Study on the mechanism of coal-rock interface hindering hydraulic fracture propagation in the process of indirectly fracturing broken soft coal seam

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Abstract. The abundant CBM in fractured soft and low-permeability coal is expected to be exploited by indirect fracturing coal technology. However, this technique often fails because the coal-rock interface hinders the hydraulic fractures (HFs) propagation. This article focuses on the root cause of the above phenomenon, that is, the mechanical properties of coal. Its ductile fracture-seepage relationship was deduced by the Park-Paulino-Roesler potential energy function and combining with Forchheimer equation. The elastoplastic damage-seepage relationship of coal matrix can be derived by combining damage mechanics, plastic mechanics and seepage experimental results. The numerical simulation results showed that the mechanism of the coal-rock interface hindering the HFs propagation lied in the large amount of hydraulic energy dissipation caused by ductile fracture of discontinuities and plastic damage of the coal matrix, which results in the proportion of elastic energy contributing to HFs propagation as low as 2% of hydraulic energy. However, this ratio will increase to 18%~30% as interface friction, stress difference and injection rate increase, especially the distance between horizontal well and interface decrease. This finding is of great significance for the CBM extraction in the fractured soft and low-permeability coal through indirect fracturing coal technology.

1. Introduction
In China, the area of broken soft and low-permeability coal accounts for 82% of the total coal seam area, and its contained coal-bed methane (CBM) resources are as high as 15×10¹²m³ [1-2]. The coal has the characteristics of low elastic modulus, low mechanical strength and low permeability under in-situ stress. In this case, indirect fracturing coal is one of the new technologies that are expected to achieve high CBM production in the coal. The step is to arrange the horizontal well in hard roof instead of the coal, implement perforation and hydraulic fracturing (Fig. 1).

![Figure 1 Schematic diagram of indirect fracturing coal technology](image-url)
The key to success of the technology is that HFIs can penetrate the coal-rock interface. Low-cost and high-efficiency numerical simulation method is widely used to study this problem. However, this method deeply relies on the fluid-solid coupling constitutive equation applicable to the coal[3]. For this issue, scholars widely use the theory of linear elastic fracture mechanics and elastic damage mechanics. Aimene et al. [4], Zhang and Donsot [5] summed up the critical stress state and differences in elastic modulus of layered rocks when the HF crosses the interface, and results showed that the small difference of stress and elastic modulus would lead to the interface strongly hindering the HF propagation. Poludasu et al. [3], Wang et al. [6] established a 2D numerical model, and obtained that the formation interface failed before the growing HF contacted it when the bond strength of interface was weak. The results obtained by Oyedere et al. [7] suggested that HF termination would be more likely during high rate injection and in low permeability formations. At the same time, based on elastic damage mechanics, Guo et al. [8] used the cohesive zone method (CZM) to simulate HF initiation and propagation, and the results illustrated that HFIs need much more energy to penetrate the interface under a situation of high vertical stress and barrier tensile strength. Lan and Goung [9] used the same theory, and they obtained the results that the overlying mudstone layer with high in-situ stress and low elastic modulus could reduce the fracture height and effectively restricted the fracture penetration.

The above literatures generally ignore the influence of the distance between horizontal well and coal-rock interface. More importantly, the theory of linear elastic fracture mechanics and cubic law[10] can not fully reflect the materiality characteristics of the broken soft low-permeability coal, that is, the significant plastic fracture and nonlinear seepage behavior.

This paper studied the plastic damage-seepage law of coal matrix, ductile fracture seepage law, then established the plastic fracture-nonlinear seepage constitutive equations. On this basis, the mechanism of coal-rock interface hindering HFIs propagation, and the law of HFIs propagation in the coal under the influence of four factors, including the distance between horizontal well and coal rock interface, water injection flow, stress difference and friction coefficient of coal-rock interface, are simulated. The optimized parameters of indirect fracturing technology are applied to Zhaozhuang Mine, and the CBM production is increased by 20 times.

2. Plastic fracture-seepage (PF-S) coupling constitutive equations of the coal

Broken soft and low-permeability coal is a typical pore (i.e. coal matrix) - fracture (i.e. coal discontinuities) medium. Its plastic fracture-seepage behaviour includes two aspects: plastic damage - seepage of coal matrix; Ductile fracture-seepage of coal discontinuities.

2.1. Elastoplastic damage-seepage constitutive equations of coal matrix

The root cause of coal matrix failure lies in the plastic deformation and the expansion of micro cracks under the load [11], both of which lead to the dissipation of hydraulic energy. The mechanical constitutive equation of coal matrix considering plastic deformation and damage is as follows.

\[
\sigma_i^e = (1 - d) E_o (\varepsilon_i - \varepsilon_i^p) + \alpha p_w I
\]

Where, \(\sigma_i^e\) is the total stress vector; \(E_o\) is the elastic stiffness matrix of the solid element; \(\varepsilon_i\) and \(\varepsilon_i^p\) are the total strain vector and compressive plastic strain vector of the solid element, respectively; \(p_w\) is the pore water pressure and \(I\) is the unit matrix; \(\alpha\) is the effective stress coefficient, and its expression before and after damage is

\[
\alpha \begin{cases} 
1 - K_s / K_b, & \text{if } d = 0 \\
1, & \text{if } d > 0
\end{cases}
\]

Where \(K_s\), \(K_b\) is the effective and drained bulk modulus of the solid constituent.

In order to obtain the displacement and water pressure, it is necessary to study the solution of \(\varepsilon_i^p\) and \(d\). For the former one, it is solved by plastic mechanics theory. The load function expression is

\[
F = \frac{1}{2} A \left( q_{\text{eff}} - 3 A p_{\text{eff}} + B (\varepsilon_i^p) \cdot (\sigma_{\text{eff}}^{\text{ini}}) - C (\sigma_{\text{eff}}^{\text{ini}}) - \sigma_{\text{eff}} (\varepsilon_i^p) \right) = 0
\]
Where, $A = (\sigma_{00} / \sigma_{0} - 1) / (2\sigma_{00} / \sigma_{0} - 1)$, $B = \hat{\sigma}_{\text{eff}} \left( \hat{e}^e \right) / \hat{\sigma}_{\text{eff}} \left( \hat{d} \right) \left( 1 - A \right) - \left( 1 + A \right)$, $C = 3(1 - K_c) / (2K_c - 1)$, $p_{\text{eff}} = \text{trace(}\sigma_{\text{eff}}\text{)} / 3$, $q_{\text{eff}} = \sqrt{2(S_{\text{eff}} : S_{\text{eff}})} / 3$, and $S_{\text{eff}} = \sigma - p_{\text{eff}} I$; and, $\sigma_{\text{eff},i}^m$ ($i = 1, 2, 3$) is the maximum effective principal stress, $\sigma_{00} / \sigma_{0}$ is the ratio of biaxial compression yield stress to uniaxial compression yield stress, $\hat{\sigma}_{\text{eff}}$ is the equivalent stress; and $K_c = 0.667$.

The expression of plastic potential function is

$$G = \sqrt{(\hat{\sigma}_{\text{eff}} \tan \psi)^2 + q_{\text{eff}}^2 - p_{\text{eff}} \tan \psi}$$ (4)

Where, $\delta = 0.1$; $\sigma_{\text{UTS}}$ is the tensile peak stress of coal matrix; and $\psi$ is the dilatancy angle.

Based on Eqs. (3) ~ (4), the $e^{\text{i}}$ can be obtained.

The remaining internal variables, $d^{(i)}$ and $d^{(i)}$, their relationship with plastic strain and stress is as follows:

$$e^{\text{i}} = e^{\text{u}} - d\sigma_{\text{eff}} / [(1 - d)E_0]$$ (5)

Where, inelastic strain $e^{\text{u}} = e_c - \sigma_{\text{eff}} / E_0$. And $e_c$, $d$, $\sigma_{\text{eff}}$ can be obtained by cyclic loading and unloading experiments of cylindrical specimens [12]. From the above process, another internal variable, the evolution law of $d$, is obtained.

As for the permeability coefficient of the coal matrix, the expression can be obtained by fitting the results of the full stress-strain and seepage experiment.

$$k = \begin{cases} k_{\text{min}} + k_{\text{max}} \exp(\{e_{\text{max}} - e / e_{\text{min}}\}^n) & \text{(Elastic deformation stage)} \\ k_{\text{min}} + \delta_k k_{\text{max}} \{e - e_{\text{min}} / e_{\text{max}}\} \exp\{(-e - e_{\text{min}} / e_{\text{min}}\}^n) & \text{(Plastic deformation stage)} \\ k_{\text{max}} \exp\{(-e - e_{\text{max}} / e_{\text{min}}\}^n) + \delta_k k_{\text{max}} & \text{(Damage failure stage)} \end{cases}$$ (6)

2.2. Ductile fracture and seepage constitutive equations of coal discontinuities

For coal discontinuities, its stress-strain relationship in the elastic deformation stage can be determined by Eq. (7) [13].

$$\sigma_s = D_{\text{st}} e_s$$ (7)

Crack initiation will occur when the normal or tangential stress reaches the following state,

$$\max \left\{ \left( \sigma_{\text{tn}} / \sigma_{\text{tn}} \right)^{\sigma_{\text{tn}}} \right\} / \left( \sigma_{\text{tn}} / \sigma_{\text{tn}} \right)^{\sigma_{\text{tn}}} = 1$$ (8)

Where $\sigma_{\text{tn}}$, $\sigma_{\text{ts}}$ and $\sigma_{\text{ct}}$ (or $\sigma_{\text{tn}}^{\text{peak}}$, $\sigma_{\text{ts}}^{\text{peak}}$ and $\sigma_{\text{ct}}^{\text{peak}}$) are the (peak) traction in the normal and two tangential directions, respectively; the symbol $\{ \}$ is the Macaulay bracket; $D_{\text{st}}$ is the elastic stiffness matrix, and $E_{\text{nn}}$, $E_{\text{nn}}$ and $E_{\text{nn}}$ representing the elastic modulus of normal, first tangent and second tangent respectively; $e_s$ is the strain vector, the relationship between $e_s$ and separation vector $S$ is $e_s = S / T_0$, $T_0$ is the constitutive thickness of cohesive element.

After the peak load, the constitutive relationship can be deduced by the Park-Paulino-Roesler (PPR) potential energy function[14], the expression of the function $\Psi (S_s, S_t)$ is:

$$\Psi (S_s, S_t) = \left[ \Gamma_s \left( \frac{\dot{S}_s - \dot{S}_s}{S_s} \right)^{\frac{\rho_s}{\gamma}} \right] \left( \frac{\dot{S}_s + \dot{S}_s}{S_s} \right)^{\frac{\rho_s}{\gamma}} + \left( G_{\text{sn}} - G_{\text{sn}} \right) \times \left( \frac{\dot{S}_s - \dot{S}_s}{S_s} \right)^{\frac{\rho_s}{\gamma}} + \left( G_{\text{nt}} - G_{\text{nt}} \right) \left[ \min\left( G_{\text{sn}} - G_{\text{sn}} \right) \right]$$ (9)

Where $S_s = \sqrt{S_s^2 + S_t^2}$, $S_t$, and $S_s$ are variables, which are the separation of the first and second tangential directions respectively; $\Gamma_n, \Gamma_s$ are fracture energy constants, and

$$\Gamma_n = \left( G_{\text{nt}} - G_{\text{nt}} \right) \left( \beta / m \right)^{\gamma}, \quad \Gamma_s = \left( G_{\text{sn}} - G_{\text{sn}} \right) \left( \gamma / m \right)^{\gamma}$$ (10)
Where, $G_s = G_t + G_r$, $G_r, G_t$ and $G_i$ are normal, first and second tangential fracture energies, respectively; $\beta$, $\gamma$ are the shape index parameters of the traction - separation curve under mode I and II, respectively, which can be obtained by fitting the experimental data. Expressions of $m$, $n$ are:

$$m = \beta(\beta - 1)\chi_2^s / (1 - \beta\chi_1^s), n = \gamma(\gamma - 1)\chi_2^s / (1 - \gamma\chi_1^s)$$

(11)

Where parameters $\chi_n = s_{n,p} / s_n$, $\chi_s = s_{s,p} / s_s$, they determine the amount of separation corresponding to the peak load; $s_{n,p}$ and $s_{s,p}$ are the displacements corresponding to peak normal load and peak tangential load, respectively.

By calculating the first derivative of Eq. (9), the constitutive equations of different fracture modes can be obtained, as shown in Eqs. (12)~(17).

$$\sigma_m = \frac{F_m}{s_n} \left[ m \left( 1 - \frac{s_n}{s_1} \right)^\frac{m}{\beta} \frac{m}{\beta} \frac{m}{\beta} \frac{m}{\beta} \frac{m}{\beta} - \beta \left( 1 - \frac{s_n}{s_1} \right)^\frac{m}{\beta} \frac{m}{\beta} \frac{m}{\beta} \frac{m}{\beta} \frac{m}{\beta} \frac{m}{\beta} \frac{m}{\beta} \frac{m}{\beta} \right] \times \left[ 1 - \frac{S_2^s + S_1^s}{S_1^s + S_2^s} \right] \left( \frac{n + \frac{S_2^s + S_1^s}{S_1^s + S_2^s}}{\gamma + \frac{S_2^s + S_1^s}{S_1^s + S_2^s}} \right) (G_t + G_r - G_i)$$

(12)

$$\sigma_c = \frac{F_c}{S_1^s} \left[ \frac{1 - \frac{s_n}{s_1}}{\gamma \frac{S_1^s + S_2^s}{S_1^s + S_2^s} \left( G_t - G_i \right)} \right] \left( \frac{1 - \frac{s_n}{s_1}}{\gamma \frac{S_1^s + S_2^s}{S_1^s + S_2^s} \left( G_t - G_i \right)} \right) \left( \frac{1 - \frac{s_n}{s_1}}{\gamma \frac{S_1^s + S_2^s}{S_1^s + S_2^s} \left( G_t - G_i \right)} \right) \left( \frac{1 - \frac{s_n}{s_1}}{\gamma \frac{S_1^s + S_2^s}{S_1^s + S_2^s} \left( G_t - G_i \right)} \right) \left( \frac{1 - \frac{s_n}{s_1}}{\gamma \frac{S_1^s + S_2^s}{S_1^s + S_2^s} \left( G_t - G_i \right)} \right)$$

(13)

$$\sigma_e = \frac{F_e}{S_1^s} \left[ \frac{1 - \frac{s_n}{s_1}}{\gamma \frac{S_1^s + S_2^s}{S_1^s + S_2^s} \left( G_t - G_i \right)} \right] \left( \frac{1 - \frac{s_n}{s_1}}{\gamma \frac{S_1^s + S_2^s}{S_1^s + S_2^s} \left( G_t - G_i \right)} \right) \left( \frac{1 - \frac{s_n}{s_1}}{\gamma \frac{S_1^s + S_2^s}{S_1^s + S_2^s} \left( G_t - G_i \right)} \right) \left( \frac{1 - \frac{s_n}{s_1}}{\gamma \frac{S_1^s + S_2^s}{S_1^s + S_2^s} \left( G_t - G_i \right)} \right) \left( \frac{1 - \frac{s_n}{s_1}}{\gamma \frac{S_1^s + S_2^s}{S_1^s + S_2^s} \left( G_t - G_i \right)} \right)$$

(14)

In the simulation, the values of $\sigma_{c,n}$, $\sigma_{c,s}$ and $\sigma_{e,t}$ in Eqs. (12)~(14) can be provided by the solid elements which share the nodes with the cohesive elements. The material parameters can be obtained by fracture mechanics experiment. On this basis, the unknown variables $S_n$, $S_s$ and $S_t$ can be obtained.

Based on the known stress and separation, the expressions of fracture energy $G_i$, $G_i^c$, $G_i^e$, elastic energy $G^e$ and inelastic energy $G^{inl}$ can be obtained by integral derivation,

$$G_i = \int s^1_i \sigma_m(S_n) dS_n, \ G_i^c = \int s^1_i \sigma_c(S_n) dS_n, \ G_i^e = \int s^1_i \sigma_e(S_n) dS_n$$

(15)

$$G^e = (\sigma_0^0_s s^0_n + \sigma_0^0_e s^0_e + \sigma_0^0_i s^0_i) / 2$$

(16)

$$G^{inl} = G_i^c + G_i^e - G^{peak}$$

(17)

Where, $\sigma_0^0_n, \sigma_0^0_e, \sigma_0^0_i$ and $s^0_n, s^0_e, s^0_i$ represent the stress and separation in three directions at any time $t_i$; $\sigma_0^0_n$ and $s^0_i$ are the stress and separation values of discontinuities in elastic deformation stage, respectively; $G^{peak}$ is the maximum elastic energy of the discontinuities (i.e. the area under the traction-separation curve before the peak stress).

In this paper, the tangential flow equation is established based on Forchheimer equation:

$$-\nabla p_t = \frac{12 \mu}{l^2 w^2} Q_t + \frac{\rho_p \rho_w}{l^2 w^2} Q_t^2$$

(18)

The normal flow (leak-off) is affected by the plastic damage of coal matrix and water pressure, the expression is as follows:

$$Q_n = 2k(p_{n,con} - p_{n,boum})$$

(19)

Where, $-\nabla p_t$ is the pressure gradient of tangential flow; $\mu$ is the dynamic viscosity of water; $w$ is the gap width; The product of $l$ and $w$ represents the area of the flow section; $Q_t$ is the total flow at the gap entrance; $\rho_p$ is the non-Darcy flow factor, $3.35 \times 10^{-12} \text{ kg/s}^2$; $\rho_w$ is the water density; $Q_t$ is the leak-off flow; $k$ is the permeability coefficient of coal matrix (Eq. 6); $p_{n,con}$ and $p_{n,boum}$ are the water pressure in the middle gap and on the gap boundary.

Based on above equations, the PF-S constitutive equations are established. Combining the equilibrium equation of solid with the geometric equation and the N-S equation of fluid, the numerical calculation process is shown in Fig. 2.
3. Verification of PF-S constitutive equations

The rationality of PF-S constitutive equations can be verified by hydraulic fracturing experiments. In the experiments, the composite specimen of coal and cement (100 mm cube) was taken as the experimental object in order to avoid the interference of the fluctuation of rock mechanical parameters of natural roof to the experimental results. The fracturing section was located in the cement with a length of 5mm, and its bottom was 25mm away from the coal-rock interface. Triaxial compression hydraulic fracturing seepage testing machine was used in the experiment. The fracturing fluid was water, the injection flow rate was 20ml/min, the coal-rock interface was dry. Stress in the experiment, including vertical stress $\sigma_v$, maximum horizontal principal stress $\sigma_h$, minimum horizontal principal stress $\sigma_h$ conditions are shown in Fig. 3. The numerical model was established according to the geometric dimensions of the specimen. Among them, the distribution of coal discontinuities in coal is represented by Voronoi polyhedron according to the literature [15], while the cement discontinuity is arranged in its middle and parallel to $\sigma_h$. Cohesive force elements with a thickness of 0 were embedded at the position of the above-mentioned discontinuities, and the rest part were solid elements. The PF-S constitutive equations were applied to coal, and its mechanical parameters are shown in Table 1. For elastic and brittle cement, the constitutive relationship of its discontinuity (solid elements) was determined by Eqs. 7–8, 18–19 (Eqs. 1–2, 6). The elastic modulus of cement was 3 times that of coal, fracture displacement was 1/2 of that of coal. For the dry interface, the friction coefficient $f_{c, r}$ and shear modulus $(E_{ss}$ or $E_n)$ can be determined by direct shear test, and $f_{c, r}=0.72$, $E_{ss}=E_n=0.032\sigma_n$0.018 (unit: Gpa, and $\sigma_n$ is the normal stress). The $E_{ss}$ is 1/3 of that of coal. In the numerical model, the excess pore water pressure was 0, the pore ratio of cement to coal was 0.2 and 0.14, the saturation was 1. The material parameters were obtained by compact tensile test and through shear test, as shown in Table 1. The results of hydraulic fracturing experiment and simulation are shown in Fig. 3.

| Table 1 | Numerical calculation parameters |
|---------|---------------------------------|
| $\phi$  | $\rho_s$ | $E_0$ | $\mu$ | $n_1$ | $n_2$ | $p_1$ | $p_2$ | $\sigma_{n0}/\sigma_0$ | $K_n$ | $\delta_t$ | $\alpha_s$ | $\epsilon_s$ | $\kappa_{ss}$ | $\kappa_{ss}$ |
| Coal matrix | 8.9 | 1.61 | 0.3 | -0.4 | 8.6 | 0.5 | 20 | 2.0 | 0.6 | 67 | 0.1 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.03 | 52 |
| Roof    | 7.9 | 6.58 | 0.2 | -0.1 | 10 | 0.1 | 28 | 1.5 | 0.6 | 67 | 0.1 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.01 | 87 |
| $E_0$   | $E_{ss}$ | $E_n$ | $\sigma_{n0}/\sigma_0$ | $K_n$ | $\delta_t$ | $\alpha_s$ | $\epsilon_s$ | $\kappa_{ss}$ | $\kappa_{ss}$ |
| Discontinuity (Coal) | 0.98 | 1.83 | 1.83 | 0.67 | 1.06 | 1.06 | 1 | 3.2 | 5.9 | 0.61 | 1.78 |
| $G_0$   | $G_{ss}$ | $G_n$ | $\Gamma_s$ | $\Gamma_n$ | $\Gamma_s$ | $\Gamma_n$ | $\Gamma_s$ | $\Gamma_n$ | $\Gamma_s$ | $\Gamma_n$ |
| Discontinuity (Coal) | 3.56 | 3.36 | 0.19 | 0.29 | 57.74 | 343.05 | 0.3 | 0.94 | 2.72 | -1132.5 | 1.2×10^-10 |

The following results can be obtained from Fig. 3: (1) Under the condition of dry coal-rock interface, the results of hydraulic fracturing experiment and numerical simulation show that the stress difference threshold of HFs crossing coal-rock interface is $\Delta\sigma=\sigma_n-\sigma_0=6$MPa; (2) The water pressure - time curves of hydraulic fracturing experiment and numerical simulation were similar, which shows the rationality of PF-S model.

4. Mechanism of coal rock interface hindering hydraulic fracture propagation

According to the engineering geological conditions of Zhaozhuang Mine, the numerical calculation model as shown in Fig. 4 is established. The influence of stress difference $\Delta\sigma$, friction coefficient of coal rock interface $f_{c, r}$, distance between horizontal well and coal rock $D_{op}$ and injection flow rate $I_w$ are analyzed. The water injection point was arranged in the center of the $xz$ plane and the $D_{op}=0.5$–2.5m. Water was injected with a rate of $8$ m$^3$/min and the injection duration of 100 min. The in-situ stress in rock formation $(\sigma_{n}/\sigma_0)$ was $15.8/12.8/8.5, 15.8/13.2/9.5, 15.8/14.2/10.5, 15.8/15.2/11.5, 15.8/15.2/12.5$, the stress value in the coal seam was set to $15.9/8.9/7.9, 15.9/9.9/8.9, 15.9/10.9/9.9, 15.9/11.9/10.9, 15.9/12.9/11.9$, that is, the stress difference in the coal was $\Delta\sigma=\sigma_n-\sigma_0=8$–4MPa. Under this condition, change the $f_{c, r}$ of the coal-rock interface until HFs crossed the interface. Thus, we get the parameters of $D_{op}$, $\Delta\sigma$, $f_{c, r}$ and $I_w$ on the HFs cross the coal-rock interface and propagation in the coal. The results are shown in Fig. 5.
Figure 2 Numerical calculation process of PF-S constitutive equation

Figure 3 Comparison of hydraulic fracturing experiment and simulation results

Figure 4 Numerical model

Figure 5 Results of hydraulic fracture opening under different conditions of $\Delta \sigma, f_c, D_p$ and $i_w$
It can be seen from Fig. 5(a)–(f) that when $D_{op}=0.5m$, as $\Delta \sigma$ increases from 4MPa to 8MPa, the critical $f_{cr}$ of HFs crossing the coal-rock interface will decrease from 0.22 to 0.02; when $\Delta \sigma=4$MPa, as $D_{op}$ increases from 0.5m to 2.5m, the critical $f_{cr}$ will increase from 0.22 to 0.90. It can be seen that under the condition of low $\Delta \sigma$ and low $f_{cr}$, $D_{op}$ needs to be reduced in order to achieve the purpose of HFs crossing the coal-rock interface. However, too small $D_{op}$ value will cause the problem of small HF area in the coal. Comparing Fig. 5b and Fig. 5g, on the basis of the critical condition that HFs can cross the coal-rock interface, appropriately increasing $D_{op}$, such as 1m, will greatly increase the HF area in the coal. This is because a large $D_{op}$ value will cause a larger area of HFs to form in the roof. Under favorable conditions of in-situ stress, coal-rock interface mechanical properties, and water injection flow, a larger HF area in the roof can control a larger area of the coal bed, and promote the full propagation of HFs in the coal. Therefore, this article considers the optimal value of $D_{op}$ to be 1m. As shown in Fig. 5(g)–(h), when $i_o=8$ and 12m$^3$/min, a complex HF network will be formed in the coal, which means that the permeability of the broken soft and low-permeability coal will be greatly improved.

It is well known that the increase of fracture surface free energy (i.e. elastic energy) is the fundamental reason driving the HFs propagation $^{[16]}$. As shown in Fig. 6, when $\Delta \sigma=6$MPa and $D_{op}=1.0m$, as $f_{cr}$ increases from 0.05 to 0.58, the proportion of inelastic energy of the coal near the coal-rock interface to hydraulic energy decreases from 98.7% to 83.5%; When $D_{op}=1.0m$ and $f_{cr}=0.37$, as $\Delta \sigma$ increases from 4MPa to 8MPa, the proportion of inelastic energy of coal to hydraulic energy decreases from 87.9% to 76.0%; When $\Delta \sigma=6$MPa and $f_{cr}=0.37$, as the $D_{op}$ increases from 0.5m to 2.5m, the proportion of the inelastic energy of coal increases from 71.3% to 97.1%. The above data shows that under the conditions of small $\Delta \sigma$ and $f_{cr}$ and large $D_{op}$ value, the proportion of elastic energy in hydraulic energy is reduced to as low as 2%, which is the fundamental reason why HFs are difficult to propagate in the coal.

![Image](image-url)

(a) Different $f_{cr}$ ($D_{op}=1.0m$, $\Delta \sigma=6$MPa)  
(b) Different $\Delta \sigma$ ($D_{op}=1.0m$, $f_{cr}=0.37$)  
(c) Different $D_{op}$ ($\Delta \sigma=6$MPa, $f_{cr}=0.37$)

**Figure 6** The evolution of the proportion of inelastic energy in hydraulic energy with different $D_{op}$, $\Delta \sigma$, $f_{cr}$

As far as Zhaozhuang mine is concerned, optimizing the position of the horizontal well to increase the value of $\Delta \sigma$ to 6MPa while ensuring a higher value of $f_{cr}$. On this basis, the $D_{op}$ is maintained at about 1m and the water injection flow rate is controlled at 8m$^3$/min. The result is that the daily output of CBM is more than 3000 m$^3$ (Fig. 7). Compared with the traditional hydraulic fracturing mode, the daily CBM production has been increased by more than 20 times after the indirect fracturing technology with optimized parameters is adopted, which shows that HFs are fully propagated in the coal, and verifies the rationality of the numerical simulation results.

![Image](image-url)

**Figure 7** Daily production of CBM after indirect fracturing of the coal
5. Conclusions

(1) The special materiality characteristics of broken soft and low-permeability coal can be well described by PF-S constitutive equations.

(2) In the indirect fracturing coal engineering, the significant plastic deformation and ductile fracture of the broken soft coal will consume most of the hydraulic energy, resulting in a minimum of only 2% of the energy used to drive the propagation of hydraulic fractures into the coal.

(3) After parameter optimization (that is, the distance between the horizontal well and the coal rock interface is maintained at about 1m, the water injection rate is increased to 8m³/min, and the position of the horizontal well is optimized to make the stress difference and friction coefficient of the coal rock interface reach a large value), the CBM production in the broken soft and low-permeability coal area reaches 20 times of that before the parameter optimization.

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