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Research Article

Rational Boreholes Arrangement of Gas Extraction from Unloaded Coal Seam

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In order to enhance gas extraction from unloaded coal seam by drilling borehole in the floor roadway, the mechanism of stress relief improving permeability by protective coal seam mining was analyzed. Based on the multiphysics field theory, the hydraulic-mechanical coupling model of gas extraction in the unloading coal seam was established, and the gas extraction process by drilling borehole in the floor roadway in the overburden of Panyi Coal Mine 1551 (1) panel was simulated. The influence of different drilling arrangements on the gas extraction effect was analyzed. The results show that the permeability of protected coal seams is characterized by zoning and can be divided into the permeability-enhanced zone, the permeability-reduced zone, and the original permeability zone according to the stress state of coal seam. Under the condition of uniform borehole distribution, the gas pressure decreased slowly in the permeability-reduced zone and is still greater than 0.74 MPa after 180 days of extraction, and there is a large extraction blind area in the protected panel. Under the condition of nonuniform borehole distribution arrangement according to the characteristics of permeability zoning, the effective extraction area can almost cover the protected panel, and the blind extraction area is reduced by 91.22% when compared to uniform borehole distribution. These can provide a reference for unloading gas extraction under similar conditions.

1. Introduction

For coal seams with low gas permeability and high gas, gas extraction measures must be taken before mining to reduce the coal seam gas content. However, in many cases, although a large number of projects have been taken, the gas extraction effect is not ideal. Protective layer mining can effectively reduce the stress and increase the permeability, and the permeability coefficient is hundreds to thousands of times [1, 2]. Drilling borehole in the floor roadway is one of the most commonly used methods in the protected coal seam gas extraction. And reasonable arrangement of boreholes is key to the efficient gas extraction of coal seam [3, 4].

Since 1960s, scholars at home and abroad have carried out various research studies on the technology of protective layer mining and pressure relief gas extraction. Li et al. [5] simulated stress distribution and deformation law of the protected layer in lower protective layer mining and determined protection scopes of the trend and tendency of the protective layer. Zhang et al. [6] made a similar material physical model and analyzed the movement law of overlying strata and effect of the expansion and deformation of the protected layer. Wang et al. [7] studied the evolution law of fracture of coal and rock strata in the upper protective layer and considered that gas extraction should consider the factors of spatial and temporal effects of the evolution of the mining fracture. Wang et al [8] and Liu [9] tested the permeability change of the protected coal seam after protective layer mining and established the coupling dynamic model of the coal rock mass deformation and gas flow.

Zhang et al. [10–13] combined with field practice, respectively, used drilling borehole in the floor roadway, high-level drilling, and ground drilling and combined the method to extract the released gas from the protected layer and achieved good gas control effect. Wang et al. [14] and Hu et al. [15] studied the gas emission and the pressure relief law of the protected layer in the mining face of the close and steep inclined and steep slope protection layer. On this basis, the parameters of pressure relief gas extraction were optimized. Ma et al. [16, 17] investigated the influence of stress rate and grain size on gas seepage characteristics in crushed coal particles.

Based on the multiphysics field theory, the hydraulic-mechanical coupling model of gas extraction in the unloading coal seam was established, and the gas extraction process by drilling borehole in the floor roadway in the overburden of Panyi Coal Mine 1551 (1) panel was simulated. The influence of different drilling arrangements on the gas extraction effect was analyzed.

2. Hydraulic-Mechanical Coupling Model for Unloaded Gas Extraction

2.1. Basic Hypothesis. After mining the protective layer, the overlying strata will form the caving zone, fracture zone, and subsidence zone (vertical three zones) in the vertical direction, which will cause the pressure relief of the protected coal seam, as shown in Figure 1 [18]. The subsidence and deformation of the protected coal seam make the fracture expand and perforate, and the permeability along the bedding direction is increased, and the gas flowability is obviously enhanced. Meanwhile, the changed gas pressure gradient will break the original gas adsorption/desorption equilibrium state and transfer partially adsorbed gas into free gas. Under the action of the gas pressure gradient and extraction negative pressure of borehole, gas flows from high-pressure area to low-pressure area. As gas is pumped out, the pressure and content of coal seam gas are gradually reduced. And the outburst danger is eliminated.

According to the law of gas occurrence and migration in the pressure-unloading coal seam, the following hypothesis is given [18–23]: (a) the coal seam is a porous elastic continuous medium. (b) Gas is transported to the pores and fractures of coal seams by adsorption and free state. (c) The gas migration process of pressure-unloading coal seam is as follows: firstly, gas is desorbed from the pore surface of the coal seam. Secondly, gas diffuses into fissures. Thirdly, the gas flows from the crack to the borehole (Figure 2). (d) Gas is ideal, neglecting the action of gravity. (e) The tensile stress is positive, and the compressive stress is negative.

2.2. Governing Equation of the Hydraulic Field. The gas in the coal seam is composed of adsorption and free state. And the gas content per unit volume of coal is defined as follows [19]:

$$m = \phi\rho_{\mathrm{g}} + V_{\mathrm{sg}}\rho_{\mathrm{c}}\rho_{\mathrm{gs}}, \tag{1}$$

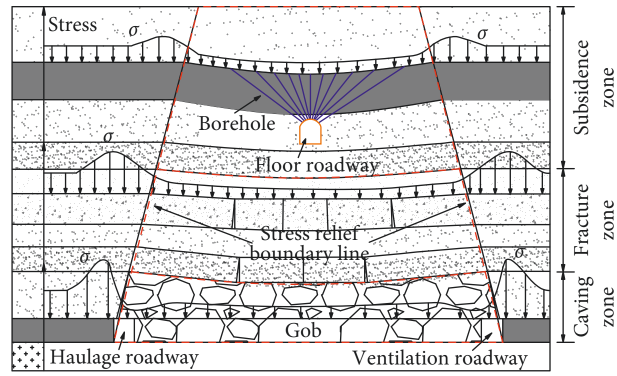

Figure 1: Gas extraction in the unloaded coal seam after protective layer mining.

where ϕ is the coal seam porosity, ρ_{g} is the gas density (kg/m^3), ρ_{c} is the coal seam density (kg/m^3), and ρ_{gs} is the gas density under standard condition (kg/m^3).

According to the equation of state of ideal gas, the gas density is defined as follows:

$$\rho_{\mathrm{g}} = \frac{M_{\mathrm{g}}}{RT}p, \tag{2}$$

where M_{g} is the molar mass of gas (kg/mol), R is the gas mole constant (J/(mol·K)), p is the gas pressure (MPa), and T is the temperature of the coal seam (K).

The volume of adsorbed gas can be expressed by the Langmuir equation [19]:

$$V_{\mathrm{sg}} = \frac{V_{\mathrm{L}}p_{\mathrm{g}}}{P_{\mathrm{L}} + p_{\mathrm{g}}}, \tag{3}$$

where V_{L} is the volume constant of Langmuir (m^3/kg), p_{L} is the pressure constant of Langmuir (Pa), and p_{g} is the gas pressure (MPa).

According to the conservation of mass, the sum of the change amount of the adsorbed gas and the free gas in the coal seam is equal to the amount of gas flowing into the borehole. Considering the effect of gas and gas slipping, combined with Darcy's law, it can be obtained as follows:

$$\frac{\partial m}{\partial t} - \nabla\cdot\left[\frac{M_{\mathrm{g}}p_{\mathrm{g}}}{RT}\left(1 + \frac{b_1}{p_{\mathrm{g}}}\right)\frac{k}{\mu_{\mathrm{g}}}\nabla p_{\mathrm{g}}\right] = 0, \tag{4}$$

where t is the time (s), T_{s} is the temperature under standard condition (K), k is the permeability (m^2), μ_{g} is the dynamic viscosity of gas (Pa·s), and b_1 is the Klingberg coefficient (Pa).

Substituting Equations (1)–(3) into Equation (4), the governing equation of the gas seepage field in coal seam is obtained as follows [20]:

$$\begin{aligned}&\frac{\partial}{\partial t}\left(\frac{V_{\mathrm{L}}p_{\mathrm{g}}}{p_{\mathrm{L}} + p_{\mathrm{g}}}\rho_{\mathrm{c}}\frac{M_{\mathrm{g}}}{RT_{\mathrm{s}}}p_{\mathrm{gs}} + \varphi\frac{M_{\mathrm{g}}}{RT}p_{\mathrm{g}}\right)\\ &\quad - \nabla\cdot\left[\frac{M_{\mathrm{g}}\left(p_{\mathrm{g}} + b_1\right)}{RT}\frac{k}{\mu_{\mathrm{g}}}\nabla p_{\mathrm{g}}\right] = 0.\end{aligned} \tag{5}$$

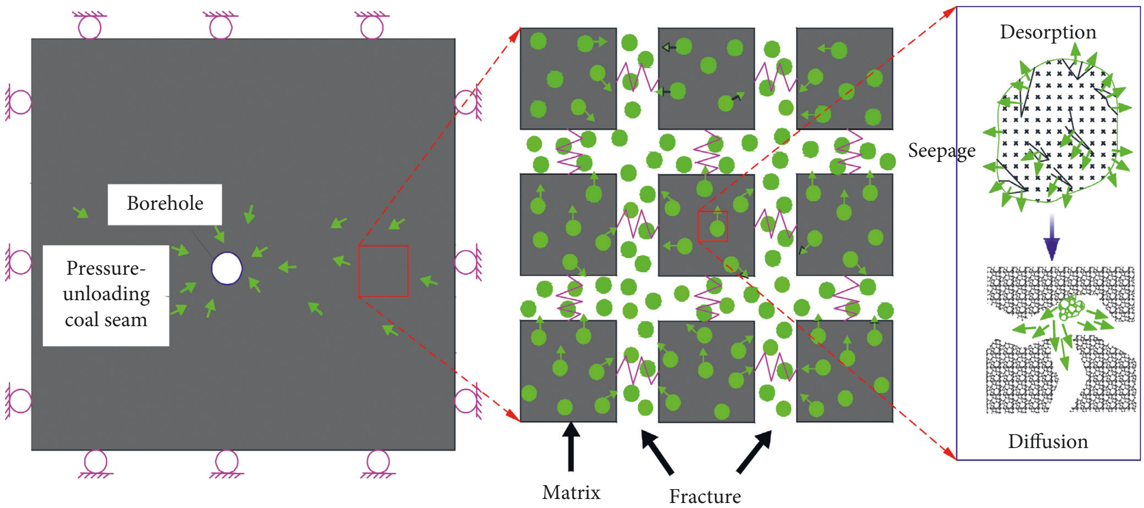

FIGURE 2: Gas migration during borehole extraction.

2.3. Governing Equation of the Mechanical Field. Coal is an elastic porous continuous medium. And its total strain is the sum of the solid stress, gas pressure, and the strain caused by gas adsorption/desorption. Therefore, we can obtain the following equation [21]:

$$\varepsilon_{ij} = \frac{1}{2G}\sigma_{ij} - \left(\frac{1}{6G} - \frac{1}{9K}\right)\sigma_{kk}\delta_{ij} + \frac{\alpha p_g}{3K}\delta_{ij} + \frac{\varepsilon_s}{3}\delta_{ij}, \quad (6)$$

where δ_{ij} is the Kronecker symbol; G is the coal shear modulus (Pa), $G = E/2(1+v)$; K is the bulk modulus of coal (Pa), $K = E/3(1-2v)$; E is Young's modulus of coal (Pa); v is Poisson's ratio of coal; α is the Biot coefficient; and ε_s is the gas adsorption strain.

Through experimental research, Levine [24] has found that the coal strain caused by gas adsorption accords with the equation of Langmuir form, which can be expressed as follows:

$$\varepsilon_s = \frac{\varepsilon_{max} p_g}{P_{50} + p_g}, \quad (7)$$

where ε_{max} is the maximum adsorption strain and P_{50} is the adsorption pressure constant, which refers to the gas pressure when strain is 50% of the maximum adsorption strain (Pa).

The geometric and static equilibrium relations of coal are as follows:

$$\begin{cases} \varepsilon_{ij} = \frac{1}{2}\left(u_{i,j} + u_{j,i}\right), \\ \sigma_{ij,j} + F_i = 0, \end{cases} \quad (8)$$

where F_i is the volume force (MPa) and u_i is the displacement in the i direction (m). $i, j = x, y, z$. Combining Equations (6) and (8), the modified Navier equation considering pore pressure and adsorption can be obtained:

$$Gu_{i,jj} + \frac{G}{1-2\nu}u_{j,ji} - \alpha p_{g,i} - K\varepsilon_{s,i} + F_i = 0. \quad (9)$$

The Mohr–Coulomb criterion is used as the criterion for judging the strength failure of coal rock:

$$-\sigma_3 + \sigma_1\frac{1+\sin\varphi}{1-\sin\varphi} \geq f_{c0}, \quad (10)$$

where σ_1 is the maximum principle stress (MPa), σ_3 is the minimum principle stress (MPa), φ is the fractural angle (°), and f_{c0} is the uniaxial compressive strength (Pa).

2.4. Porosity and Permeability of the Unloading Coal Seam. The permeability of coal seam is closely related to the stress state, mechanical property, and adsorption property of coal. And it can be expressed as follows [25, 26]:

$$k = k_0 \exp\left\{-3C_p\lfloor(\sigma - \sigma_0) - \left(p_g - p_{g0}\right)\rfloor + (1-\gamma)\varepsilon_s\right\}, \quad (11)$$

where k_0 is the initial permeability of coal seam (m^2), C_p is the compression coefficient of coal seam (Pa^{-1}), and γ is the adsorption strain coefficient. The subscript "0" is the initial value.

The relation between permeability and porosity is described by the cubic law, which can be expressed as follows [27–29]:

$$\frac{\phi}{\phi_0} = \left(\frac{k}{k_0}\right)^{1/3}, \quad (12)$$

where φ_0 is the initial porosity of coal seam (m^2).

Substituting Equation (10) into Equation (11), the dynamic evolution equation of coal seam porosity is obtained as follows:

$$\phi = \phi_0 \exp\left\{-C_p\left[(\sigma - \sigma_0) - \left(p_g - p_{g0}\right)\right] + \frac{(1-\gamma)\varepsilon_s}{3}\right\}. \quad (13)$$

The fluid-solid coupling model of coal seam gas extraction is obtained by the combination of Equations (5), (9), (11), and (13). We can use Comsol Multiphysics to carry out numerical simulation, to study the law of gas extraction in the unloading coal seam of protective layer mining, and to determine the reasonable drilling arrangement scheme.

3. Numerical Simulation of Rational Holes Arrangement in Gas Extraction

3.1. Geometric Model and Fixed Solution Condition. The Panyi Coal Mine in the Huainan mining area is an outburst mine, and coal and gas outburst accidents have occurred many times, which seriously restricts the safe and efficient production of the mine [9]. C13 coal seam is the main mining seam in coal mine; the average thickness of the coal seam is 5 m, the gas pressure is 4.2 MPa, and the permeability is $2.25 \times 10^{-17}\,\mathrm{m}^2$, which belongs to the high-gas, low-permeability, and dangerous coal seam. B11 coal seam is located at the bottom of C13 coal seam; the thickness of the coal seam is 2 m, the average distance between the two layers of coal is 64 m, and the risk of B11 coal seam outburst is relatively small. Therefore, B11 coal seam is used as the lower protection layer to shield the mining of C13 coal seam.

The tilt width of 1551 (1) working face in B11 coal seam is 220 m, the strike length is 1460 m, and the average seam inclination angle is 5°. The tilt width of 1551 (3) working face in C13 coal seam is 200 m and the strike length is 1400 m. Limited by the memory performance of the computer, we only simulate the gas extraction in unloading coal seam when the 1551 (1) working face is mined to 800 m, and the geometric model size is $1000\,\mathrm{m} \times 400\,\mathrm{m} \times 95\,\mathrm{m}$ (Figure 3). For the physical model, the bottom boundary is fixed and a slip boundary was applied for other sides. The load from the weight of overlying strata with an average pressure of 10 MPa is applied to the top boundary. All the external boundaries for gas are adiabatic and impermeable boundary. Under the initial condition, the coal seam is in the free stress state, and the mechanical parameters of overlying strata are shown in Table 1 [11]. The diameter of gas extraction borehole is 113 mm, and the suction negative pressure is 25 kPa. And other related parameters are shown in Table 2.

3.2. Simulation Result Analysis. Vertical stress distribution of the protected-layer C13 coal seam is shown in Figure 4 after the protective-layer B11 coal seam is mined to 800 m. The stress concentration is formed on both sides of the gob in B11 coal seam, and stress transfer results in stress concentration in the corresponding area of C13 coal seam. The maximum vertical stress is 15 MPa, and the stress concentration coefficient is 1.5. The C13 coal seam area corresponding to the B11 coal seam gob produces pressure relief, the minimum vertical stress is 7 MPa, and the pressure-unloading ratio is 0.32.

According to Equation (10), permeability of the coal seam relief zone rises and permeability of the coal seam stress concentration zone is reduced. As shown in Figure 5, the permeability of the protected coal seam is divided into the enhanced zone, the reduced zone, and the original zone. The maximum permeability is $2.85 \times 10^{-14}\,\mathrm{m}^2$, which is 1266 times as high as $2.25 \times 10^{-17}\,\mathrm{m}^2$ of the initial permeability in coal seam, while the minimum permeability is $3.65 \times 10^{-18}\,\mathrm{m}^2$, which is 0.162 times the initial permeability in coal seam.

In order to determine the reasonable spacing of boreholes, two types of gas extraction drilling layouts are studied, as shown in Figure 6.

Original arrangement: the boreholes are evenly distributed in the coal seam. Borehole spacing is 20 × 20 m.

Optimized arrangement: the boreholes are nonuniformly distributed in the coal seam. Borehole spacing of the core enhancement zone is 40×40 m, that of the general penetration zone is 20×20 m, and that of the permeability reduction zone is 5×20 m.

From Figure 6, we can see that the layout of boreholes near the open-off cut and working face is relatively dense. If we increase the strike length of the working face, there will be a small difference in the number of boreholes in the two layout types.

By using the fluid-solid coupling model of coal seam gas extraction, the law of gas extraction under the above two types is simulated so as to determine the reasonable way of borehole distribution. Figure 7 is the distribution map of gas pressure in the unloaded coal seam with gas extraction up to 180 days. Obviously, the initial gas pressure of the coal seam is 4.2 MPa; when it is reduced to 0.74 MPa, the coal seam gas extraction rate is more than 30%. Therefore, the reduction of gas pressure to 0.74 MPa can be considered to be the standard.

As shown in Figure 7(a), under the uniform distribution mode (original arrangement), the gas pressure is reduced rapidly in the core enhancement zone, and it can be lower than 0.74 MPa after the extraction of 30 days. In the permeability reduction zone, the gas pressure is reduced slowly, the extraction of 180 days is still greater than 0.74 MPa, and the extraction blind area is $4.1 \times 10^4\,\mathrm{m}^2$. However, as shown in Figure 7(b), under the optimized nonuniform hole layout mode (optimized arrangement), the coal seam gas pressure decreases rapidly. After 180 days of extraction, the effective extraction area basically covers the working face of the protected seam, and the blind area is only $0.36 \times 10^4\,\mathrm{m}^2$, which is 0.0878 times that of the original arrangement.

Figure 8 displays the gas pressure of the cutoff line CD in the middle coal seam after 180 days of extraction. Generally, in the middle area of coal seam 150–250 m, gas pressure of original arrangement is almost equal to that of optimized arrangement. In the areas of 100–150 m and 250–300 m, the gas pressure of original arrangement is larger than that of optimized arrangement. It can be found that an extraction blind area at both sides of the researched coal seam will occur if we use the original arrangement. The range of blind area at each side is about 25 m.

Gas extraction capacity of two types of borehole layouts is compared and analyzed, as shown in Figure 9. In the early stage of extraction, gas extraction capacity is increased rapidly by the promotion of high gas pressure gradient. In 30 days of extraction, gas extraction capacity of the two kinds of cloth hole schemes reached $4.77 \times 10^6\,\mathrm{m}^3$ and $5.84 \times 10^6\,\mathrm{m}^3$, respectively. With the increase of extraction time, gas pressure of the coal seam decreases, the gas pressure gradient

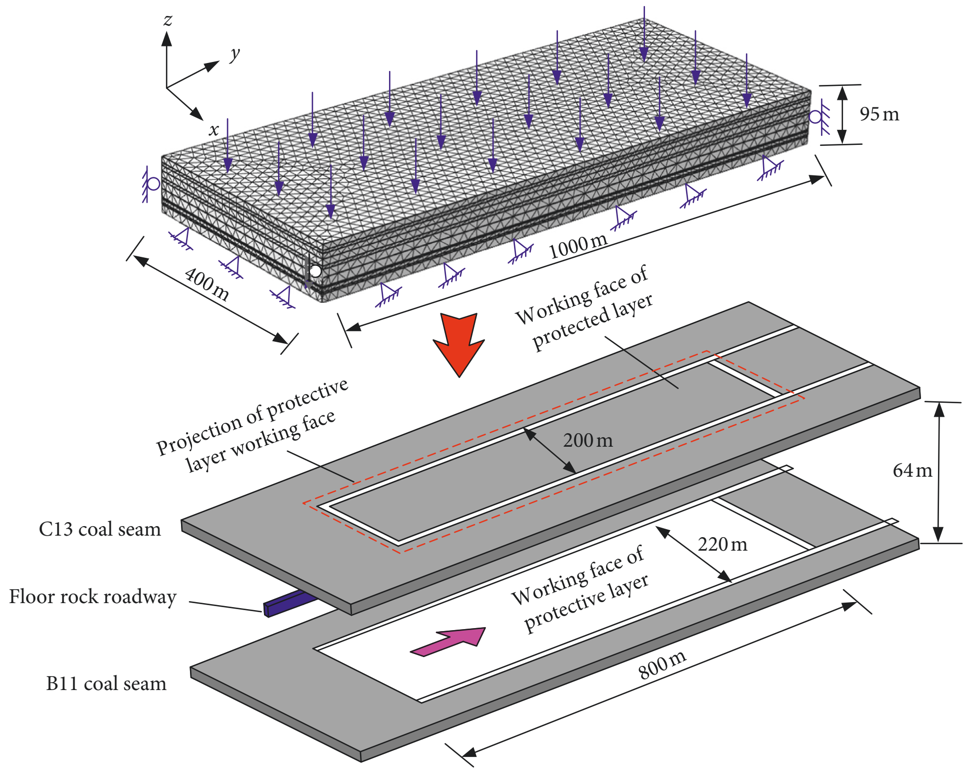

Figure 3: Geometric model for numerical simulation.

Table 1: Mechanical properties of overlying strata.

No.	Lithology	Elastic modulus (GPa)	Compressive strength (MPa)	Poisson's ratio	Friction angle (°)	Density ($kg \cdot m^{-3}$)	Thickness (m)
1	Sandy mudstone	38	63	0.4	29	2400	10
2	Coal seam C13	10	15	0.4	30	1400	5
3	Sandy mudstone	26	33	0.3	32	2400	8.5
4	Medium-grained sandstone	28	76	012	30	2600	11
5	Speckled mudstone	57	50	0.12	26	2600	7
6	Fine sandstone	47	50	0.4	21	2500	13
7	Sandy mudstone	38	37	0.38	26	2400	16
8	Fine sandstone	20	48	0.4	24	2500	2.5
9	Sandy mudstone	38	37	0.26	37	2400	6
10	Coal seam B11	10	20	0.4	30	1400	2
11	Sandy mudstone	38	70	0.26	26	2400	14

Table 2: Parameters of gas extraction in the coal seam.

Parameter	Value	Remark
Porosity Φ_0	0.055	Experiments
Gas dynamic viscosity μ_g (Pa·s)	1.03×10^{-5}	Reference [19]
Langmuir pressure constant P_L (MPa)	2.45	Experiments
Langmuir volume constant V_L ($m^3 \cdot kg^{-1}$)	0.032	Experiments
Compression coefficient of the coal seam C_p (Pa^{-1})	2.39×10^7	Experiments
Maximum adsorption strain ε_{max}	0.01266	Reference [20]
Poisson's ratio ν	0.28	Experiments
Klingberg coefficient b_1 (MPa)	0.76	Reference [21]
Coal seam temperature T (K)	315.15	Reference [21]
Strain constant ε_L	0.0083	Reference [24]
Adsorption strain coefficient γ	52.8	Reference [24]
Adsorption pressure constant P_{50} (MPa)	5.17	Reference [24]

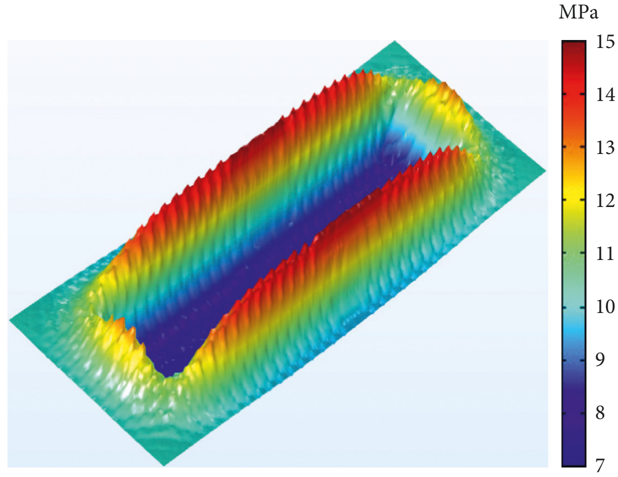

Figure 4: Vertical stress distribution of the protected coal seam.

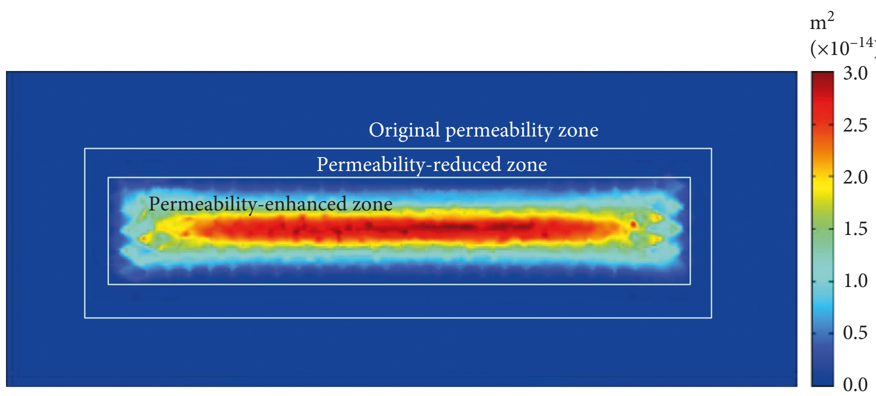

Figure 5: Permeability distribution of the protected coal seam.

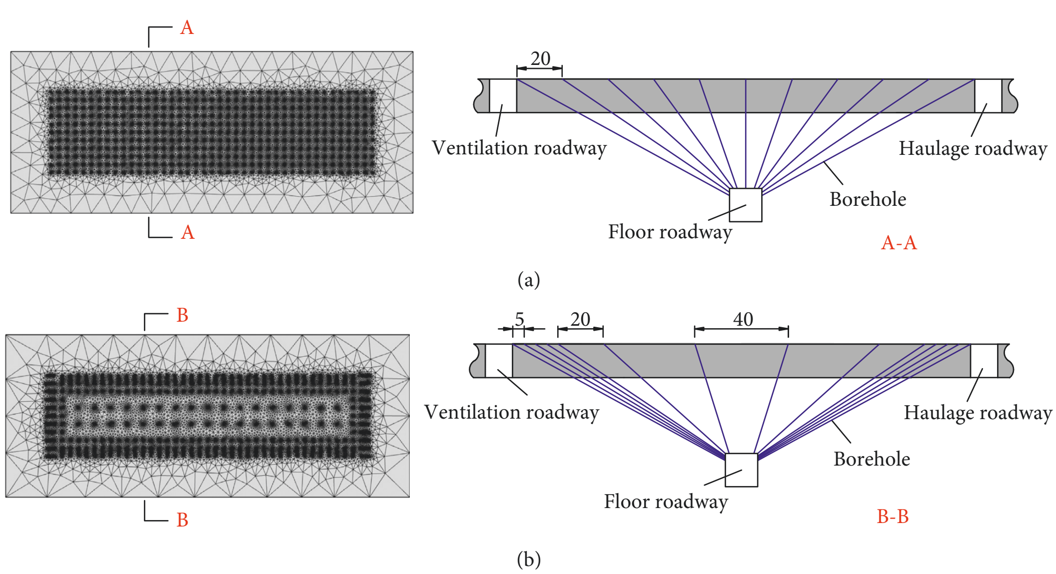

Figure 6: Drilling arrangement schemes for gas extraction. (a) Original arrangement. (b) Optimized arrangement.

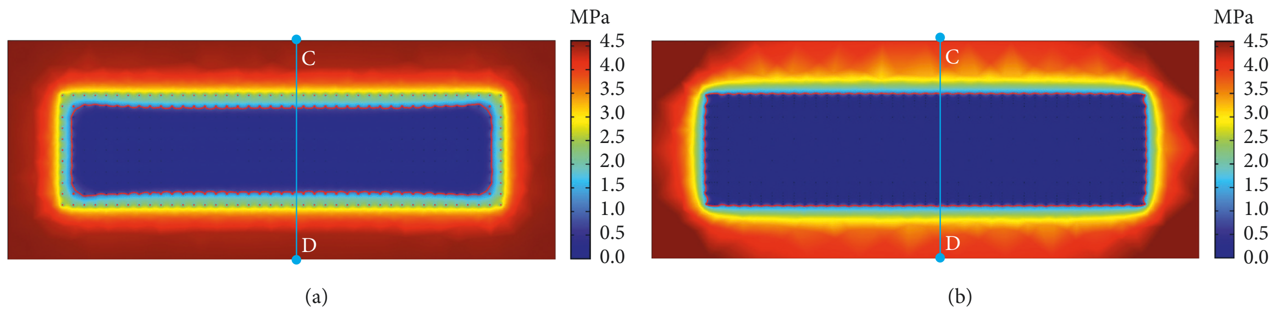

FIGURE 7: Gas pressure in the coal seam after 180 days of extraction. (a) Original arrangement. (b) Optimized arrangement.

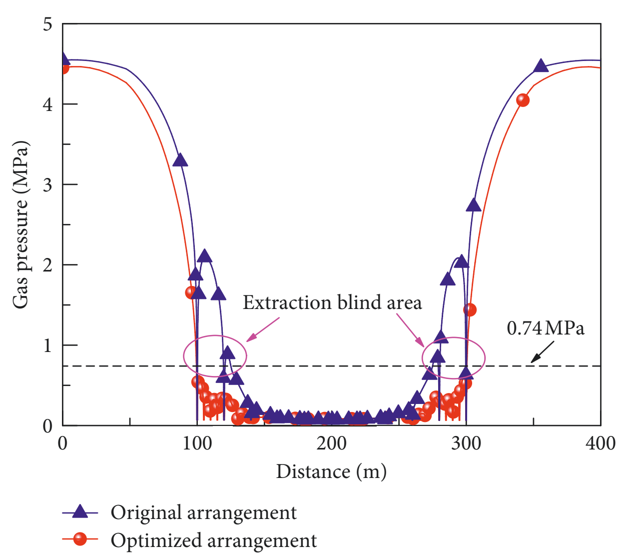

FIGURE 8: Gas pressure of the cutoff line CD after 180 days of extraction.

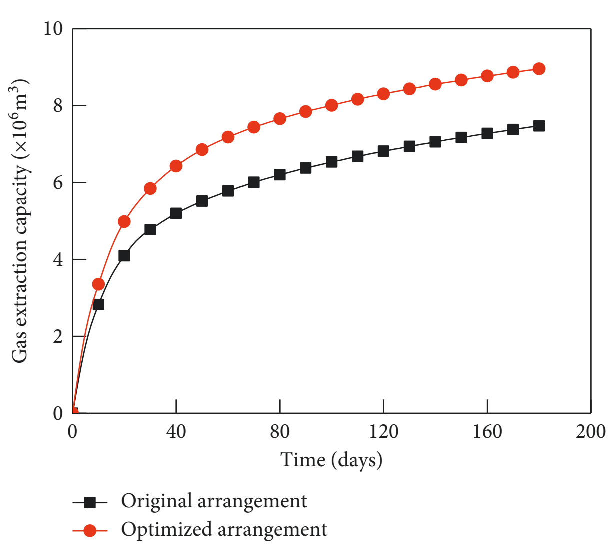

FIGURE 9: Different drilling arrangement schemes for gas extraction.

decreases, the extraction rate decreases, and extraction capacity increases slowly. When the extraction time is 180 days, gas extraction capacity is $7.47 \times 10^6\,m^3$ and $8.95 \times 10^6\,m^3$, respectively. Gas extraction capacity of optimized arrangement is greater than that of original arrangement. According to the distribution of gas pressure, it is found that optimized arrangement makes full use of the zoning characteristics of the permeability of the protected coal seam and improves the efficiency of gas extraction.

4. Conclusions

(1) The fluid-solid coupling model of gas extraction in the unloading coal seam and the dynamic evolution equation of permeability and porosity of the coal seam are constructed. Numerical simulation of the gas extraction process in the unloading coal seam of the floor roadway is carried out.

(2) The stress on both sides of the gob of the protective layer is higher than that of the protected coal seam zone, and the permeability of coal seam decreases. In the middle of the gob, the stress of the coal seam zone is reduced and the permeability is increased. The protected coal seam has the characteristics of permeability zoning, which can be divided into the permeability-enhanced zone, the permeability-reduced zone, and the original permeability zone.

(3) In the 1551 (3) working face of C13 coal seam, when the uniform borehole distribution method is adopted, the gas pressure in the permeability reduction zone is lower than 0.74 MPa after 180 days of extraction, and the extraction blind area is $4.1 \times 10^4\,m^2$. The effective extraction area after 180 days of extraction is basically covered with the protected layer when the nonuniform distribution method is used for the permeability zoning.

Data Availability

The data used in the article are from the simulation results by Comsol Multiphysics. And we wrote the equations as Comsol codes independently to conduct these simulations. Therefore, you can contact Chaojun Fan (chaojunfan@139.com) if you want to learn more about our work.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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