability coefficient can be divided into three stages: (1) linear seepage, (2) rapid increase, and (3) nonlinear and stable stage of seepage stage.

By fitting the data in Figure 4, the expression of the evolution law of the permeability coefficient during the elastoplastic damage of the coal matrix can be obtained as follows:

$$k = \begin{cases} k_{\min} + k_{\min} e^{[(\varepsilon_{\min} - \varepsilon)/\varepsilon_{\min}]^{\eta_1}} & \text{(The first stage),} \\ k_{\min} + \delta_1 k_{\min} [(\varepsilon - \varepsilon_{\min})/\varepsilon_{\min}]^{\eta_2} e^{[-(\varepsilon - \varepsilon_{\min})/\varepsilon_{\min}]^{\eta_3}} & \text{(The second stage),} \\ k_{\max} e^{[-(\varepsilon_{\max} - \varepsilon)/\varepsilon_{\max}]^{\eta_4}} + \delta_1 k_{\max} & \text{(The third stage).} \end{cases} \quad (5)$$

For coal discontinuities, this paper established the ductile fracture and seepage-coupled constitutive model under different fracture modes and assigned this attribute to cohesive elements. The steps for establishing the constitutive equations are as follows.

The constitutive equation at the stage of elastic deformation is [25]

$$\sigma_c = D_{0,c} \varepsilon_c. \quad (6)$$

Once the following stress conditions are reached, cracks begin to form.

$$\max \left\{ \frac{\langle \sigma_{c,n} \rangle}{\sigma_{c,n}^{\text{peak}}}, \frac{\sigma_{c,s}}{\sigma_{c,s}^{\text{peak}}}, \frac{\sigma_{c,t}}{\sigma_{c,t}^{\text{peak}}} \right\} = 1, \quad (7)$$

where $\sigma_{c,n}$, $\sigma_{c,s}$, and $\sigma_{c,t}$ (or $\sigma_{c,n}^{\text{peak}}$, $\sigma_{c,s}^{\text{peak}}$, and $\sigma_{c,t}^{\text{peak}}$) are (peak) normal and tangential stress. The symbol $\langle \cdot \rangle$ is the Macaulay bracket. $D_{0,c}$ is the elastic stiffness matrix. ε_c is the strain vector. The relationship between ε_c and separation vector S is $\varepsilon_c = S/T_0$, and T_0 is the constitutive thickness of the cohesive element.

After the peak load, the constitutive relationship can be deduced by the following method.

Use Park–Paulino–Roesler (PPR) potential energy function [26] to derive stress-displacement response during the ductile fracture. The expression of the potential energy function $\Psi(S_n, S_s)$ is as follows:

$$\Psi(S_n, S_s) = \left[\Gamma_n \left(1 - \frac{S_n}{s_n} \right)^\beta \left(\frac{m}{\beta} + \frac{S_n}{s_n} \right)^m + \langle G_n - G_s \rangle \right] \times \left[\Gamma_s \left(1 - \frac{|S_s|}{s_s} \right)^\gamma \left(\frac{n}{\gamma} + \frac{|S_s|}{s_s} \right)^n + \langle G_s - G_n \rangle \right] + \min(G_n, G_s), \quad (8)$$

where S_s is the vector sum of S_s and S_p , and Γ_n, Γ_s are fracture energy constants.

FIGURE 3: Yield curve.

FIGURE 4: Evolution law of coal matrix permeability coefficient during the full stress-strain process.

$$\begin{cases} \Gamma_n = (-G_n)^{\langle G_n - G_s \rangle / (G_n - G_s)} (\beta/m)^m, \\ \Gamma_s = (-G_s)^{\langle G_s - G_n \rangle / (G_s - G_n)} (\gamma/n)^n, \end{cases} \quad (9)$$

$$\begin{cases} m = \beta(\beta - 1)\chi_n^2 / (1 - \beta\chi_n^2), \\ n = \gamma(\gamma - 1)\chi_s^2 / (1 - \gamma\chi_s^2), \end{cases} \quad (10)$$

where G_n and G_s are normal and tangential fracture energies, and β and γ are material parameters, which are obtained by fitting the traction force-separation curve. The parameters m and n are related to β and γ . The expression of m and n is as follows:

where χ_n and χ_s represent the relative peak displacement. By calculating the first derivative of $\Psi(S_n, S_s)$, the constitutive equations of different fracture modes can be obtained, as shown in Eqs. 11~ (13).

$$\sigma_{c,n} = \frac{\Gamma_n}{s_n} \left\{ m \left(1 - \frac{S_n}{s_n} \right)^\beta \left(\frac{m}{\beta} + \frac{S_n}{s_n} \right)^{m-1} - \beta \left(1 - \frac{S_n}{s_n} \right)^{\beta-1} \left(\frac{m}{\beta} + \frac{S_n}{s_n} \right)^m \right\} \times \left[\Gamma_s \left(1 - \frac{S_s}{s_s} \right)^\gamma \left(\frac{n}{\gamma} + \frac{S_s}{s_s} \right)^n + \langle G_s - G_n \rangle \right], \quad (11)$$

$$\sigma_{c,s} = \frac{\Gamma_s}{s_s} \left[\Gamma_n \left(1 - \frac{S_n}{s_n} \right)^\beta \left(\frac{m}{\beta} + \frac{S_n}{s_n} \right)^m + \langle G_n - G_s - G_t \rangle \right] \times \left\{ n \left(1 - \frac{S_s}{s_s} \right)^\gamma \left(\frac{n}{\gamma} + \frac{S_s}{s_s} \right)^{n-1} \frac{S_s}{\sqrt{S_s^2 + S_t^2}} \gamma \left(1 - \frac{S_s}{s_s} \right)^{\gamma-1} \left(\frac{n}{\gamma} + \frac{S_s}{s_s} \right)^n \frac{S_s}{s_s} \right\}, \quad (12)$$

$$\sigma_{c,t} = \frac{\Gamma_t}{s_s} \left[\Gamma_n \left(1 - \frac{s_n}{s_n} \right)^\beta \left(\frac{m}{\beta} + \frac{s_n}{s_n} \right)^m + \langle G_n - G_s - G_t \rangle \right] \times \left\{ n \left(1 - \frac{s_s}{s_s} \right)^\gamma \left(\frac{n}{\gamma} + \frac{s_s}{s_s} \right)^{n-1} \frac{S_t}{\sqrt{S_s^2 + S_t^2}} \gamma \left(1 - \frac{s_s}{s_s} \right)^{\gamma-1} \left(\frac{n}{\gamma} + \frac{s_s}{s_s} \right)^n \frac{S_t}{S_s} \right\}. \quad (13)$$

Thus, the constitutive equation of the ductile fracture under the mixed fracture mode is obtained, and pure mode I and pure mode II fractures can be regarded as special cases of them.

According to the stress data obtained from the above constitutive model, the elastic energy G^e and inelastic energy G^{in} fracture energy can be obtained by integrating the displacement.

$$G^e = \frac{(\sigma_{c,n}^0 s_n^e + \sigma_{c,s}^0 s_n^e + \sigma_{c,t}^0 s_n^e)}{2}, \quad (14)$$

$$G^{in} = G_n + G_s + G_t - G^{e,peak},$$

where $\sigma_{c,n}^0$ (s_n^e) is the stress (separation) in elastic deformation stage, respectively. $G^{e,peak}$ is the maximum elastic energy.

Coal discontinuities are the main seepage channels of fluid [27]. In addition to the mechanical equation of coal discontinuities, the tangential and normal seepage equations of water in discontinuities should also be given. Considering that fluid migration in fractures often exhibits nonlinear characteristics, the tangential flow equation is established based on the Forchheimer equation.

$$-\nabla p_t = \frac{12\mu}{lw^3} Q_t + \beta_w \frac{\rho}{(lw)^2} Q_t^2. \quad (15)$$

At the same time, the fluid seepage along the normal direction of the fracture cannot be ignored, especially after the coal matrix is damaged. The expression is as follows:

$$Q_n = 2k(p_{n,cen} - p_{n,boun}), \quad (16)$$

where $-\nabla p_t$ is the pressure gradient, μ is the dynamic viscosity, w is the gap width, Q_t is total flow, $\beta_w = 3.35 \times 10^{-15} \text{ kg/s}^2$ is the non-Darcy flow factor, ρ_w is water density, Q_n is the leak-off flow, k is the permeability coefficient (Eq. 5), and $p_{n,cen}$ and $p_{n,boun}$ are the water pressure in the middle and boundary gap, respectively.

Based on above equations, DF-S constitutive equations are established, and the numerical calculation process is shown in Figure 5.

4. Parameter Identification and Constitutive Model Verification

4.1. Experimental Results of Fracture Mechanics. The fracture mechanics experiment shown in Figure 6 [28] is an important method to obtain coal fracture parameters and verify the rationality of the constitutive equation. In addition, the mechanical parameters of the coal matrix are obtained using loading and unloading experiments and seepage

experiments [29]. The results are shown in Table 1 and Figure 7. Establish a numerical calculation model consistent with the fracture experiment and the cohesive elements arranged along the fracture surface, and its mechanical properties are controlled by equations described in Sec. 3. The comparison result of numerical simulation and experiment is shown in Figure 6.

Using the above comparison, we find that the PF-S constitutive equations can better describe the mechanical properties of fractured coal.

4.2. Hydraulic Fracturing Experiment and Simulation. Zhaozhuang coal is rich in discontinuities, which is the main propagation channel of HFs. Therefore, before numerical simulation, it is necessary to establish a discrete fracture network model close to the actual discontinuities.

According to related research [30], we use the Voronoi polyhedron to simplify the spatial distribution of coal discontinuities. The geometric parameters of the Voronoi polyhedron are obtained by CT scanning (Figure 8(a)), including discontinuous spacing, and the respective fluctuation amplitudes. Thus, the reconstructed discontinuities spatial distribution is obtained (Figure 8(b)). Comparing figures 8(a) and 8(b), it can be seen that the Voronoi polyhedron is similar to the discontinuities network geometry obtained from the CT experiment.

Based on the above geometric model, the constitutive equation can be further verified by hydraulic fracturing experiments. The boundary conditions of the hydraulic fracturing experiment are shown in Table 2, and the test results are shown in figures 9(a) and 9(b) [21]. The numerical model is established according to figure 9(a), in which the discontinuities in cement are arranged in the middle and parallel to σ_H , and the discontinuities in coal are consistent with figure 8(b). The constitutive equations in Sec.3 were applied to coal, and parameters are shown in Table 1 and Figure 6. The elastic modulus and strength of cement are 3 times that of coal, however, the fracture displacement is 0.5 times that of coal. The friction coefficient of the interface is taken according to the literature [21]. The excess pore water pressure was set to 0, the pore ratio of cement and coal was 0.2 and 0.14, and the saturation was 1. The results of experiments and simulation are shown in Figure 9.

According to the above results, two conclusions can be summarized: (1) the stress difference threshold of hydraulic fracture passing through the coal-rock interface is 6 MPa. (2) The simulation results of the pressure-time curve (figures 9(c) and 9(e)), based on the third constitutive model, are close to the experimental results, indicating the rationality of the constitutive model.

FIGURE 5: Numerical calculation process.

5. Optimization of Indirect Fracturing Process Parameters

Based on the numerical simulation in Section 4, we further study the influence of stress difference $\Delta\sigma$, coal-rock interface friction coefficient $f_{c,r}$, drilling and interface spacing D_{op} , and water flow i_w parameters on the effect of indirect fracturing coal technology under the condition of field-scale.

The numerical models with length, width, and height of 20 m, 14 m, and 10 m are established. Among them, the discontinuity in the rock is located in the middle of the model, and coal discontinuities are modeled according to the discrete fracture network in Sec. 3.3. As the geological structure of the Zhaozhuang Mine is relatively small, it has a little impact on the discontinuity distribution shown in

Figure 8. The water injection point in the model was located at the distance of $D_{op} = 0.5$ m to 2.5 m from the coal-rock interface, and the water injection flow was $8 \text{ m}^3/\text{min}$. The stress difference ($\Delta\sigma = \sigma_v - \sigma_h$) was set as 4, 6, and 8 MPa by changing the interface friction coefficient until the HF passes through the interface. The numerical results are shown in Figure 10.

The numerical simulation reflects two results: (1) the stress difference $\Delta\sigma$ and interface friction coefficient $f_{c,r}$ are the key factors to determine whether HFs can cross the coal-rock interface. Taking $D_{op} = 0.5$ m and $i_w = 8 \text{ m}^3/\text{min}$ as an example, when $\Delta\sigma$ increases from 4 MPa to 8 MPa, the critical friction coefficient $f_{c,r}$ decreases from 0.22 to 0.02. Under the conditions of other values of $\Delta\sigma$ and D_{op} , the critical $f_{c,r}$ also has similar changes. (2) D_{op} , i_w will have a

(A)

(B)

(C)

■ Test data of mode I fracture
— Numerical simulation data of mode I fracture

(D)

(a)
FIGURE 6: Continued.

FIGURE 6: Numerical simulation and experimental results. (a) Numerical simulation and experimental results of mode I fracture. (A) Size of a specimen or numerical model with mode I fracture. (B) Specimen and fracture pattern of test [2]. (C) Fracture pattern from numerical calculation. (D) Comparison of traction-separation curves obtained by two methods. (b) Numerical simulation and experimental results of mode II fracture. (A) Size of a specimen or numerical model with mode II fracture. (The left one is the top view, and the right one is the B-B section). (B) Specimen and fracture pattern of laboratory test [2]. (C) Numerical calculation model and fracture pattern. (D) Comparison of traction-separation curves obtained by two methods.

significant impact on the HF area in coal. Taking $i_w = 8 \text{ m}^3/\text{min}$ and $\Delta\sigma = 6 \text{ MPa}$ as an example, the HF area decreases rapidly with the increase of D_{op} from 1 m to 2.5 m. When D_{op} decreases from 1 m to 0.5 m, a single HF form is gradually formed by the hydraulic fracture network. In other words, under the condition of numerical simulation, $D_{op} = 1 \text{ m}$ will maximize the hydraulic fracture area. Furthermore, the HF area will increase with the increase of i_w . Take $D_{op} = 1 \text{ m}$ and $\Delta\sigma = 6 \text{ MPa}$ as an example. With the increase of i_w from $4 \text{ m}^3/\text{min}$ to $12 \text{ m}^3/\text{min}$, a complex fracture network is gradually formed in the coal, and the HF area increases rapidly.

Summarizing the above phenomena, it can be found that the HF area in coal is positively correlated with i_w , $f_{c,r}$, $\Delta\sigma$, and the law of first-increasing-and-then-decreasing with the increase of D_{op} -increasing.

In terms of engineering practice (Figure 11), the stress field in the coal mine area and the mechanical strength of coal-rock interface are judged according to the geological drilling data, and the areas with large $\Delta\sigma$ and $f_{c,r}$ were selected. On this basis, the value of $D_{op} = 1 \text{ m}$ and $i_w = 8 \text{ m}^3/\text{min}$ was taken, and then drainage and gas production were carried out. In situ experiments show that after the above indirect fracturing process optimization, the daily output of

TABLE 1: Mechanical parameters.

	ϕ (%)	E_0 (GPa)	μ	η_1	η_2	η_3	Ψ (°)	σ_{b0}/σ_{c0}	K_c	σ_{UTS}	δ	ε_{min}	ε_{max}	k_{min} (10^{-6}ms^{-1})	k_{max} (10^{-6}ms^{-1})
Coal matrix	8.9	1.61	0.3	-0.4	8.6	0.5	20	2.0	0.667	0.1	0.1	0.012	0.016	0.03	52
Roof	7.9	6.58	0.2	-0.1	10	0.1	28	1.5	0.667	4.70	0.1	0.008	0.01	0.01	87
	E_n (GPa)	E_{ss} (GPa)	E_{tt} (GPa)	$\sigma_{c,n}^0$ (MPa)	$\sigma_{c,s}^0$ (MPa)	$\sigma_{c,t}^0$ (MPa)	T0	s_n (10^{-4}m)	s_s (10^{-4}m)	$s_{n,p}$ (10^{-4}m)	$s_{s,p}$ (10^{-4}m)				
Coal discontinuity	0.98	1.83	1.83	0.67	1.06	1.06	1	3.2	5.9	0.61	1.78				
	B	γ	χ_n	χ_s	G_n (N/m)	GS (N/m)	m	n	Γ_n	Γ_s	l/m^3 (s·MPa)				
Coal discontinuity	3.56	3.36	0.19	0.29	57.74	343.05	0.3	0.94	2.72	-1132.5	1.2×10^{-10}

FIGURE 7: Damage mechanical properties coal matrix.

FIGURE 8: CT scanning and discontinuities network model of fractured coal. (a) Discontinuities in coal sample. (b) Reconstruction model of discontinuities.

CBM was increased from 1000 m^3 to more than 5000 m^3 , as shown in Figure 12.

6. Discussion

In this paper, the plastic fracture-seepage constitutive relation and discrete fracture network model of the fractured coal were established, which were verified by fracture mechanics, hydraulic fracturing experiment, and CT

experiment. On this basis, a calculation model was established. The evolution law of the HF area in the coal seam with stress difference $\Delta\sigma$, interface friction coefficient $f_{c,r}$, spacing between the well and interface D_{op} , and water injection flow i_w was studied. The simulation results show that higher $f_{c,r}$ and $\Delta\sigma$ values are helpful for HF to cross the coal-rock interface, while larger i_w and appropriate D_{op} will help form a complex fracture network in the coal seam and improve CBM production. As far as we know, it is the first time to

TABLE 2: Stress state of hydraulic fracturing experiments.

Specimen number	Stress (MPa)		
	σ_v	σ_H	σ_h
1#	9	5	3
2#	9	5	3
3#	8	5	3
4#	8	5	3
5#	7	5	3

FIGURE 9: Continued.

FIGURE 9: Results of experiments and simulation. (a) Specimen [21]. (b) Simulation results of HF opening displacement (left, unit: m) and fracture pattern of 3# specimen (right, [21]) (stress state: σ_v , σ_H , $\sigma_h = 6, 5, 3$ MPa). (c) Water pressure-time curves at injection point obtained from results of simulation and experiments (3# specimen). (d) Simulation results of HF opening displacement (left, unit: m) and fracture pattern of 5# specimen (right, [21]) (Stress state: σ_v , σ_H , $\sigma_h = 9, 5, 3$ MPa). (e) Pressure-time curves at water injection point obtained from numerical simulation and HF experiments (1# specimen).

FIGURE 10: Continued.

FIGURE 10: Numerical simulation results of indirect fracturing coal technology. (a) HF opening ($D_{op}=0.5$ m, $\Delta\sigma=4$ MPa, $f_{cx}=0.22$, $i_w=8$ m³/min). (b) HF opening ($D_{op}=0.5$ m, $\Delta\sigma=6$ MPa, $f_{cx}=0.05$, $i_w=8$ m³/min). (c) HF opening ($D_{op}=0.5$ m, $\Delta\sigma=4$ MPa, $f_{cx}=0.22$, $i_w=8$ m³/min). (d) HF opening ($D_{op}=0.5$ m, $\Delta\sigma=8$ MPa, $f_{cx}=0.22$, $i_w=8$ m³/min). (e) HF opening ($D_{op}=0.5$ m, $\Delta\sigma=4$ MPa, $f_{cx}=0.72$, $i_w=8$ m³/min). (f) HF opening ($D_{op}=1.5$ m, $\Delta\sigma=6$ MPa, $f_{cx}=0.53$, $i_w=8$ m³/min). (g) HF opening ($D_{op}=1.5$ m, $\Delta\sigma=8$ MPa, $f_{cx}=0.40$, $i_w=8$ m³/min). (h) HF opening ($D_{op}=2.5$ m, $\Delta\sigma=4$ MPa, $f_{cx}=0.90$, $i_w=8$ m³/min). (i) HF opening ($D_{op}=2.5$ m, $\Delta\sigma=6$ MPa, $f_{cx}=0.70$, $i_w=8$ m³/min). (j) HF opening ($D_{op}=2.5$ m, $\Delta\sigma=8$ MPa, $f_{cx}=0.71$, $i_w=8$ m³/min). (k) HF opening ($D_{op}=1.0$ m, $\Delta\sigma=6$ MPa, $f_{cx}=0.52$, $i_w=4$ m³/min). (l) HF opening ($D_{op}=1.0$ m, $\Delta\sigma=6$ MPa, $f_{cx}=0.14$, $i_w=8$ m³/min). (l) HF opening ($D_{op}=1.0$ m, $\Delta\sigma=6$ MPa, $f_{cx}=0.14$, $i_w=12$ m³/min).

(a)

(b)

FIGURE 11: In situ test of indirect fracturing and CBM production. (a) Field test. (b) CBM production.

FIGURE 12: Hydraulic fracturing results obtained from 2D numerical model.

combine the plastic fracture-seepage constitutive relation and the discrete fracture network model of the coal discontinuities to carry out the three-dimensional numerical model and then optimize the parameters of indirect fracturing coal technology.

The fractured coal has the characteristics of plastic deformation and ductile fracture, which will cause complex nonlinear seepage response in the coal matrix and the coal discontinuities. Obviously, the theory of linear elastic fracture mechanics [7], elastic damage mechanics [11], and fluid-solid coupling model based on Darcy's law [31] cannot fully reflect the nonlinear mechanics and seepage characteristics mentioned above. At the same time, most numerical models do not consider the joint effect of D_{op} , i_w on HF area in coal. The numerical calculation model based on the constitutive relation (Section 3) and considering the influence of D_{op} and i_w make the results more meaningful.

In addition to the constitutive equations, another issue worthy of attention is the 3D discrete fracture network model of coal. At present, the material was mostly simplified into an equivalent continuous medium model [32] and a dual-porous medium model [33], or a 2D discrete fracture network (DFN) model [16]. However, the results obtained by the 2D numerical model may mislead the optimization of indirect fracturing process parameters. When the geological parameters and fracturing process parameters of the 2D model and the 3D model are the same, the HFs in the roof terminate at the coal-rock interface. Only when the stress difference reaches 10 MPa, the HFs will propagate into the coal (Figure 12). Obviously, the results obtained from the 2D model are far from the results of the 3D model and the laboratory test.

Based on the constitutive relationship and discrete fracture network model in this paper, a numerical model of indirect fracturing coal technology was established, and the

influence of stress difference, interface friction coefficient, spacing between the well and interface, and the water injection flow on the HF area was studied. The results show that $\Delta\sigma$ and $f_{c,r}$ are the key parameters to ensure that HFs cross the coal-rock interface, and the larger they are, the easier the HF is to enter the coal seam. More importantly, it is not that the smaller the D_{op} , the larger the HF area in the coal seam, however, there is an optimal D_{op} value. By optimizing the above indirect fracturing parameters, the production of CBM is greatly improved.

7. Conclusions

Upon applying the optimized parameters of indirect fracturing coal technology, the CBM production was greatly increased. The results obtained in this paper could facilitate increased CBM production in fractured low-permeability coal regions and help China achieve its "carbon neutrality by 2060" goal. The main conclusions of this study can be summarized as follows:

- (1) The nonlinear characteristics of fractured low-permeability coal, including plastic deformation, ductile fracture, and seepage, can be well-represented by PF-S constitutive relationship.
- (2) The remarkable nonlinear failure characteristic of fractured coal is the root cause of hydraulic fractures that are difficult to cross the coal-rock interface.
- (3) Increasing the water injection flow rate and reducing the spacing between the well and the coal-rock interface can greatly improve the success rate of indirect fracturing projects.

Data Availability

The data are available on request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This research was funded by 2017 Special Project of Subject Frontiers Scientific Research in China University of Mining and Technology (2017XKQY047).

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