

Research Article

Coal Seam Gas Extraction by Integrated Drillings and Punchings from the Floor Roadway considering Hydraulic-Mechanical Coupling Effect

Chaojun Fan ¹, Haiou Wen,¹ Sheng Li,¹ Gang Bai,² and Lijun Zhou²

¹College of Mining, Liaoning Technical University, Fuxin 123000, China

²College of Safety Science and Engineering, Liaoning Technical University, Fuxin 123000, China

Correspondence should be addressed to Chaojun Fan; chaojunfan@139.com

Received 18 October 2021; Accepted 9 November 2021; Published 7 January 2022

Academic Editor: Peng Hou

Copyright © 2022 Chaojun Fan et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Owing to the exhaustion of shallow coal resources, deep mining has been occupied in coal mines. Deep buried coal seams are featured by the great ground stress, high gas pressure, and low permeability, which boost the risk of gas disasters and thus dramatically threaten the security about coal mines. Coal seam gas pressure and gas content can be decreased by gas extraction, which is the primary measure to prevent and control mine gas disasters. The coal mass is simplified into a continuous medium with dual structure of pores and fractures and single permeability. In consideration of the combined effects of gas slippage and two-phase flow, a hydraulic-mechanical coupling model for gas migration in coals is proposed. This model involves the equations of gas sorption and diffusion, gas and water seepage, coal deformation, and evolution of porosity and permeability. Based on these, the procedure of gas extraction through the floor roadway combined with hydraulic punching and ordinary drainage holes was simulated, and the gas extraction results were used to evaluate the outburst danger of roadway excavation and to verify the engineering practice. Results show that gas extraction can reduce coal seam gas pressure and slow down the rate of gas release, and the established hydraulic-mechanical coupling model can accurately reveal the law of gas extraction by drilling and punching boreholes. After adopting the gas extraction technology of drilling and hydraulic punching from the floor roadway, the remaining gas pressure and gas content are reduced to lower than 0.5 MPa and 5.68 m³/t, respectively. The achievements set a theoretical foundation to the application of drilling and punching integrated technology to enhance gas extraction.

1. Introduction

As the depth of coal mining increases, the gas pressure and content in coals have increased. Gas accidents such as coal and gas outbursts and gas explosions have occurred frequently, which threaten coal mine safety production [1, 2]. Gas extraction can reduce coal seam gas pressure and gas content, eliminate outburst hazards, and seems significant to forestall gas accidents [3]. Reasonable drainage borehole layout parameters can avoid drainage blind areas between boreholes, increase gas extraction volume, decrease the amount of drilling, and lower the capital expenditure of gas extraction engineering projects. The rule of gas migration

in coal seam is figured out, which is critical to determine rational drainage drilling arguments [4].

With regard to the gas migration in coals, the interaction between coal and gas has been explored by numerous scholars. They believe that changes in coal seam forces and changes in gas pressure will deform the coal body, causing changes in porosity and permeability, and proposed many gas-solid coupling models. For instance, the gas-solid coupling model of coal and gas under different stress conditions was demonstrated by Wang et al. [5], Yang et al. [6], and Connell [7]. After that, the effect of gas sorption on coal deformation was illustrated to the gas-solid coupling responses [8, 9]. Xia et al. [10, 11] and Wang et al. [12]

proposed a coupled model of coal deformation and compositional flow for the premining coal seam gas extraction. Yang et al. [13] combined the evolution of stress, damage, and gas permeability with the deformation of coal and rock. Gao et al. [14] and Liu et al. [15] considered the thermal effect for extraction of coal seam gas with slotted boreholes. Zhao et al. [16] simulated the influence of combination forms of an intact sublayer and a tectonically deformed sublayer of coal on the gas drainage performance of boreholes.

As a matter of fact, water migration in coals will block the transport of coalbed methane controlled by the gas relative permeability [17, 18]. In the meantime, the effective permeability is affected by compressibility and pressure of the gas, which results in difference between the gas flow and the liquid flow in the coal seam [19]. Coal permeability, relying on the width of fractures, gas pressure, and Klinkenberg effect, has a crucial effect on the mass transport and heat transfer [20]. In existing literatures, the effects of groundwater and slippage are often ignored, causing large errors in the design of drainage boreholes and calculation of gas extraction volume [21, 22].

This paper considers the combined effect of gas slippage effect and two-phase seepage, and a hydraulic-mechanical coupling model is established for gas extraction from coal seams involving equations of the gas seepage field, water seepage field, and stress field and embeds the mathematical equations into a finite set of equations. The mathematical model is appertained to simulating the gas extraction process of drilling and hydraulic punching integrated boreholes from the floor roadway and carries out in situ engineering applications according to the optimal design scheme. The research results have guiding significance for the optimization of drainage hole layout.

2. Hydraulic-Mechanical Coupling Model for Gas Extraction from Coal Seams

In accordance with the gas storage environment in coals, some hypotheses are proposed [10, 21–23]. (1) Coal mass is an elastic continuous medium with dual structure of pores and fractures and single permeability. (2) Water only occurs and migrates. The adsorbed and desorbed gas exists within both pores and fractures, while water is only transported in the fracture. The process of gas adsorption/desorption is consummated in a moment. (3) Gas migration seems to closely correlate with the microcosmic structure of coals. It can be divided into three steps in series: firstly, the adsorbed gas desorbs into the space of pores satisfying the Langmuir law; then, the gas diffuses from the pores to fractures satisfying Fick's law; finally, the gas seeps from the fracture into the gas well satisfying Darcy's law. (4) Gas seems in accord with the equation of ideal gas. (5) The volume force of the gas is ignored.

2.1. Controlling Equation of Seepage Field. Coal seam is a porous organic mineral buried in the rock stratum. Coal seam is not only the gas source of coalbed methane but also the storage reservoir for coalbed methane. It is featured by pore-fracture dual structure. The gas mass in the coal matrix

seems comprised of adsorbed and free gas, which can be defined as [24]

$$m_m = \phi_m \rho_g + V_{sg} \rho_s \rho_{gs}, \quad (1)$$

where ϕ_m is the matrix porosity, ρ_g is the density of the gas (kg/m^3), V_{sg} is the adsorbed gas content (m^3/kg), ρ_s is the density of the coal skeleton (kg/m^3), and ρ_{gs} is the density of gas under standard conditions (kg/m^3).

In accordance with the ideal gas equation of state, the density of gas is

$$\rho_g = \frac{M_g}{RT} p, \quad (2)$$

where M_g is the gas molar mass (kg/mol), R is the gas molar constant ($\text{J}/(\text{mol}\cdot\text{K})$), p is the gas pressure (MPa), and T is the coal bed temperature (K).

Considering the modified Langmuir law, the adsorbed gas in the coal matrix can be illustrated [10]:

$$V_{sg} = \frac{V_L p_m}{P_L + p_m}, \quad (3)$$

where V_L is the Langmuir volume constant (m^3/kg), P_L is the Langmuir pressure constant (Pa), and p_m is the CBM pressure in the matrix (MPa).

In the initial state, the gas desorption rate equals the gas adsorption rate in the coal matrix, namely, the equilibrium state of sorption. The gas pressure in pores is the same with that in the fractures. The operation of gas extraction will break this equilibrium state. As a result, the adsorbed gas desorbs and migrates to the fractures by means of gas diffusion. Based on Fick's law and mass conservation law, the equation of gas transport in the matrix is [19]

$$\frac{\partial m_m}{\partial t} = -\frac{M_g}{\tau RT} (p_m - p_{fg}), \quad (4)$$

where p_{fg} is the gas pressure in the fissure (MPa) and τ is the gas desorption time, which equals the time it takes for the matrix to desorb 63.2% of the adsorbed gas and can be acquired through the desorption experiment of coal samples.

Submitting equations (1)–(3) into equation (4), the gas transport equation in the coal matrix can be acquired:

$$\frac{\partial}{\partial t} \left(\frac{V_L p_m}{P_L + p_m} \rho_s \frac{M_g}{RT_s} p_s + \phi_m \frac{M_g}{RT} p_m \right) = -\frac{M_g}{\tau RT} (p_m - p_{fg}). \quad (5)$$

Groundwater and gas exist in the fracture system at the same time, and the fluid migration is a two-phase flow. The desorbed gas from the coal matrix acts as the mass

source of fractures. The governing equations for gas transport in the fracture can be defined as [25]

$$\frac{\partial(s_g \varphi_f \rho_g)}{\partial t} + \nabla \cdot (\rho_g q_g) = (1 - \varphi_f) \frac{M_g}{\tau RT} (p_m - p_{fg}), \quad (6)$$

$$\frac{\partial(s_w \varphi_f \rho_w)}{\partial t} + \nabla \cdot (\rho_w q_w) = 0, \quad (7)$$

where S_g is the gas phase saturation, φ_f is the fracture porosity, q_g is the gas flow velocity (m/s), S_w is the water phase saturation, ρ_w is the water density (kg/m³), and q_w is the water flow velocity (m/s).

In consideration of the slippage effect, combined with the generalized Darcy's law of gas-water two-phase seepage, the flow velocity of gas and water in the fracture is [25, 26]

$$q_g = -\frac{kk_{rg}}{\mu_g} \left(1 + \frac{b_1}{p_{fg}}\right) \nabla p_{fg}, \quad (8)$$

$$q_w = -\frac{kk_{rw}}{\mu_w} \nabla p_{fw}, \quad (9)$$

where k is the absolute permeability of the fracture (m²), k_{rg} is the relative permeability of the gas phase, μ_g is the gas phase dynamic viscosity (Pa·s), b_1 is the slip factor (Pa), μ_w is the water phase dynamic viscosity (Pa·s), and p_{fw} is the water pressure in the fissure (MPa).

Incorporating equation (8) into equation (6) and equation (9) into equation (7), the control equation of the gas and water seepage field can be obtained:

$$\frac{\partial}{\partial t} \left(\varphi_f \frac{M_g}{RT} p_{fg} \right) + \nabla \cdot \left(-\frac{M_g (p_{fg} + b_1)}{RT} \frac{kk_{rw}}{\mu_g} \nabla p_{fg} \right) \quad (10)$$

$$= (1 - \varphi_f) \frac{M_g}{\tau RT} (p_m - p_{fg}),$$

$$\frac{\partial}{\partial t} (s_w \varphi_f \rho_w) + \nabla \cdot \left[-\rho_w \frac{kk_{rw}}{\mu_w} \nabla p_{fw} \right] = 0. \quad (11)$$

2.2. Controlling Equation of Stress Field. The coal deformation is caused by the combination of stress, gas and water pressure, and gas sorption. Thus, the strain of coal mass is presented as [23]

$$\varepsilon_{ij} = \frac{1}{2G} \sigma_{ij} - \left(\frac{1}{6G} - \frac{1}{9K} \right) \sigma_{kk} \delta_{ij} + \frac{\alpha_m p_m + \alpha_f p_f}{3K} \delta_{ij} + \frac{\varepsilon_a}{3} \delta_{ij}, \quad (12)$$

where δ_{ij} is the Kronecker symbol; D is the equivalent coal elastic modulus (GPa), and $D = 1/(1/E_s + 1/(aK_n))$; G is the coal shear modulus (GPa), and $G = D/2(1 + \nu)$; K is the bulk modulus of coal (GPa), and $K = D/3(1 - 2\nu)$; K_s is the bulk modulus of the coal skeleton (GPa), and $K_s = E_s/3(1 - 2\nu)$; E_s is the elastic modulus of the coal skeleton (GPa); K_n is

the fracture stiffness (GPa); ν is Poisson's ratio; α_m and α_f are the Biot effective stress coefficients corresponding to pores and cracks, respectively, $\alpha_m = 1 - K/K_s$, and $\alpha_f = 1 - K/(aK_n)$; ε_a is the adsorbed gas strain of the framework; p_f is the pressure of the fracture fluid (MPa); and a is the width of the coal matrix (m).

The adsorbed gas strain of the skeleton is proportional to the adsorbed amount [19]:

$$\varepsilon_a = a_s g V_{sg}, \quad (13)$$

where α_{sg} is the adsorption strain coefficient (kg/m³) and V_{sg} is the gas adsorption capacity (m³/kg).

Obedying the elastic mechanics theory, the following equations can be obtained:

$$\begin{cases} \varepsilon_{ij} = \frac{1}{2} (u_{i,j} + u_{j,i}), \\ \sigma_{i,jj} + F_i = 0, \end{cases} \quad (14)$$

where F_i is the volume force (MPa) and u_i is the displacement in the i direction (m), where $i = x, y, z$.

Combining equations (12) and (14), the modified Navier equation that considers pore pressure, changes, and adsorption, that is, the stress field governing equation is obtained:

$$G u_{i,jj} + \frac{G}{1 - 2\nu} u_{j,ji} - \alpha_m p_{m,i} - \alpha_f p_{f,i} - K \varepsilon_{a,i} + F_i = 0. \quad (15)$$

2.3. Porosity and Permeability Equation. Porosity and permeability are the critical arguments for gas migration in the procedure of extraction and closely correlate with the stress and the mechanical properties of coals. The meso-structure of coal mass with the conceptual model is shown in Figure 1. The variation of the width of the matrix and fracture will change the magnitude of porosity and permeability in coal, resulting in the evolution of mass transport in coal seam.

The porosity in the coal matrix can be described as [27]

$$\varphi_m = \frac{1}{(1 + S)} [\varphi_{m0}(1 + S_0) + \alpha_m(S - S_0)], \quad (16)$$

where $S = \varepsilon_v + p_m/K_s - \varepsilon_a$, ε_v is the volumetric strain of coal, and subscript "0" means the initial state of variables.

The fracture porosity can be defined as [27]

$$\varphi_f = \varphi_{f0} - \frac{3\varphi_{f0}(\Delta\varepsilon_a - \Delta\varepsilon_v)}{\varphi_{f0} + 3K_f/K}, \quad (17)$$

where K_f is the improved fracture stiffness, $K_f = bK_n$ (GPa), and b is the width of the fracture (m).

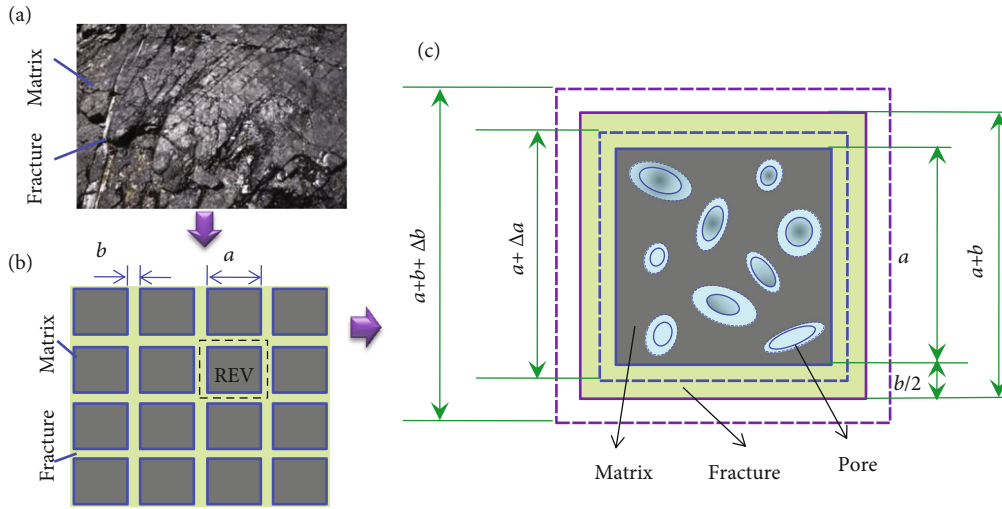


FIGURE 1: Mesostructure of coal mass: (a) actual coal surface; (b) conceptual model of coals; (c) size change in coal matrix and fracture.

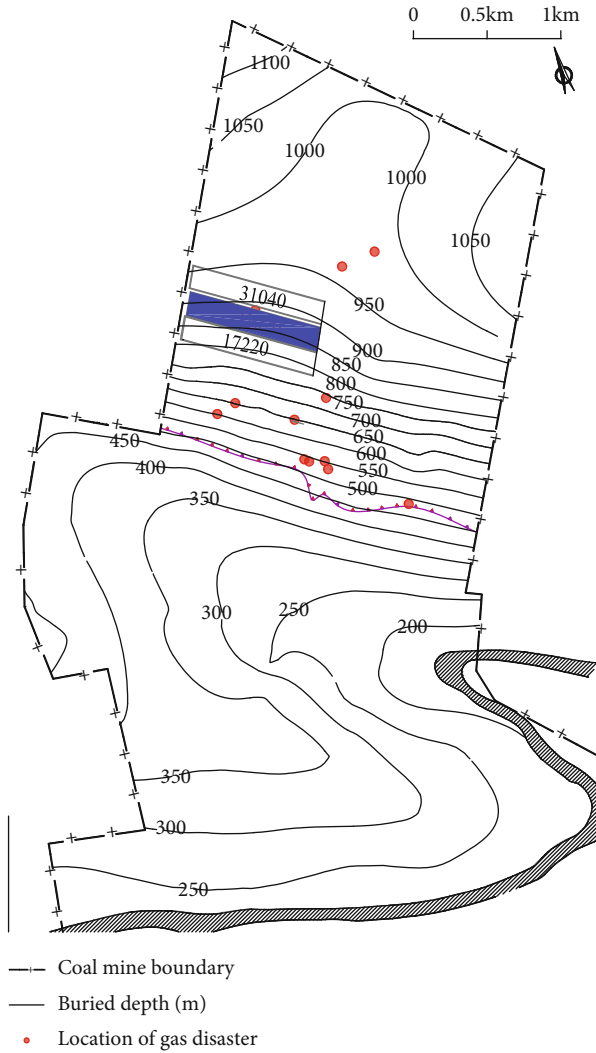


FIGURE 2: Schematic diagram of panel 31020.

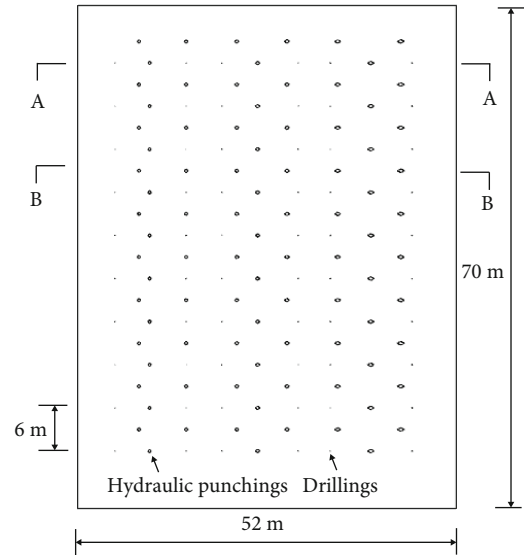


FIGURE 3: Gas extraction layout of integrated drillings and punchings from the floor roadway.

The cubic law is used to express the association between the coal seam fracture permeability ratio and the porosity ratio [28, 29]:

$$\frac{k}{k_0} = \left(\frac{\phi_f}{\phi_{f0}} \right)_3. \quad (18)$$

Substituting equation (17) into equation (18), the fracture permeability can be acquired:

$$k = k_0 \left(1 - \frac{3(\Delta\varepsilon_a - \Delta\varepsilon_v)}{\phi_{f0} + 3K_f/K} \right)^3, \quad (19)$$

where k_0 is the initial permeability (m^2).

Combining equations (5), (10), (11), and (15), the hydraulic-mechanical coupling model for gas migration in

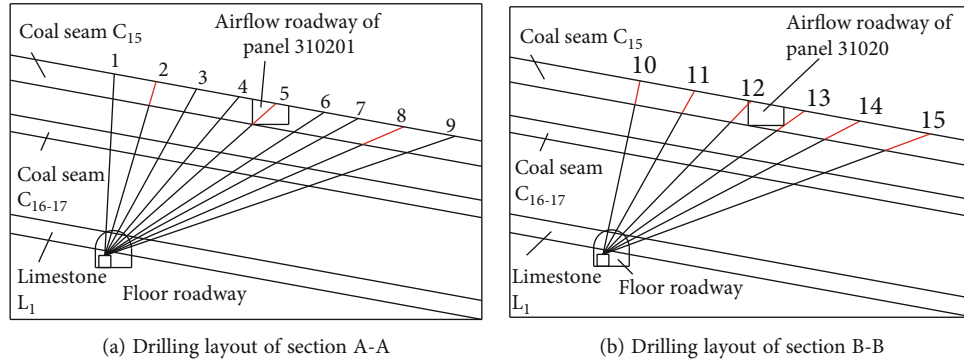


FIGURE 4: Section of gas extraction boreholes drilling from the floor roadway, modified from literature [30].

coal seams is established. These equations can be programmed into COMSOL Multiphysics to simulate gas extraction through boreholes from the floor roadway.

3. Geometric Model and Definite Solution Conditions

3.1. Research Background. The studied coal mine is located at Pingdingshan, with about 4 km in length and 3 km in width. The area is about 12.87 km², and the approved production capacity is 1.4 Mt/a. The dynamic disaster phenomenon transpired 28 times in this mine. The maximum volume of outburst gas is 25704 m³, and the maximum outburst coal is 293 t. As the shallow coal resources are exhausted, mining operation has been moving into deep seam. The deep buried coal seams show the characteristics of complex occurrence conditions, large in situ stress, high gas content, and low penetrance. Gas extraction becomes more difficult and the outburst risk increases.

The panel 31020 is located in the upper part of the west wing of the third level (Figure 2). It is adjacent to the panel 17220 that has been mined to the south and the panel 31040 that has not yet been mined to the north. Panel 31020 is mining the coal seam. The coal seam is relatively stable and the structure is simple. The inclination angle of the coal seam is 8°-11°, with an average of 10°. The thickness of the coal seam is about 3.2 m~4.5 m, the average coal thickness is 3.3 m, the original gas content is 14.97 m³/t, the original gas pressure is 1 MPa, and the original ground temperature is 29.4°C~32.2°C.

The roadway 31020 for air intake has a strike length of 761 m and is driven along the roof of coal seam C15, with a distance of 11 m to 14 m from the overlying coal seam C14 and 1.5 m to 12 m from the underlying coal seam C16-17. The construction of roadway 31020 was carried out at a position staggered 20 m outside the floor gas extraction roadway, and the distance between the two roadways was 18 m. The elevation of the roadway 31020 is -630 m to -696 m, and the vertical buried depth is 880 m to 976 m. The cross section of the roadway is 4.6 m × 3.4 m, and it is supported by rectangular anchor mesh cable beams, and the row spacing is 700 mm.

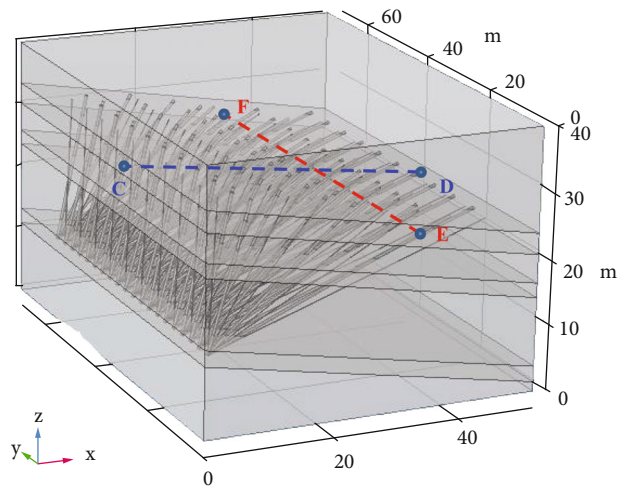


FIGURE 5: Geometric model of gas extraction for roadway 31020.

3.2. Geometric Model Construction. The roadway 31020 for air intake needs to adopt effective gas extraction measures to reduce gas pressure and ensure safe operation of roadway advancing. Therefore, the gas extraction plan of drilling through the floor roadway is adopted to prevent outburst in the area of the roadway 31020. Starting from the opening of the floor roadway at 35 m inward, a set of drilling holes are designed every 6 m. Each set of designed drilling holes has a diameter of 89 mm, and the hole depth is 0.5 m from the roof of C15 coal seam. 127 sets of predrainage drilling boreholes were constructed in the floor roadway, including 1143 ordinary drillings and 318 punchings. In addition, hydraulic punching begins at the 462 m distance from the opening of the floor roadway (15 m ahead of the roadway 31020), and 54 sets of hydraulic punchings were constructed in the direction of roadway 31020, with an interval of 6 m for each group. 6 punchings with an average hole depth of 28 m and a drilling with diameter of 89 mm are arranged. Figure 3 shows the layout plan of gas extraction by integrated drillings and punchings from the floor roadway. Among them, section A-A has 3 hydraulic punchings and 6 ordinary drillings [30], and section B-B has 6 hydraulic punchings, respectively, as shown in Figure 4.

TABLE 1: Relevant parameters for numerical simulation.

Parameter	Value	Parameter	Value
Coal seam initial gas pressure(p_0 , MPa)	1.0	Formation temperature(T_0 , K)	300
Gas adsorption volume constant (V_L , m ³ /kg)	0.0266	Adsorption gauge factor (ϵ_{\max} , kg/m ³)	0.06
Gas adsorption pressure constant (P_L , MPa)	0.568	Gas molar mass(M_g , g/mol)	16
Gas dynamic viscosity (μ_g , Pa·s)	1.84×10^{-5}	Molar gas constant (R , J/(mol·K))	8.314
Hydrodynamic viscosity(μ_w , Pa·s)	1.03×10^{-3}	Standard temperature (T_s , K)	273.5
Gas desorption time (τ , d)	1.21	Standard atmospheric pressure (p_s , kPa)	101
Initial coal porosity (φ_{m0})	0.035	Coal density (ρ_c , kg/m ³)	1410
Initial fissure degree of coal (φ_{f0})	0.012	Initial permeability (k_{f0} , m ²)	1.8×10^{-17}
Slippage factor (b_k , MPa)	0.36	Coal Poisson's ratio (ν)	0.35

In accordance with the gas extraction plan of roadway 31020, a geometric model was established to research the gas extraction effect and gas migration characteristics of the air intake roadway driving face, as shown in Figure 5. In order to observe the changes in gas pressure in the coal seam, two reference lines are set in the geometric model. They are the reference line C-D located in the middle of coal seam and the reference line E-F of the axis of roadway 31020.

3.3. Determination of Solution Conditions. The definite solution conditions of numerical simulation include boundary conditions and initial conditions. For the boundary conditions for the simulation of gas extraction by drilling through the floor roadway, the overburden gravity of 15.3 MPa in the z direction, horizontal stress of 18.8 MPa in the x direction, and horizontal stress of 12.8 MPa in the y direction are applied to the model. The bottom side of the geometry model is set as fixed boundary with zero of horizontal and vertical displacements, and the other two horizontal directions are the sliding boundaries that limit the horizontal displacement. The model is surrounded by an impermeable boundary. There is no flow of gas and water at the boundary. The external seepage boundary of the model is a gas non-permeable boundary. The drainage borehole wall is set as Dirichlet boundary conditions, and the drainage negative pressure is 20 kPa. Aimed at the initial conditions for the simulation of gas extraction by drilling through the floor roadway, the initial gas pressure of the coal seam is 1.0 MPa and the initial permeability is 1.8×10^{-17} m². Relevant parameters are shown in Table 1.

4. Simulated Results of Gas Extraction before and after Roadway Excavation

4.1. Gas Pressure Distributions in Coal Seam before Roadway Excavation. As extraction time prolongs, the gas pressure decreases in coal seam, and the reduction range gradually expands until it extends to the entire coal seam. Figure 6 shows the distribution of coal seam gas pressure after extraction for different times. The gas pressure around the boreholes in the coal seam decreased in a small range after being extracted for 10 days. When gas extraction is operated

for 120 days, the gas pressure decreased more significantly, and the gas pressure in most areas of coal seam decreased from the initial gas pressure of 1 MPa to less than 0.4 MPa. The effect of hydraulic punching seems significantly effective compared to that of ordinary drilling. There exist several dominant reasons. Firstly, hydraulic punching punches the coal body out of the borehole, which extends the touch area between the hole wall of the borehole and the coal seam. Secondly, the stress in coal seam around the hydraulic punchings is released after the coal mass is washed out, which increases the permeability of the coal seam and accelerates the rate of gas migration to the borehole; in consequence, the gas extraction productiveness is promoted.

The values of gas pressure on the reference line C-D and the reference line E-F in the coal seam are extracted to draw the curve lines, as shown in Figure 7. The gas pressure on the reference line gradually decreases with the increase in operating time. In the early stage of extraction, the gas pressure descends significantly. As the gas pressure gradient between coal seam and borehole descends, the gas migration speed decreases, and the gas pressure is slower in the later stage of the drainage. The reference line E-F is close to the borehole, and the gas pressure around the borehole changes more widely, so the gas pressure change on the reference line E-F is more obvious. The reference line CD is located in the direction of the inclination of the coal seam. Affected by the hole layout method, the inclination angle of the borehole through the coal seam near the side of the roadway is smaller. The greater the length of the borehole in the coal seam and the area of the borehole wall, the greater the decrease in gas pressure in this area (20~45 m) and the more obvious the drainage effect. For example, when the drainage time is 120 days, the maximum gas pressure in the range of 20~45 m is 0.357 MPa and the maximum gas pressure in the range of 10~20 m is 0.475 MPa.

4.2. Gas Pressure Distributions in Coal Seam after Roadway Excavation. The coal seam gas pressure distribution after different extraction times is taken as the initial pressure of gas in the coal seam during roadway excavation, which is imported into the outburst hazard simulation model to reevaluate the danger of coal and gas outburst after different

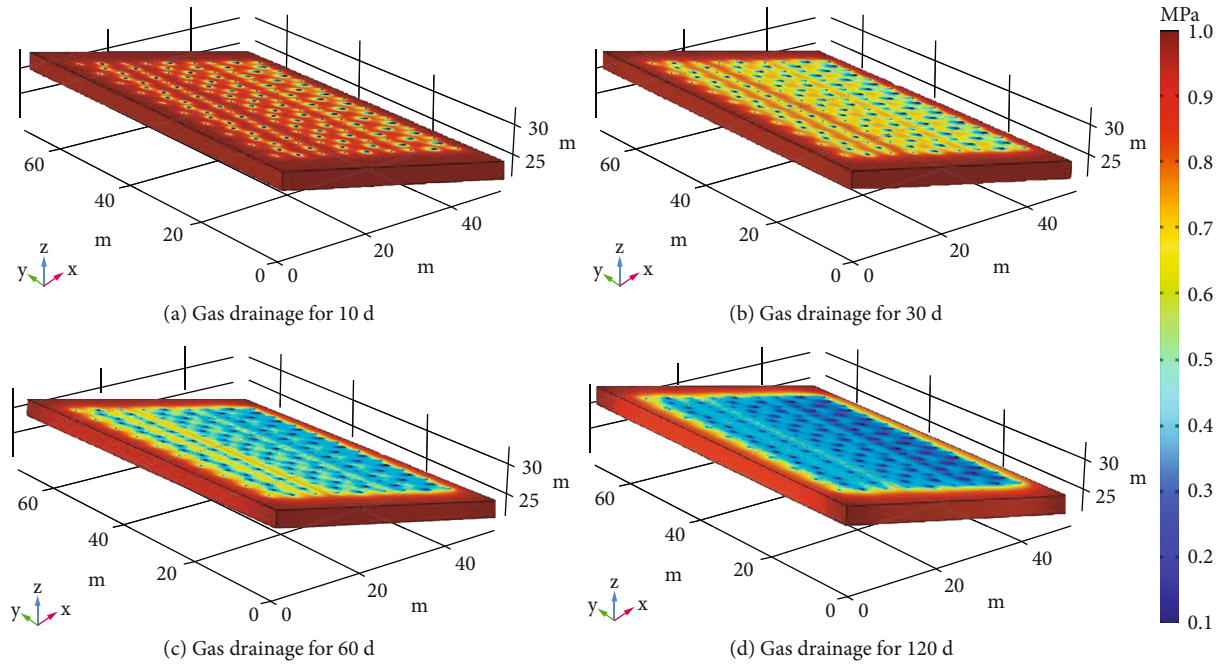


FIGURE 6: Gas pressure distributions in coal seam before roadway excavation.

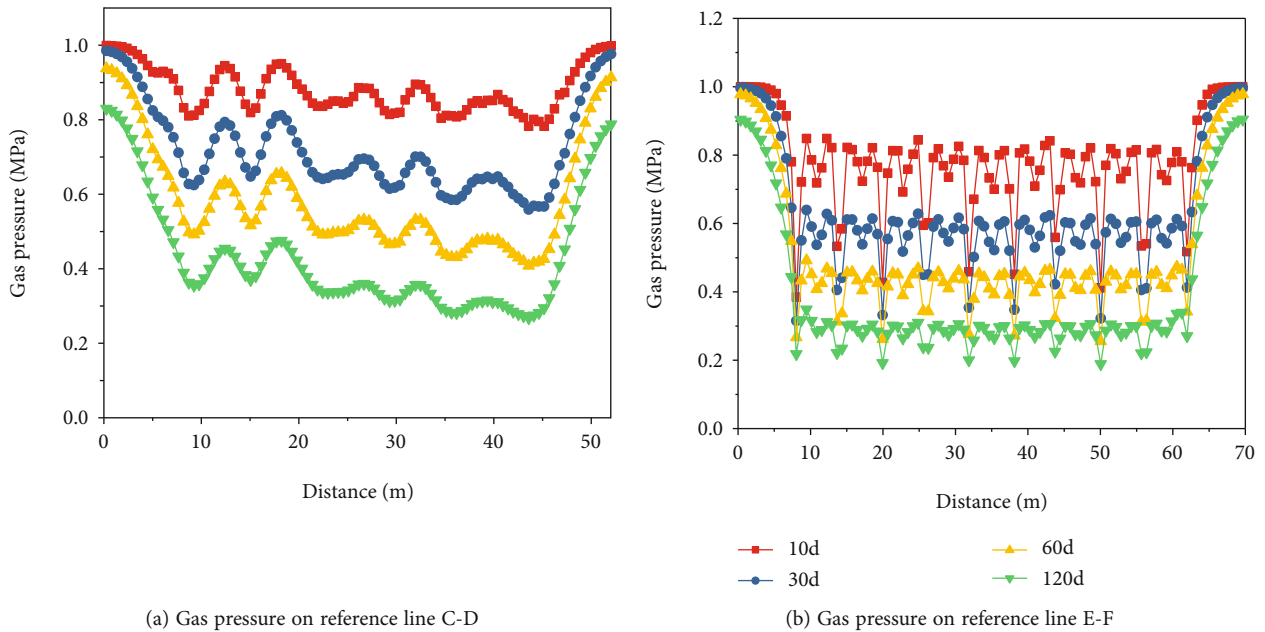


FIGURE 7: Gas pressure along the reference lines in coal seam after different extraction times.

extraction times. Figure 8 shows the distribution of gas pressure in the coal seam when the roadway is driven 60 m after 10, 30, 60, and 120 days of gas extraction.

After being extracted 10 days, the gas pressure in the coal seam is greater than 0.8 MPa, the gas in the coal seam before the excavation work quickly moves to the roadway, and the gas pressure decreases greatly. As the extraction time prolongs, the gas pressure gradient between the roadway wall and the coal seam decreases, the gas migration speed in the square coal body before the tunneling work decreases, and the amount of gas transported in a short time is greatly

reduced. When the drainage time is 120 days, the gas pressure in the coal seam is reduced to about 0.3~0.4 MPa, the outburst risk is eliminated, and the outburst can be effectively controlled.

5. Drainage Effect during Field Application

The in situ experimental method is adopted to evaluate the remaining gas content and gas pressure. The remaining gas content and pressure are measured by setting gauges through the cross-layer boreholes in the floor roadway of

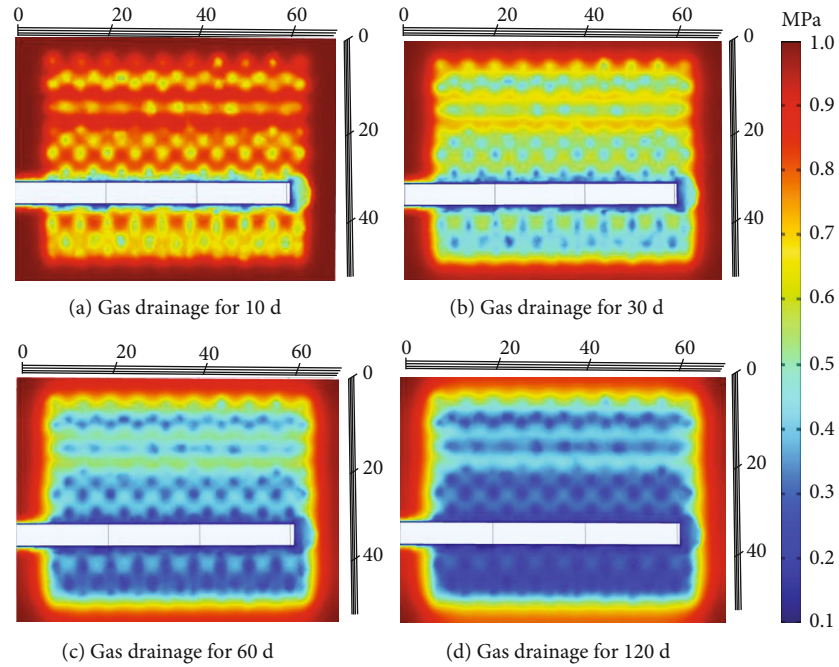


FIGURE 8: Gas pressure distribution when roadway drives 60 m with different extraction times.

TABLE 2: Measured results of gas pressure and gas content.

Drilling position	Drilling number	Vertical depth of measuring point (m)	Measuring point elevation (m)	Maximum pressure (MPa)	Gas content (m^3/t)
50 m inward from the opening of the floor roadway	B1-1	904	-654	0.3	5.0667
	B1-2	904	-654	0.35	4.7032
100 m inward from the opening of the floor roadway	B2-1	906	-656	0.25	4.8338
	B2-2	906	-656	0.3	4.1869
150 m inward from the opening of the floor roadway	B3-1	909	-659	0.4	5.4853
	B3-2	909	-659	0.5	4.733
200 m inward from the opening of the floor roadway	B4-1	910	-660	0.35	4.8716
	B4-2	910	-660	0.3	5.229
250 m inward from the opening of the floor roadway	B5-1	911	-661	0.3	5.0219
	B5-2	911	-661	0.4	5.6859
300 m inward from the opening of the floor roadway	B6-1	913	-663	0.45	4.5965
	B6-2	913	-663	0.4	4.3454
350 m inward from the opening of the floor roadway	B7-1	915	-665	0.3	5.1005
	B7-2	915	-665	0.3	4.8301
400 m inward from the opening of the floor roadway	B8-1	918	-668	0.4	5.0038
	B8-2	918	-668	0.5	4.9156
450 m inward from the opening of the floor roadway	B9-1	918	-668	0.3	5.2622
	B9-2	918	-668	0.4	5.0408
500 m inward from the opening of the floor roadway	B10-1	920	-670	0.3	5.2569
	B10-2	920	-670	0.35	5.1177

the roadway 31020 for air intake. It is judged that the regional outburst prevention measures are effective when the remaining gas content and the residual gas pressure are less than $6 \text{ m}^3/\text{t}$ and 0.6 MPa, respectively. If the remaining

gas content is greater than or equal to $6 \text{ m}^3/\text{t}$ or the remaining gas pressure is greater than or equal to 0.6 MPa, continue to implement regional outburst prevention measures until the regional standard is reached. A set of test boreholes are

constructed every 50 m at the opening of the low-level gas extraction roadway from 50 m to 500 m. 10 groups are arranged. The remaining gas content and pressure are shown in Table 2.

In the measured results, the coal seam gas pressure is reduced by ~75%, and the gas content is reduced by ~70.27% after implementing the integrated drillings and punchings from the floor roadway. The maximum gas pressure and maximum gas content are reduced to 0.5 MPa and 5.68 m³/t, respectively. There was no gas dynamic phenomenon during the excavation of the roadway 31020. This proves the established hydraulic-mechanical model and its application in numerical simulation of gas extraction by integrated drillings and punchings from the floor roadway in underground coal mines.

6. Conclusions

- (1) A hydraulic-mechanical coupling model of gas migration in coal seams was established, including the governing equations of the gas seepage field, water seepage field, and stress field, as well as porosity and permeability evolution equations. The influence of gas slippage effect and gas-water two-phase seepage was considered comprehensively
- (2) The process of gas extraction through the floor roadway through the integrated drillings and punchings was simulated, and the drainage results were used to reevaluate the outburst risk of roadway excavation. Results show that gas extraction can reduce coal seam gas pressure, slow down the rate of gas release, and effectively prevent outbursts
- (3) The integrated drillings and punchings from the floor roadway were adopted for engineering practice. The gas pressure in coal seam is lower than 0.5 MPa, while the gas content in coal seam is smaller than 5.68 m³/t

In future works, the effect of geological structure and heterogeneity of mechanical properties of coal seam on the efficiency of gas extraction by integrated drillings and punchings from the floor roadway may be considered in the hydraulic-mechanical coupling model.

Data Availability

The data used in this article were from the simulation results by COMSOL Multiphysics. The data are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This research was financially supported by the National Natural Science Foundation of China (Grant Nos. 52174117, 52004117, and 52074146), the Basic Research Project of

Key Laboratory of Liaoning Provincial Education Department (Grant No. LJ2020JCL005), the project supported by the Postdoctoral Science Foundation of China (Grant Nos. 2021T140290 and 2020M680975), and the project supported by the discipline innovation team of Liaoning Technical University (Grant no. LNTU20TD-03).

References

- [1] I. Palmer, "Coalbed methane completions: a world view," *International Journal of Coal Geology*, vol. 82, no. 3-4, pp. 184-195, 2010.
- [2] Y. Liang, F. Tian, B. Guo, and Z. Liu, "Experimental investigation on microstructure evolution and spontaneous combustion properties of aerobic heated coal," *Fuel*, vol. 306, p. 121766, 2021.
- [3] A. Zhou, M. Zhang, K. Wang, and D. Elsworth, "Near-source characteristics of two-phase gas-solid outbursts in roadways," *International Journal of Coal Science & Technology*, vol. 8, pp. 685-696, 2020.
- [4] C. Fan, S. Li, M. Luo, W. du, and Z. Yang, "Coal and gas outburst dynamic system," *International Journal of Mining Science and Technology*, vol. 27, no. 1, pp. 49-55, 2017.
- [5] E. Wang, X. Kong, S. Hu, Z. Li, and Q. Liu, "Multi-scale fractured coal gas-solid coupling model and its applications in engineering projects," *Transport in Porous Media*, vol. 121, no. 3, pp. 703-724, 2018.
- [6] T. Yang, B. Li, and Q. Ye, "Numerical simulation research on dynamical variation of permeability of coal around roadway based on gas-solid coupling model for gassy coal," *International Journal of Mining Science and Technology*, vol. 28, no. 6, pp. 925-932, 2018.
- [7] L. D. Connell, "Coupled flow and geomechanical processes during gas production from coal seams," *International Journal of Coal Geology*, vol. 79, no. 1-2, pp. 18-28, 2009.
- [8] D. Rudakov and V. Sobolev, "A mathematical model of gas flow during coal outburst initiation," *International Journal of Mining Science and Technology*, vol. 29, no. 5, pp. 791-796, 2019.
- [9] W. C. Zhu, C. H. Wei, J. Liu, H. Y. Qu, and D. Elsworth, "A model of coal-gas interaction under variable temperatures," *International Journal of Coal Geology*, vol. 86, no. 2-3, pp. 213-221, 2011.
- [10] T. Xia, F. Zhou, J. Liu, and F. Gao, "Evaluation of the pre-drained coal seam gas quality," *Fuel*, vol. 130, pp. 296-305, 2014.
- [11] T. Xia, F. Zhou, J. Liu, S. Hu, and Y. Liu, "A fully coupled coal deformation and compositional flow model for the control of the pre-mining coal seam gas extraction," *International Journal of Rock Mechanics and Mining Sciences*, vol. 72, pp. 138-148, 2014.
- [12] H. Wang, E. Wang, Z. Li et al., "Study on sealing effect of pre-drainage gas borehole in coal seam based on air-gas mixed flow coupling model," *Process Safety and Environmental Protection*, vol. 136, pp. 15-27, 2020.
- [13] T. H. Yang, T. Xu, H. Y. Liu, C. A. Tang, B. M. Shi, and Q. X. Yu, "Stress-damage-flow coupling model and its application to pressure relief coal bed methane in deep coal seam," *International Journal of Coal Geology*, vol. 86, no. 4, pp. 357-366, 2011.

- [14] F. Gao, Y. Xue, Y. Gao, Z. Zhang, T. Teng, and X. Liang, "Fully coupled thermo-hydro-mechanical model for extraction of coal seam gas with slotted boreholes," *Journal of Natural Gas Science and Engineering*, vol. 31, pp. 226–235, 2016.
- [15] J. Liu, L. Z. Xie, B. He, Q. Gan, and P. Zhao, "Influence of anisotropic and heterogeneous permeability coupled with in-situ stress on CO₂ sequestration with simultaneous enhanced gas recovery in shale: quantitative modeling and case study," *International Journal of Greenhouse Gas Control*, vol. 104, article 103208, 2021.
- [16] Z. Wei, W. Kai, Z. Rong, D. Huzi, L. Zhen, and A. Fenghua, "Influence of combination forms of intact sub-layer and tectonically deformed sub-layer of coal on the gas drainage performance of boreholes: a numerical study," *International Journal of Coal Science & Technology*, vol. 7, no. 3, pp. 571–580, 2020.
- [17] T. Lin, X. Liu, J. Zhang et al., "Characterization of multi-component and multi-phase fluids in the Upper Cretaceous oil shale from the Songliao basin (NE China) using T1–T2NMR correlation maps," *Petroleum Science and Technology*, vol. 39, no. 23–24, pp. 1060–1070, 2021.
- [18] R. Yuan, C. Chen, X. Wei, and X. Li, "Heat–fluid–solid coupling model for gas-bearing coal seam and numerical modeling on gas drainage promotion by heat injection," *International Journal of Coal Science & Technology*, vol. 6, no. 4, pp. 564–576, 2019.
- [19] W. C. Zhu, J. Liu, J. C. Sheng, and D. Elsworth, "Analysis of coupled gas flow and deformation process with desorption and Klinkenberg effects in coal seams," *International Journal of Rock Mechanics and Mining Sciences*, vol. 44, no. 7, pp. 971–980, 2007.
- [20] G. Hu, H. Wang, X. Fan, Z. Yuan, and S. Hong, "Mathematical model of coalbed gas flow with Klinkenberg effects in multi-physical fields and its analytic solution," *Transport in Porous Media*, vol. 76, no. 3, pp. 407–420, 2009.
- [21] C. Fan, S. Li, D. Elsworth, J. Han, and Z. Yang, "Experimental investigation on dynamic strength and energy dissipation characteristics of gas outburst prone coal," *Energy Science & Engineering*, vol. 8, no. 4, pp. 1015–1028, 2020.
- [22] T. Liu, B. Lin, X. Fu, Y. Gao, and W. Yang, "Modeling coupled gas flow and geomechanics process in stimulated coal seam by hydraulic flushing," *International Journal of Rock Mechanics and Mining Sciences*, vol. 142, article 104769, 2021.
- [23] Q. Q. Liu, Y. P. Cheng, W. Li, and W. Zhao, "Mathematical model of coupled gas flow and coal deformation process in low-permeability and first mined coal seam," *Chinese Journal of Rock Mechanics and Engineering*, vol. S1, pp. 2749–2758, 2015.
- [24] C. Fan, D. Elsworth, S. Li et al., "Modelling and optimization of enhanced coalbed methane recovery using CO₂/N₂ mixtures," *Fuel*, vol. 253, pp. 1114–1129, 2019.
- [25] P. Thararoop, Z. T. Karpyn, and T. Ertekin, "Development of a multi-mechanistic, dual-porosity, dual-permeability, numerical flow model for coalbed methane reservoirs," *Journal of Natural Gas Science and Engineering*, vol. 8, no. 9, pp. 121–131, 2012.
- [26] C. R. Clarkson and F. Qanbari, "Transient flow analysis and partial water relative permeability curve derivation for low permeability undersaturated coalbed methane wells," *International Journal of Coal Geology*, vol. 152, pp. 110–124, 2015.
- [27] Y. Wu, J. Liu, D. Elsworth, X. Miao, and X. Mao, "Development of anisotropic permeability during coalbed methane production," *Journal of Natural Gas Science and Engineering*, vol. 2, no. 4, pp. 197–210, 2010.
- [28] C. J. Fan, L. Yang, G. Wang, Q. M. Huang, X. Fu, and H. O. Wen, "Investigation on coal skeleton deformation in CO₂ injection enhanced CH₄ drainage from underground coal seam," *Frontiers in Earth Science*, vol. 9, article 766011, 2021.
- [29] Q. Zou, H. Liu, Z. Jiang, and X. Wu, "Gas flow laws in coal subjected to hydraulic slotting and a prediction model for its permeability-enhancing effect," *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, pp. 1–15, 2021.
- [30] G. Li and J. Teng, "Research and optimization of gas extraction by crossing-seam boreholes from floor roadway," *Geofluids*, vol. 2021, Article ID 7499012, 10 pages, 2021.