

Research Article

Study of the Law of Hydraulically Punched Boreholes on Effective Gas Extraction Radius under Different Coal Outputs

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Hydraulic punching technology has recently developed into an effective pressure relief measure and permeability enhancement method for soft and low permeability coalbeds. Different coal outputs directly affect the shape and size of boreholes as well as the effective extraction radius. Taking the Zhongmacun mine as an example, the influence of different coal outputs and different extraction periods on effective extraction radius was analyzed and studied through field tests and numerical simulation. The results show that the increase in coal outputs from hydraulic punching can improve the effective extraction radius of the boreholes. For example, when the gas extraction reaches 90 days, with a coal output of 0.5 t/m, 1.0 t/m, and 1.5 t/m, the effective extraction radius is 3.08 m, 3.46 m, and 3.83 m, respectively. The difference in gas extraction effect of different coal output boreholes increases significantly with the extension of the extraction time, but the speed of growth gradually decreases, which is consistent with the conclusions obtained on-site. This result has important practical significance for optimizing the technical parameters of hydraulic punching, guiding the accurate layout of extraction and drilling, and enhancing the effect of gas control in mines.

1. Introduction

Coalbed methane (CBM) is one of the main factors restricting the safe production of coal in underground coal mines, but it is also a form of high-quality energy that can be used in many fields such as power generation, heating, and chemical industries. Therefore, extracting gas safely and efficiently can not only reduce the gas content substantially, thereby reducing the probability of dynamic gas disasters during coal production, but it can also be used as a low-pollution energy source [1–3]. Due to mine burial conditions, more than 95% of the high gas content coalbeds and outburst mines across China feature heterogeneity, micro-porosity, low permeability, and high adsorption [4], with a permeability rate of about 10^{-18} – 10^{-19} m² in most cases. The

low permeability and heterogeneity of a coalbed can make it difficult to extract gas effectively [5, 6]. However, for a single high outburst coalbed without protective layer mining, the main method of gas control is by extracting gas through drilling [7]. In order to increase the gas extraction rate, shorten the preextraction time, and reduce the number of boreholes, measures must be taken to increase the gas permeability of the coal seam [8]. Therefore, scholars have proposed a variety of drilling pressure relief and permeability enhancement technologies, such as deep-hole blasting, hydraulic fracturing, hydraulic punching, and hydraulic slotting [9–13], which have improved the efficiency of gas extraction in China to a certain extent. With the increasing development of high-pressure water jet, hydraulic technology including hydraulic punching and hydraulic slotting

has been widely used in solving the gas extraction problem in low permeability coal seams in recent years [1]. Hydraulic slotting is to cut the coal by high-pressure water jets to form slots around the borehole, thereby broadening the scope of influence of the borehole, improving gas flow, and increasing coal seam permeability. However, it has poor continuity in soft coal seams.

Hydraulic punching technology utilizes rock lanes as safety barriers. Firstly, a high-pressure water jet is pushed through a borehole and is used to break the coal mass, and a large amount of coal mass is flushed out within a certain period of time to form a hole with a larger diameter, thus disrupting the original stress balance of the coal mass. The coal mass around the hole is displaced towards the direction of the hole, which causes the stress to be redistributed, the concentrated stress zone to move forward, and the effective stress to decrease. Secondly, the new cracks in the coalbed and the reduction in stress level break the dynamic balance between gas adsorption and gas desorption, so that part of the adsorbed gas is converted into free gas. The free gas is discharged by means of fissure migration, which releases the elastic potential and gas expansion energy in the coal mass and surrounding rocks to a large extent. As a result, the gas permeability of the coalbed is significantly improved. Finally, when high-pressure water wets the coal mass, its plasticity increases and brittleness decreases, which reduces the desorption rate of the residual gas in the coal mass. In the process of hydraulic punching, a large amount of gas and a certain amount of coal are flushed out, so an area of pressure relief and gas discharge is formed in the coal mass. In this safe area, the basic conditions required for the occurrence of outbursts are removed and effective gas outburst prevention is achieved. The technical process is shown in Figure 1. However, in some areas where the coalbed is soft and has low permeability, the efficacy of some permeability enhancement technologies are limited; in such cases, hydraulic punching technology can achieve better effects in permeability enhancement and is one of the widely used methods [1], which is the method that has been used in this study.

After utilizing hydraulic punching technology, the amount of coal output through the boreholes is increased significantly and per unit of coal output through the boreholes varies greatly. As a result, the scope and degree of pressure relief of a borehole differ after punching, and the effective extraction radius of the borehole varies. Therefore, it is necessary to carry out a study on the influence of different effective extraction radius on coal output, which can provide a theoretical and practical basis for optimizing the hydraulic punching process parameters and enhancing the gas control effect of mines.

2. Theoretical Basis for Determining the Effective Influence Radius of Borehole Gas Extraction

The effective influence radius of gas extraction in a borehole refers to the minimum range within which a single borehole can reach the gas extraction target along its radius within a certain time [14]. At present, the commonly used methods for measuring the effective extraction radius of boreholes are

based on pressure reduction [15] and content reduction of gas. As the method using pressure reduction requires on-site measurement [16] of gas pressure, it has many disadvantages such as longer measurement period, higher cost, and lower accuracy. Moreover, the Zhongmacun mine produces anthracite with strong adsorption capacity and shows characteristics of low gas pressure and high gas content, and hence, the method of content reduction is adopted. This method is based on the original gas content and residual gas to determine the gas extraction rate. Finally, the effective extraction radius of the boreholes can be determined when these values are considered along with the total amount of gas extraction from boreholes during a certain period of time.

The effective extraction radius of boreholes is mainly influenced by gas content, air permeability coefficient, borehole diameter, negative extraction pressure, extraction target, extraction time, etc. We aim to measure the effective extraction radius of the borehole under the condition of hydraulic punching, in this paper. The boreholes formed by hydraulic punching show inhomogeneity, and hence, hydraulic punching needs to be carried out in accordance with the same operating standard. It is considered that the formed boreholes are homogeneous cylinders, based on which the effective extraction radius of the boreholes can be investigated.

The extraction targets are determined in accordance with the Coal Mine Safety Rules [17] and the Detailed Rules for Prevention and Control of Coal and Gas Outburst [18].

2.1. Gas Extraction Rate. According to the extraction standard, it is considered that the standard has been met when the gas content falls below $8 \text{ m}^3/\text{t}$ and gas pressure falls below 0.74 MPa . The calculation formulas for gas extraction rate are as follows:

$$\eta_1 = \frac{W - 8}{W} \times 100\%, \quad (1)$$

$$\eta_2 = \frac{W - W_{0.74}}{W} \times 100\%, \quad (2)$$

$$\eta = \max(\eta_1, \eta_2), \quad (3)$$

where W is the original coal seam gas content, measured in m^3/t ; $W_{0.74}$ is the coal seam gas content when the gas pressure drops to 0.74 MPa , in m^3/t ; η is the coal seam gas extraction rate, in %; η_1 is the gas extraction rate when the coal seam gas content drops to $8 \text{ m}^3/\text{t}$, in %; and η_2 is the gas extraction rate when the coal seam gas pressure drops to 0.74 MPa , in %.

According to the characteristics of high gas occurrence and low gas pressure in the Zhongmacun mine, we take $\eta = \eta_1$.

2.2. Cumulative Quantity of Gas Extraction. According to the gas flow theory, the relationship between gas extraction quantity and time conforms to the law of exponential function [19]. In practical applications, the relationship

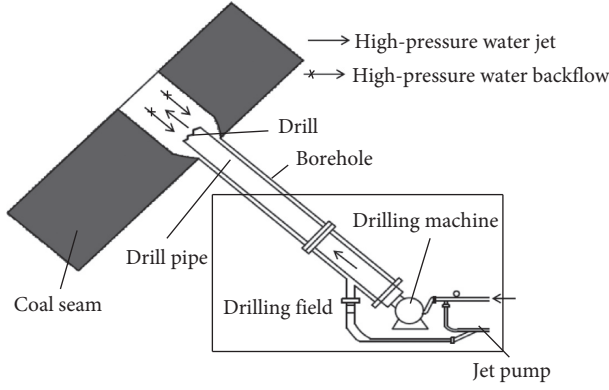


FIGURE 1: Schematic diagram of hydraulic punching equipment and technical process.

between gas extraction quantity Q and time t at any time is as follows:

$$Q = Q_0 e^{-nt}, \quad (4)$$

where Q_0 is the initial gas extraction volume per meter of the borehole, measured in m^3/m , and n is the attenuation coefficient of borehole gas flow.

By integrating formula (4), the relationship between cumulative gas extraction quantity Q_t and time can be obtained as follows:

$$Q_t = \int_0^t 2460Q_0 e^{-nt} dt = 1440Q_0 \frac{(1 - e^{-nt})}{a}. \quad (5)$$

2.3. Extraction Radius. According to the law of conservation of mass,

$$\int_{r_1}^{r_2} 2\pi r L \rho M \eta dr = Q_t, \quad (6)$$

where r is the gas extraction radius, in m; L is punching length, in m; ρ is coal density, in kg/m^3 ; r_2 is effective extraction radius, in m; and r_1 is drilling radius, also in m.

By integrating formula (6) as follows:

$$r_2^2 - r_1^2 = \frac{Q_t}{(\pi L \rho M \eta)}. \quad (7)$$

Since the borehole radius is very small when compared with the extraction radius, we omit the second-order infinitesimal and obtain

$$r_2 = \sqrt{\frac{Q_t}{(\pi L \rho M \eta)}}. \quad (8)$$

3. Field Testing of Effective Extraction Radius with Different Coal Outputs

3.1. Overview. The Zhongmacun mine, located in Jiaozuo, Henan Province, is a mine that has serious coal and gas outbursts incidents. The mineable coal seam in this mine is II₁, i.e., the No. 1 coal bed of the 2nd member of Lower

Permian Shanxi Fm; this seam has a mean obliquity of 12° , coal seam thickness of 0.1–13.53 m, and average thickness of 4.90 m. There have been many coal and gas outbursts accidents in the mine from the time it was established. During these accidents, the maximum coal outburst quantity was 900 t, the maximum gas content was $1.285 \times 10^5 \text{ m}^3$, the measured content of raw coal and gas was 2.67 to $36.65 \text{ m}^3/\text{t}$, the gas pressure was 0.29 to 1.56 MPa, the absolute gas emission rate was 45–55 m^3/min , the relative gas emission rate was 30 to 40 m^3/t , and the permeability coefficient of the coal seam was $1.08 \text{ m}^2/\text{MPa}^2 \cdot \text{d}^{-1}$.

Gas extraction in this mine is mainly conducted to prevent regional outbursts of gas extraction during crossing-measure. With reference to the mining-excavation relay and drilling construction plan, the second section of the 27001-floor return airway in the No. 27 mining area of the Zhongmacun mine was selected as the test site. The gas extraction borehole of this mine tunnel was designed in 5 sections. As shown in Figure 2, the working face 27001 is located in the upper part of the west wing of the No. 27 mining area. The working face has a strike length of 747 m and an oblique length of 171 m. The thickness of the coal seam in the second test section of the 27001-floor return airway is 2 to 5 m, and the average coal thickness is 3 m. The inclination angle of the coal seam is 8° to 17° , the gas content of the coal seam is 18 m^3/t on average, and the coal firmness coefficient f is 0.2 to 0.5.

3.2. Project Design. Three groups of hydraulic punching boreholes in the second section of the 27001-floor return airway were designated for investigation. To reduce the influence among boreholes, the distance between each group of boreholes was kept as 15 meters, as shown in Figures 3 and 4; there are 5 boreholes in each group among which the minimum distance is 23 meters. The borehole design parameters are shown in Table 1. Hydraulic punching operation requirements are as follows: punching pressure 3 MPa; drilling and punching time per meter 1 h. After punching is completed, the holes are promptly sealed and the gas drainage concentration and flow rate are measured daily.

3.3. Test Result. There are three groups of data—1#, 2#, and 3#, based on the collected data on gas extraction concentration and flow rate of hydraulic punching from the field test; these collectively reveal the rule that the net quantity of gas extraction changes with time (Figure 5).

From the extraction data collected in the field test and the cumulative gas extraction quantity calculation methodology, we can obtain the function for gas extraction quantity per unit coal output and time, through fitting; then, the gas extraction quantity can be calculated with this function, and the extraction radius of the hydraulic punching hole can be obtained. Since the unit coal outputs of these three groups are different, while the coal quality, region condition, gas occurrence, construction technology, and other conditions are basically the same, it can be considered that the key factor resulting in the difference in effective

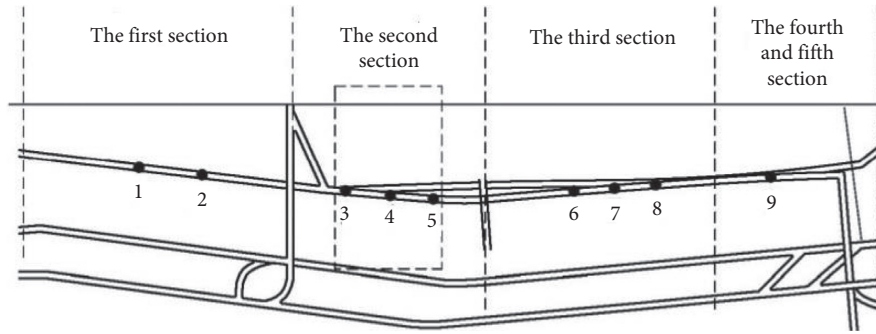


FIGURE 2: Location of the hydraulic punching test area of 27001-floor return airway.

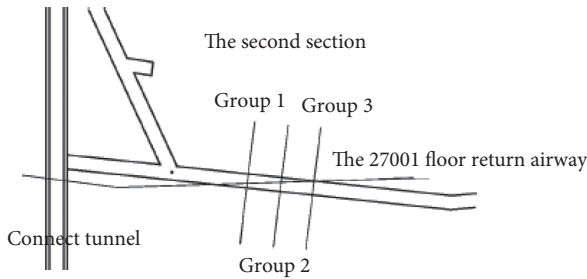


FIGURE 3: Investigation hole location for the effective extraction radius of hydraulic punching.

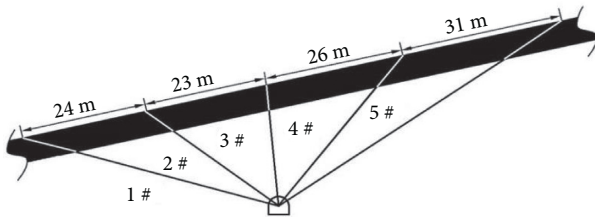


FIGURE 4: Borehole design profile.

extraction radius is the per unit coal output. Based on the coal output of each borehole, the corresponding relationship between effective extraction radius and per unit coal output for the three groups of hydraulic punching boreholes in different periods (30 days, 90 days, and 180 days) is obtained (Figure 6).

It can be seen from Figure 6 that the extraction radius of hydraulic punching increases with an increase in per unit coal output, the growth rate shows an attenuation trend, and the fitted linear relation conforms to the law of exponential function. Practical investigation of the boreholes' extraction radius distribution reveals that the extraction radius is relatively stable when the coal output is 0.5 to 1.5 t/m. Therefore, the standard of hydraulic punching coal output in the Zhongmacun mine should be 0.5 to 1.5 t/m. Based on the increase in the extraction radius during different periods, we can obtain the effective extraction radius of different coal outputs in different periods (Table 2).

Based on the above analysis, it can be seen that the effective extraction radius of the hydraulic punching borehole increases with the increase in the per unit coal output, however, the rate of the increment gradually

decreases. For example, when per unit coal output is 1.0 t/m and 180 days is taken as the extraction limit value, then the effective extraction radius is 3.31 m; the effective extraction radius for 30 days is 2.72 m, 82% of the limit value; the effective extraction radius for 90 days is 3.23 m, 98% of the limit value. Therefore, the optimal extraction period for the Zhongmacun mine should be 3 months. When the extraction time is 90 days, per unit of coal output of 0.5 t/m, 1.0 t/m, and 1.5 t/m correspond with the values of the extraction radius of 2.78 m, 3.23 m, and 3.53 m, respectively.

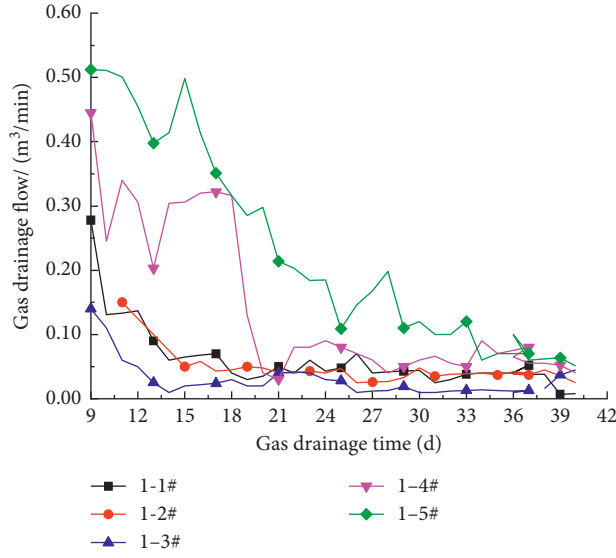
4. Numerical Simulation Analysis

To further analyze the influence of different coal outputs on extraction radius, this study uses COMSOL Multiphysics numerical simulation software to simulate and analyze the gas pressure distribution around the borehole after hydraulic punching and the consequent effective influence radius of gas extraction. In this method, it is essential to study the law of gas migration. Several theoretical studies have shown that gas migration is controlled by the seepage field and stress field, which is a process of coupling between gas seepage and coal seam deformation. Therefore, it is necessary to comprehensively analyze the controlling effect of the seepage field and stress field on gas migration in order to analyze the gas migration rule of coal around the borehole after hydraulic punching [20]. For this reason, we studied the stress distribution characteristics of the coal mass around boreholes established a fluid-structure interaction dynamic model of the extraction process and carried out numerical simulation analysis. The fluid-structure interaction dynamic model is mainly realized by the solid mechanics module in the COMSOL structural mechanics module and the custom equation.

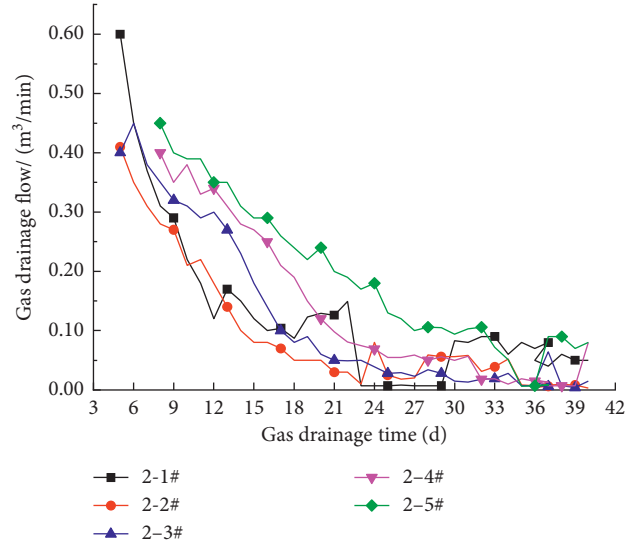
4.1. Basic Assumption. The flow of gas in a coalbed can be divided into the one-way flow, radial flow, and spherical flow based on the type of spatial flows; it can be divided into a steady flow field and an unsteady flow field from the characteristics of the flow timing. In this study, we assume that when the free gas in the coal mass seeps and causes an increase in the gas concentration gradient, the adsorbed gas is transformed into free gas instantly. We studied the gas migration from a macroperspective only,

TABLE 1: Borehole design parameters.

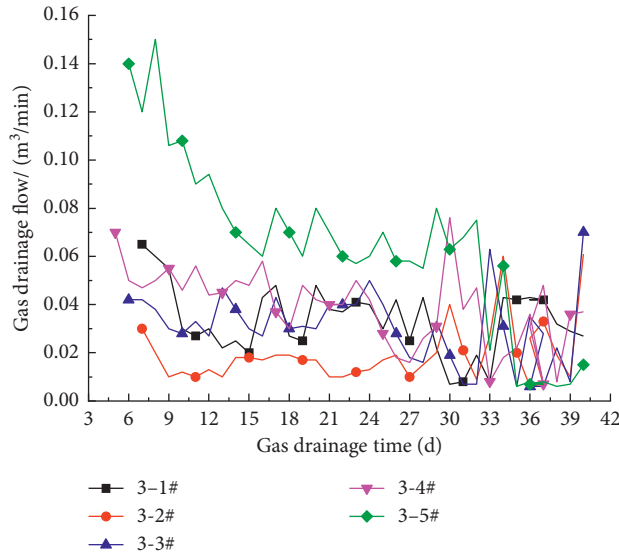
Drilling number	Inclination (°)	Azimuth (°)	Meeting coal point (m)	Borehole length (m)	Coal crossing section (m)
1-#	11	270	45.4	55.6	10.2
1-2#	38	270	22.4	27.7	5.3
1-3#	88	90	17.2	24.3	4.1
1-4#	51	90	27.4	33.7	6.3
1-5#	36	90	44.0	53.9	9.9



(a)



(b)



(c)

FIGURE 5: Three groups of borehole drainage gas flow attenuation quantity. (a) 1#, (b) 2#, and (c) 3#.

and the proposed hypotheses are as follows: there is only single-phase saturated gas fluid in the coalbed, and the coal mass is a uniform continuous medium; the change in coalbed gas pressure does not affect its permeability coefficient or the porosity rate of coal mass; the

permeability of the coalbed floor is very small so that gas only flows in the coalbed; the absorbed gas and free gas in the coal mass are subject to the modified Langmuir equation and the ideal gas law, respectively; the seepage law of gas in coalbed is in accordance with Darcy's law.

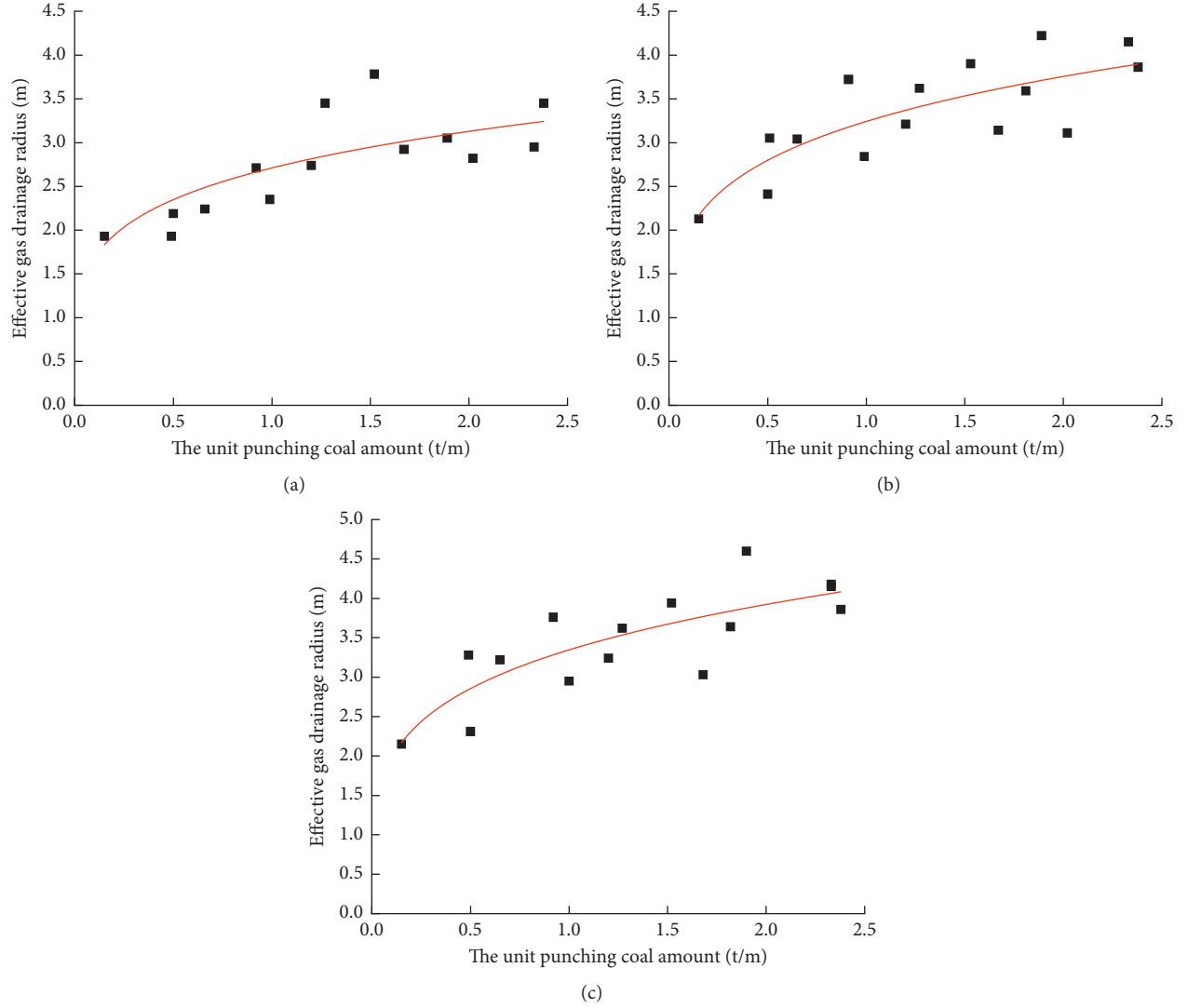


FIGURE 6: Correspondence between different coal output in different extraction periods and effective extraction radius. (a) 30 days. (b) 90 days. (c) 180 days.

TABLE 2: Parameters of effective extraction radius in different periods of the borehole with different coal outputs.

Coal output (t/m)	Effective borehole extraction radius (for different gas extraction time periods)		
	30 days (m)	90 days (m)	180 days (m)
0.5	2.33	2.78	2.85
1.0	2.72	3.23	3.31
1.5	2.95	3.53	3.60

4.2. Theoretical Model

4.2.1. Continuity Equation of Gas Flow in Coalbed.

According to the law of conservation of mass, the continuity equation of gas flow in the coal seam can be expressed as [21] follows:

$$\frac{\partial Q}{\partial t} + \nabla(\rho_g v_g) = 0, \quad (9)$$

where Q is coal gas content, in m^3/t ; ρ_g is coal seam gas density, in kg/m^3 ; v_g is Darcy seepage velocity, in m/s ; and t is time variable, in s .

The gas content is composed of two parts [22]: free gas and adsorbed gas, so it can be expressed as

$$Q = Q_g + Q_a = \varphi \rho_g + \frac{abc p \rho_n}{1 + bp}, \quad (10)$$

where Q_g is free content, in m^3/t ; Q_a is absorption content, in m^3/t ; φ is coal porosity, in %; a and b are Langmuir absorption constants, with the unit of m^3/kg and Pa^{-1} , respectively; c is correction coefficient, in kg/m^3 ; p is gas pressure, in Pa ; $p_n = \beta p$, p_n is the standard

atmospheric pressure, in Pa; and β is the gas compression coefficient, in $\text{kg}/(\text{m}^3 \cdot \text{Pa})$.

The process of gas seepage and migration in a coalbed conforms to Darcy's law. According to the gas seepage test [23], the Klinkenberg effect of gas seepage occurs in coalbeds. Therefore, the gas permeability equation of the coal mass around the punching hole can be obtained as follows:

$$2\alpha p \frac{\partial \varepsilon_v}{\partial t} + 2 \left(\varphi + \frac{abc p_n}{(1+bp)^2} - \frac{2ab\rho_s RT p (1-\varphi_0)}{3V_m k_s (1+bp)} + \frac{(1-\varphi_0)p}{k_s} \right) \frac{\partial p}{\partial t} - \nabla \left(\frac{k}{\mu} \left(1 + \frac{m}{p} \right) 2p \cdot \nabla p \right) = 0. \quad (12)$$

4.2.2. Coupling Model of Porosity and Permeability. According to the definition of porosity and considering the influence of temperature and coal gas adsorption on the deformation of coal and rock mass, the deformation of the coal and rock skeleton affected by the change of free gas pressure results in the change of porosity as follows [24]:

$$\varphi = 1 - \frac{1-\varphi_0}{1+\varepsilon_v} \left(1 - \frac{p_0-p}{k_s} + \frac{2a\rho_s RT}{3V_m k_s} \ln(1+bp) \right), \quad (13)$$

where p_0 is initial gas pressure, in MPa; ε_v is volumetric strain of coal mass; V_m is molar volume, 22.4 L/mol; k_s is bulk modulus; and ρ_s is the apparent density of coal, in kg/m^3 .

Similarly, permeability is also dynamic [25], and k equation of permeability can be obtained as follows:

$$k = \frac{k_0}{1+\varepsilon_v} \left\{ 1 + \frac{\varepsilon_v}{\varphi_0} + \left(\frac{1-\varphi_0}{\varphi_0} \right) \left(\frac{p_0-p}{k_s} - \frac{2a\rho_s RT}{3V_m k_s} \ln(1+bp) \right) \right\}^3, \quad (14)$$

where k is the coupling permeability.

4.2.3. Governing Equation of Coal Deformation in the Process of Gas Extraction from the Borehole. As the formation of coal is influenced by many factors, consequently, coal has a certain degree of heterogeneity. However, from a macro-point of view, it can be assumed that coal is homogeneous in a large area, except for geological structural zones such as faults. The equilibrium equation of the coal unit, geometric equation, and the constitutive equation can be established based on the principle of effective stress [26]. Plugging the geometric equation and constitutive equation into the equilibrium equation, the Governing Equation of Coal Deformation can be obtained as follows:

$$G \sum_{j=1}^3 \frac{\partial^2 u_i}{\partial x_j^2} + \frac{G}{1-2\nu} \sum_{j=1}^3 \frac{\partial^2 u_j}{\partial x_j \partial x_i} + \left(\alpha - \frac{(3\lambda-2G)}{3K_s} \right) \frac{\partial p}{\partial x_i} + F_i = 0, \quad (15)$$

where ν is Poisson's ratio; G is Lamé constant and F_i is volume force.

4.3. Geometric Model and Boundary Conditions. Based on the experience of using hydraulic punching in coal mines across

$$v_g = -\frac{k}{\mu} \left(1 + \frac{m}{p} \right) \nabla p. \quad (11)$$

Combining equations (9)–(11), the seepage field equation can be obtained as follows:

China, the effective extractive radius is generally 3 m to 10 m. Taking the practical field data of the bottom roadway of 27001 in the Zhongmacun mine as the basis, the thickness of the coal seam, and the cross-section of the strike direction as research objects, the size of the model is established as 80 m \times 23 m in length and width, respectively. The model is divided into four areas: roof flagstone, floor flagstone, middle coal seam, and hydraulic punching hole. The size of the roof and floor flagstones are both 80 m \times 10 m, and the size of the coal seam is 80 m \times 3 m. The hydraulic punching hole is simplified as a cylinder whose specific size is shown in Figure 7.

4.3.1. Initial Conditions and Boundary Conditions. Before conducting numerical simulation according to equations (12)–(15), it is necessary to set the boundary type and defining conditions, so that the coupling equation can obtain a unique solution. Based on the requirements, the requisite defining conditions are given as follows:

- (1) *Displacement Fixed Boundary.* The displacement of the model bottom does not change during the simulation.
- (2) *Free Boundary.* As the upper boundary of the model needs to be applied to the ground stress, the boundary is set as a free boundary; the boundary of the coal-rock boundary and the edge of the punched hole should be examined in terms of stress, strain, and displacement, and the free boundary.
- (3) *Roller Boundary.* The lateral pressure of coal and rock is transferred from the infinite to the roller boundary.

4.3.2. Boundary Conditions

- (1) The first kind of boundary condition is that the pressure on the boundary of the model is constant, and the pressure gradient is zero.
- (2) The second kind of boundary condition is that the pressure in the punched hole, which is constant and negative, is usually 20 kPa in the mine. The simulation uses 20 kPa.
- (3) The third kind of boundary condition is that the surrounding rock at the top and bottom of the coal

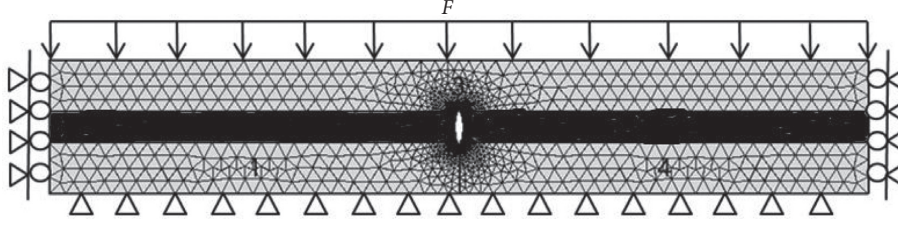


FIGURE 7: Geometric calculation model.

seam is airtight, and the gas flow at the boundary is zero.

Whether the physical parameters can be selected reasonably and correctly is of vital importance in ensuring the numerical simulation can effectively verify and guide the fieldwork. According to the above measurement results of the coal and rock parameters of the Zhongmacun mine, the basic parameters of fluid-structure interaction numerical simulation of hydraulic punching are determined, as shown in Table 3.

TABLE 3: Main model parameters.

Parameters	Symbol	Values	Unit
Adsorption constant a	A	32.37	m^3/t
Adsorption constant b	B	0.72	MPa^{-1}
Elasticity modulus	E	2.74	GPa
Bulk modulus	K_s	3.5	GPa
Poisson's ratio	ν	0.33	
Initial gas pressure	p_0	1.2	MPa
Standard atmospheric pressure	P_n	101	kPa
Initial permeability	K_0	4.2×10^{-17}	m^2
Temperature	T	293	K

4.4. Simulation Analysis of Effective Extraction Radius of Conventional Gas Extraction of Crossing Measure. Firstly, the built model needs to be verified. According to practical extraction experience in the Zhongmacun mine, under a 30 kPa negative pressure condition, the effective extraction radius is around 1.3 m with a borehole of 94 mm diameter when the extraction time is 3 months. Numerical simulations were carried out under these conditions, and the results are as shown in Figures 8 and 9.

According to the above figures, when the extraction time is 60 days, the gas pressure around the borehole is reduced to 0.74 MPa in the range of 1.32 m, that is, the effective extraction radius simulated by this model is 1.32 m, which is basically consistent with field measurement results.

4.5. Numerical Value of Effective Extraction Radius of Boreholes with Different Coal Outputs

4.5.1. Equivalent Aperture Radius of Hydraulic Punching. In the process of hydraulic punching, the final shapes of holes produced by the punching are irregular due to the variability in coal seam occurrence conditions. To facilitate the research on related problems of hydraulic punching, we simplified the shape of the punched hole into a cylindrical shape with the same diameter for the whole section, as shown in Figure 10. Equivalent aperture r_0 is an important parameter to measure the shape of the hole. The calculation method for hydraulic punching equivalent aperture r_3 is as follows:

$$\frac{m_1}{\gamma} + \pi \left(\frac{r_0}{2} \right)^2 L = \pi \left(\frac{r_3}{2} \right)^2 L. \quad (16)$$

After deformation,

$$r_3 = 2 \sqrt{\frac{m_1}{\pi \gamma L} + \left(\frac{r_0}{2} \right)^2}, \quad (17)$$

where m_1 is the coal output from hydraulic punching, in t; γ is the apparent density of coal, in t/m^3 ; the apparent density of the coal in the Zhongmacun mine is $1.38 \text{ t}/\text{m}^3$; r_0 is the borehole diameter before punching, in m; and L is the length of coal by hydraulic punching, in m.

Differences in coal output affect variation in the pressure relief range, which further affects the effective extraction radius. In the numerical simulation, the size of the aperture is the main dependent variable for analyzing stress and gas migration. The equivalent aperture of the hydraulic punching can be obtained using formula (17). The calculation results are shown in Table 4, which indicates the hole size corresponding to the coal outputs.

With other conditions unchanged, the extraction boreholes were changed to the above three types of apertures for numerical simulation, and then, the gas pressure distribution cloud maps of the single-hole extraction coal seam gas pressure for different extraction times were simulated. The results are shown in Figure 11.

It can be seen from Figure 11 that when gas extraction is conducted after hydraulic punching, the gas pressure increases along with the increase in distance from the borehole until it approaches the original gas pressure. However, influenced by the gas extraction borehole, the scope of effective influence of the extraction borehole is gradually expanded and the effective extraction radius also increases with the extension of extraction time and the expansion of the pressure relief scope around the boreholes.

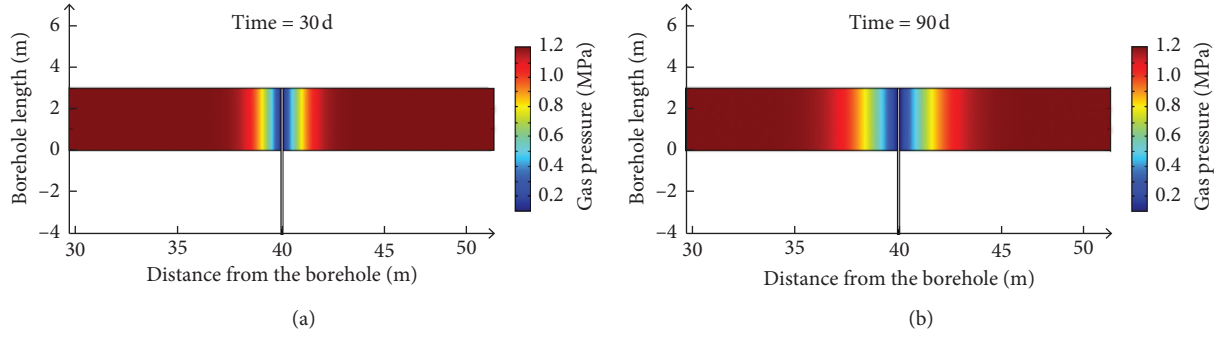


FIGURE 8: Cloud map of gas pressure when extracting gas from the borehole with 94 mm diameter. (a) Time = 30 d. (b) Time = 90 d.

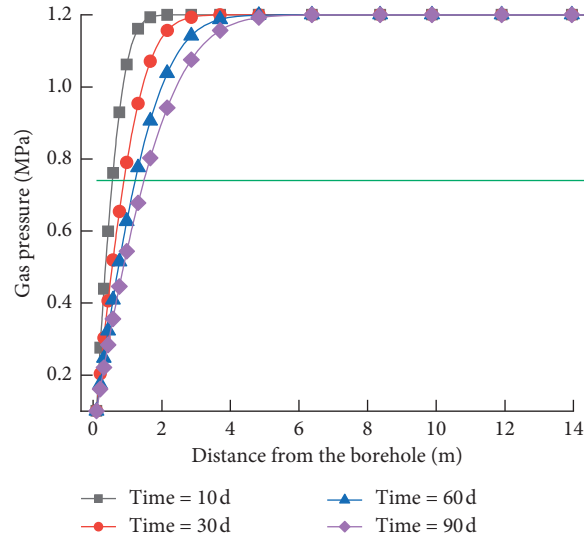


FIGURE 9: Gas pressure change curve when extracting gas from the borehole with 94 mm diameter.

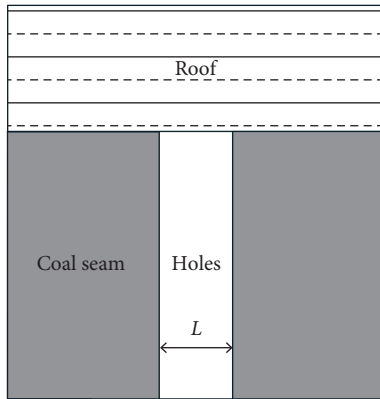


FIGURE 10: Equivalent aperture.

To fully investigate the influence of different coal outputs on the effective extraction radius of the gas extraction borehole, we take the line segment whose ends are (40, 1.5) and (55, 1.5) on the x -axis on the right side of the borehole as the monitoring line, select different calculation time in the

TABLE 4: The equivalent aperture of per unit coal output.

Coal output (t/m)	Equivalent aperture (m)
0.5	0.70
1.0	1.02
1.5	1.24

simulation results and draw the gas pressure isoline map for different coal outputs for different extraction periods for the gas pressure in the borehole. The results are as shown in Figure 12.

It can be seen from the simulation results that when the extraction time is fixed, the effective extraction radius is positively correlated with per unit coal output, that is, when the per unit coal output increases, the effective extraction radius increases gradually, however the rate of increase also weakens gradually. When per unit coal output is fixed, the effective extraction radius is positively correlated with the extraction period, that is, the effective extraction radius gradually increases as the drainage time increases. When the extraction time is 90 days, per unit

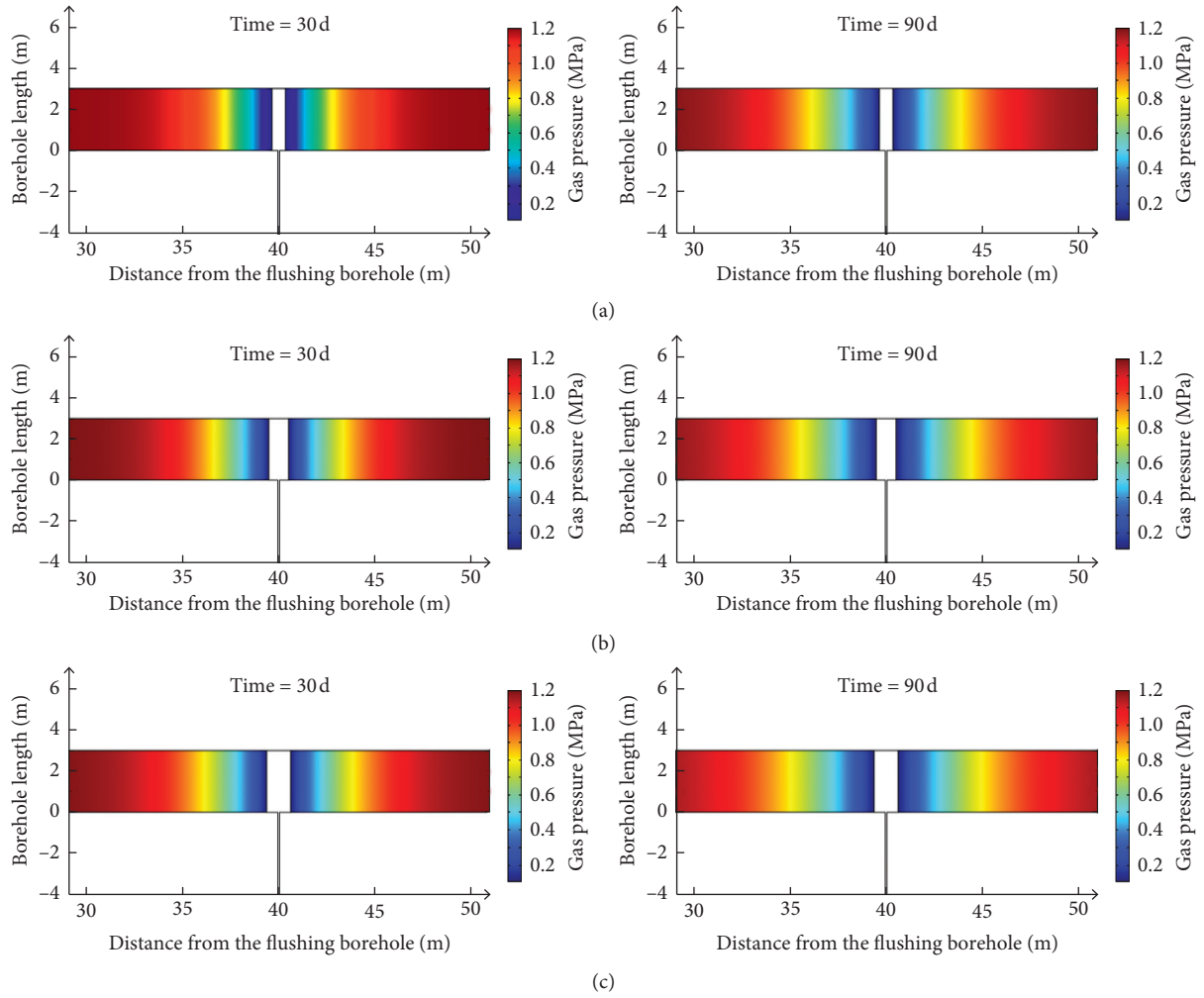


FIGURE 11: Cloud map of gas pressure distribution on the 30th and 90th day with different coal outputs. (a) Coal outputs = 0.5 t/m, (b) coal outputs = 1.0 t/m, and (c) coal outputs = 1.5 t/m.

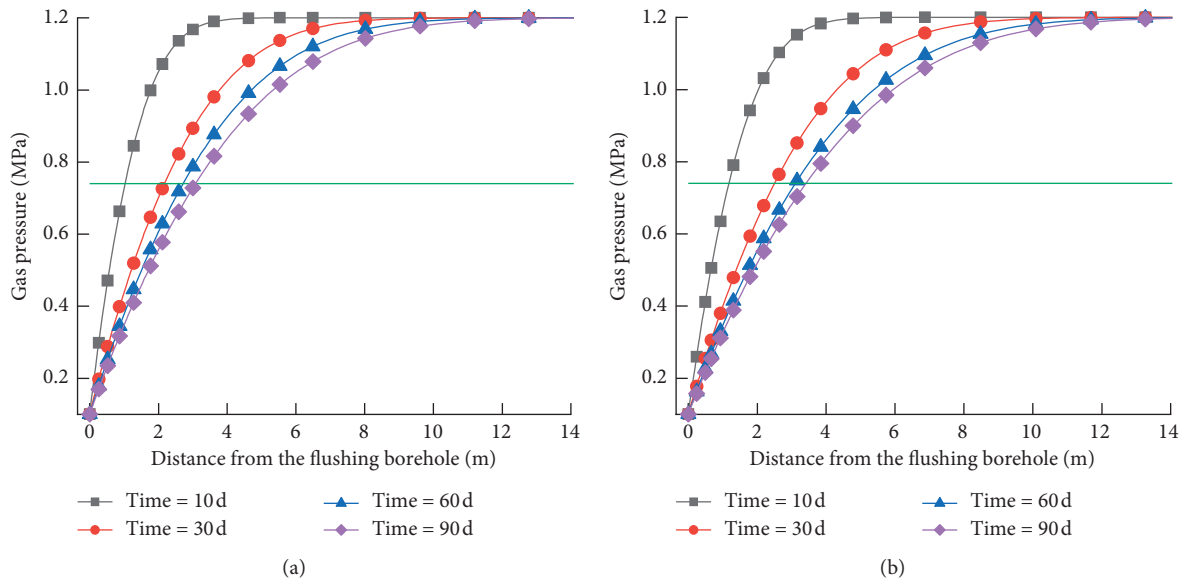


FIGURE 12: Continued.

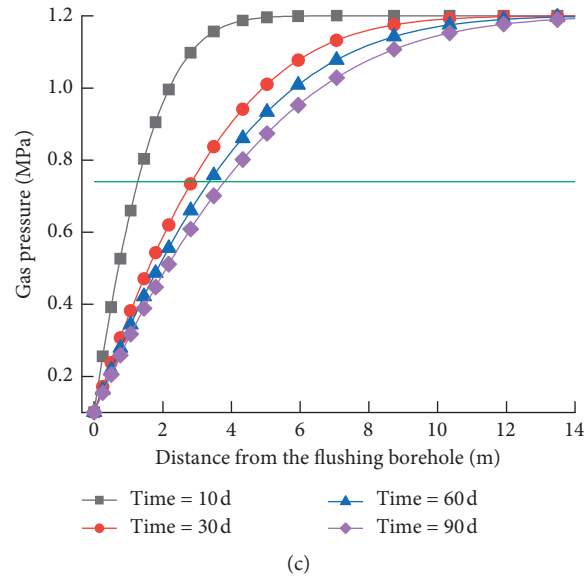


FIGURE 12: Gas pressure distribution curve with different coal outputs for different periods. (a) Coal outputs = 0.5 t/m, (b) coal outputs = 1.0 t/m, and (c) coal outputs = 1.5 t/m.

coal output of 0.5 t/m, 1.0 t/m, and 1.5 t/m correspond to an effective extraction radius of 3.08 m, 3.46 m, and 3.83 m, respectively.

5. Conclusion

- (1) The results of the field test and the numerical simulation show that when the extraction time is fixed, the effective extraction radius is positively correlated with per unit coal output, that is, when the per unit coal output increases, the effective extraction radius increases gradually, but the rate of increase weakens gradually. When per unit coal output is fixed, the effective extraction radius is positively correlated with the extraction time, that is, the effective extraction radius gradually increases as the drainage time increases.
- (2) It can be seen from the simulation results that when the extraction time is 90 days, per unit coal output of 0.5 t/m, 1.0 t/m, and 1.5 t/m correspond to an effective extraction radius of 3.08 m, 3.46 m, and 3.83 m, respectively, which are basically consistent with field test results.
- (3) The effect of hydraulic punching extraction can effectively be improved and the outburst risk can be eliminated by utilizing the influence law of different coal output on an effective extraction radius, by applying the per unit coal output determined on-site and rationally arranging the layout of the hydraulic punching boreholes.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

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

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