Theoretical, numerical, and experimental analysis of effective extraction radius of coalbed methane boreholes by a gas seepage model based on defined criteria

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Abstract
The effective extraction radius of borehole is the main parameter for determining the design and layout for coalbed methane extraction. This paper is aimed at the problem that the criteria and calculation methods for the effective extraction radius of coal seams are not comprehensive. With Wudong Coal Mine in China taken as an example, the critical gas pressure (0.441 MPa) for the calculation of effective extraction radius is first defined. Next, the gas seepage unit model around the borehole is developed, and the theoretical mathematical expression to calculate the effective extraction radius is derived. Then, the numerical simulation of gas extraction is carried out through a computational fluid dynamics program, and the effective extraction radius is obtained numerically. Furthermore, the influence of original gas pressure, borehole diameter, and negative pressure of gas extraction on gas extraction is analyzed. Finally, the results from the theoretical calculation and numerical simulation are validated by the field engineering measurement and the average relative error is small (less than 10%). The results indicate that the effective extraction radius has a linear relationship with the extraction time. Moreover, it is found that the original gas pressure is the main factor affecting the effective extraction radius and the effective extraction radius is proportional to the borehole diameter and negative pressure through analysis. Therefore, the above findings can provide a theoretical basis for determining parameters such as borehole spacing and extraction time of gas extraction in coal mines.

KEYWORDS
coalbed methane, computational fluid dynamics, effective extraction radius, gas flow model, gas pressure

1 INTRODUCTION
Coal industry serves an important role in the rapid growth of China's economy, and the increase in coal demand has brought an increase in the depth of mining. As a result, many disasters have occurred, causing a large number of casualties and property losses.1-6 Figure 1 shows a statistical chart of the causes for different coal mine accidents (eg, blasting, gas,
fire, floor, transportation, electromechanical, and other disasters) in China from 2007 to 2017. It indicates that the proportion of gas-related accidents is gradually increasing although the total number of accidents is declining year by year. Gas-related disasters are still considered to be the most serious disasters threatening the safety of coal mines in China. To ensure mine safety and efficient production, effective measures must be taken to control the occurrence of gas disasters.

It is well-known that the methane generated in coal seams is an efficient and clean source of energy. In recent years, coalbed methane (CBM) development has received special attention in areas with multiple coal seams. Several unconventional gas resources located in coal deposits have been studied as systems. At present, gas predrainage along coal seam boreholes is mainly used in China, which is also an effective method for coal seam gas recovery and gas disaster prevention and control in coal mines, as shown in Figure 2. The effective extraction radius of borehole is an important parameter for this method, which is used for the determination of borehole spacing in coal seams. If the gas extraction borehole spacing is too large, there will be extraction blind zones formed between extraction boreholes, bringing extremely large potential accidents to production in coal mines. If the gas extraction borehole spacing is too small, the gas extraction rate and gas extraction volume may be increased to a certain extent, but this will increase the borehole construction workload, resulting in an increase in the gas extraction cost. Therefore, the accurately determined effective extraction radius of coal seam boreholes is the key to increasing CBM production and reducing coal mine disasters.

At present, the main methods for calculating the effective extraction radius are theoretical calculation, field measurement, and numerical simulation. concluded that the extraction radius increased nonlinearly with the borehole radius, while Kong et al. found that the relationship between the extraction radius and the borehole radius was linear. This difference in research results is mainly due to the lack of in-depth discussion and unification of the effective extraction radius evaluation criteria. Actually, the main difference between different kinds of numerical simulation and theoretical analysis methods lies in the different ways of mathematical model development. Because of the complex geological conditions of coal seams, the gas occurrence of the same coal seam may vary greatly, and the results of numerical simulation or theoretical calculation often deviate from the actual situation. Although some errors may be generated in numerical simulation, they are within acceptable limits. It is undeniable that numerical simulation has become an important method to study the effective extraction radius. Researchers have established mathematical models to describe the laws of gas flow in coal seams around boreholes and have used the CFD software for numerical simulation to obtain the effective extraction radius of boreholes along coal seams.

Among the gas extraction test methods, the gas pressure method, gas content method, and gas tracer method are three common methods for measuring the effective extraction radius. The gas tracer method has low reliability, and thus, it cannot be used to analyze the degree of influence and obtain the effective extraction radius accurately. The gas content method is simpler than the gas pressure method in operation, but the results from it are not reliable and cross validation is needed. The gas pressure method is relatively easy for observation, and the results from it are more intuitive. According to the variation law of the gas extraction parameters with the extraction time, the extraction gas flow in coal seams can be obtained. At present, the measuring technology and testing instruments used to obtain gas parameters have been perfected. The variation of gas pressure with the extraction or mining pressure relief is continuously observed until the gas pressure measurement is completed. When the measured gas pressure drops to a safe range, the effective extraction radius of boreholes can be obtained more accurately.

**Figure 1** Statistics of coal mine accidents in China from 2007 to 2017
by the gas pressure method. In accordance with the Regulations on Prevention and Control of Coal and Gas Outburst, the effective extraction radius can be determined at the maximum gas pressure (0.74 MPa), the maximum gas content (8 m³/t), or the gas content decreased by more than 30%. However, most researchers only considered one or two of these criteria, not all the three criteria, to evaluate the effective extraction radius, which leads to inaccurate results.

In summary, existing studies show inadequacy in the following three aspects: (a) there is no unified standard for evaluating the extraction radius, resulting in little comparability between different studies. (b) The existing methods of calculating the effective extraction radius of coal seam gas are different, and the related research is not systematic and comprehensive. (c) There are relatively few field test studies on the effective extraction radius, and thus, there are very little reference data for numerical simulation and theoretical calculation. Therefore, this paper is aimed at studying the effective gas extraction radius around boreholes through theoretical calculation, numerical simulation, and field test. First, the gas pressure criterion for evaluating the gas extraction radius is established. Next, the theoretical mathematical model for determining the gas extraction radius is developed, and the CFD numerical simulation of the effective gas extraction radius of coal seam borehole is carried out. Then, the effective extraction radius is determined based on the variation of gas pressure in coal seam with the distance from the borehole center, and the influence of original gas pressure, borehole diameter, and negative pressure on gas extraction is analyzed. Finally, the gas pressure drop around the borehole is analyzed by field test, and the effective extraction radius is determined accordingly. The comparison of the effective extraction radius obtained by theoretical calculation and numerical simulation with that from the field measurement indicates that the average relative error is small. Therefore, the study in this paper can provide a basis for the design of gas extraction systems.

2 | DEFINITION OF EFFECTIVE GAS EXTRACTION RADIUS

2.1 | Engineering geology of Wudong Coal Mine

As shown in Figure 3, Wudong Coal Mine is located in the northeastern area of Urumqi, Xinjiang Province, China. The minefield is located in the southeastern part of Huainan coalfield specifically. There are Carboniferous, Permian, Triassic, Jurassic, Cretaceous, Tertiary, and Quaternary strata in this area. The mine is divided into south, north, and west mining areas with a designed annual production of 6 million tons. The Badaowan syncline in the northern mining area of Wudong Coal Mine is mined mainly in its northern flank. The coal-bearing strata are Xishanyao Formation of Middle Jurassic with a total thickness of 762.65 m. At present, the...
2.2 Criteria for calculating effective extraction radius

The radius range in which the gas pressure or content drops to an allowable safe value in a specified time is called the effective extraction radius. The Chinese government has specified two relevant criteria for evaluating the gas extraction effect. According to the Specification of Coal and Gas Outburst Prevention, mining operations should not be performed in coal seams where outburst hazards have not yet been eliminated, and a gas pressure criterion of 0.74 MPa or a gas content criterion of 8 m³/t is used to determine whether there are outburst hazards. The relationship between gas pressure and gas content can be expressed by the modified Langmuir equations as follows:

\[ W = \frac{abc \rho_n P}{(1 + bP)} + \frac{n \rho_n P}{P_n} \]  

where \( W \) is the gas content of coal seam, m³/t; \( P \) is the gas pressure of coal seam, MPa; \( a \) is the maximum value of adsorbed gas, m³/t; \( b \) is the constant amount of adsorbed gas, MPa⁻¹; \( c \) is the mass parameter of coal, and \( c = 1 - A_d - M_{ad} \). In which \( A_d \) is the ash content, \( M_{ad} \) is the water content, %; \( n \) is the coal porosity, %; \( P_n \) is the standard atmospheric pressure, MPa; \( \rho_n \) is the gas density at the gas pressure \( P_n \), kg/m³.

Wudong Coal Mine is a high gas mine, and thus, gas extraction and control should be carried out. From the laboratory measurement of the #43 coal seam in the 5004301 working face of this coal mine in this paper, the adsorption constant and industrial analysis parameters are obtained as shown in Table 1. The parabolic relationship between the residual gas content and the gas pressure after gas extraction can be obtained by combining Equation (1) and Table 1, as shown in Figure 4.

### Table 1 Parameters of gas adsorption constant and industrial analysis for #43 coal seam

| Coal mine | Coal seam | Industrial analysis | Adsorption constants of gas |
|-----------|-----------|---------------------|-----------------------------|
|           |           | \( M_{ad} \) (%)    | \( A_d \) (%)               | \( P_n \) (MPa) | \( \rho_n \) (kg/m³) | \( n \) (%) | \( a \) (m³/t) | \( b \) (m³/t) |
| Wudong    | #43       | 3.26                | 5.59                        | 0.101325      | 0.717                 | 6.43       | 30.7856       | 1.176         |

According to Figure 4, when the gas pressure is 0.74 MPa, the corresponding gas content is 9.69 m³/t, and when the gas content is 8 m³/t, the corresponding gas pressure is 0.53 MPa. For the sake of safety, 0.53 MPa is selected as the critical gas pressure value to investigate the gas extraction effect, and the corresponding critical gas content value is 8 m³/t. Coal seams in which the gas pressure is less than 0.53 MPa are defined as the effective influence zone of a borehole. This criterion can be described as:

\[ P_{c1} < 0.53 \text{ MPa} \]  

where \( P_{c1} \) is the residual gas pressure in coal seams.

The Coal Mine Safety Regulations specifies that the gas predrainage efficiency \( y \) must be greater than 30%, that is, the residual gas content after predrainage must be less than 70% of the original gas content. This can be expressed as:

\[ X_c < 70\%X \]  

where \( X_c \) is the residual gas content in coal seams and \( X \) is the original gas content in coal seams.

Within the limits of allowable errors in engineering, the relationship between the gas pressure and the gas content in coal seams follows the parabolic function:

\[ X = a \sqrt{P_0} \]  

where \( a \) is the coefficient of gas content and \( P_0 \) is the original gas pressure.

With Equations (3) and (4) combined, the second criterion can be expressed as:

\[ P_{c2} < 49\%P_0 \]  

where \( P_{c2} \) is the residual gas pressure of coal seam.

Therefore, the second criterion is that the index of the extraction radius is less than 49% of the original gas pressure.

Figure 5 shows the critical gas pressure for these two criteria. The red line represents the first criterion, which was used in some literatures, while the blue line represents the second criterion, which was adopted in other literatures. The two lines intersect where the original gas pressure \( P_0 \) is 1.08 MPa. When \( P_0 \) is less than 1.08 MPa, the second criterion \( \{ P_{c2} < 0.49P_0 \} \) is more severe, and when \( P_0 \) is greater
than 1.08 MPa, the first criterion \( P_{c1} < 0.53 \text{ MPa} \) is more severe. Therefore, the purple shaded area \( P_{c} < 0.49 P_{0} \) when \( P_{0} < 1.08 \text{ MPa} \) and the light blue shaded area \( P_{c} < 0.53 \text{ MPa} \) when \( P_{0} > 1.08 \text{ MPa} \) in Figure 5 satisfy the two criteria at the same time, namely \( P_{c} < 0.53 \text{ MPa} \cap \delta > 30\% \). The original gas pressure of the #43 coal seam measured at 2179 m head-on drilling site of the 5004301 working face for South Roadway of Wudong Coal Mine is about 0.9 MPa, less than 1.08 MPa. Therefore, the distance from the borehole center is defined as the effective gas extraction radius when the gas pressure of coal seam is reduced to 0.441 MPa.

3 | THEORETICAL CALCULATION OF EFFECTIVE EXTRACTION RADIUS

3.1 | Theoretical assumptions

Gas extraction is one of the main measures to prevent gas emission, regional outburst, and local outburst. The extraction radius of boreholes is an important parameter for rational design of extraction systems, and it is closely related to the law of gas flow in the coal seam around boreholes. Gas flow in coal seams is a very complicated seepage process, mainly including diffusion movement and laminar flow seepage movement. In order to develop the mathematical model for the relationship between the extraction radius and the extraction time, the mathematical relationship between the gas influx into the borehole and the gas outflow from the borehole for the gas migration around the borehole in coal seams needs to be described. To simplify the problem and highlight key points, the following assumptions are made \(^{30,48}\): (a) The surrounding rock of the coal seam roof and floor can be assumed impermeable and gas-free. (b) The original gas pressure around the borehole is uniformly distributed, and the original gas pressure, gas content, and temperature in the coal seam are the same at the same level. (c) The gas can be regarded as ideal gas, and the coal seam gas seepage is treated as an isothermal process, obeying the ideal gas state equation. (4) The adsorbed gas conforms to the Langmuir equation, and the time of coal seam adsorbed gas analysis can be neglected. (5) The gas seepage velocity in coal seams is low, the gas flow in coal seams obeys Darcy Law, the permeability of the coal seam around boreholes is isotropic, and the seepage process conforms to the conservation of mass. (6) The axial gas flow along the borehole is ignored, and the gas flow field around the borehole is regarded as an axisymmetric radial flow field.

3.2 | Theoretical model

Coal is a porous medium consisting of pores and cracks. Gas in coal seams is mainly extracted by flowing into borehole through pores and cracks of coal. Here a thin-walled unit around the borehole is taken for an example with the borehole radius \( r_{0} \), the length of borehole along the axis \( L \), the wall thickness \( dr \), and the variable radius of the radial flow field \( r \), as shown in Figure 6.

Assuming that at time \( t \), the gas pressure on the wall with radius \( r \) is \( P \) and the mass velocity is \( pv_{r} \). Then, the mass velocity on the wall with radius \( r + dr \) is:

\[
\rho v_{r} + \frac{\partial (\rho v_{r})}{\partial r} \text{dr}
\]

where \( \rho \) is the gas density at pressure \( P \), kg/m; \( r \) and \( dr \) is the radius and radius increment, respectively, m; \( v_{r} \) is the linear velocity of radial flow of gas, m/s.

When the time reaches \( t + dt \), the gas mass \( M_{1} \) flowing into the unit body in the \( dt \) time is as follows:

\[
M_{1} = 2\pi L(r + dr) \left( \rho v_{r} + \frac{\partial (\rho v_{r})}{\partial r} \text{dr} \right) dt
\]
When the time reaches \( t + dt \), the gas mass \( M_2 \) flowing out of the unit body in the \( dt \) time is as follows:

\[
M_1 = 2\pi rL(\rho v_r)dr
\]  
(8)

Assuming that the gas mass in the unit body is increased during the \( dt \) time, the gas mass increment \( \Delta M \) in the unit body during the \( dt \) time is as follows:

\[
\Delta M = M_1 - M_2 = 2\pi rL(r + dr) \left( \rho v_r + \frac{\partial(\rho v_r)}{\partial r}dr \right) dt - 2\pi rL(\rho v_r)dt
\]  
(9)

After Equation (9) is simplified and the higher order terms with \((dr)^2\) are neglected, the following equation is obtained:

\[
\Delta M = 2\pi rL \left[ \frac{\partial(\rho v_r)}{\partial r} + \frac{1}{r}(\rho v_r) \right] dr dt
\]  
(10)

From the change in gas content, the increment of gas mass in the \( dt \) time can also be expressed as follows:

\[
\Delta M' = \rho(\pi(r + dr)^2 - \pi r^2)L \frac{\partial w}{\partial t} dt = 2\pi rLdr \frac{\partial w}{\partial t} dt
\]  
(11)

where \( \frac{\partial w}{\partial t} \) is the rate of change in gas content.

According to the law of mass conservation in gas flow, Equations (10) and (11) can be combined into the following equation:

\[
\frac{\partial(\rho v_r)}{\partial r} + \frac{1}{r}(\rho v_r) = \rho \frac{\partial w}{\partial t}
\]  
(12)

Equation (12) is the continuity equation of gas flow in the radial flow field.

The French scientist, H. Darcy, pointed out that the seepage velocity of fluid in porous media has a linear relationship with the hydraulic gradient. The equation of Darcy’s law is as follows:

\[
v_r = \frac{k}{\mu} \frac{\partial P}{\partial r}
\]  
(13)

where \( k \) is the permeability of coal seam around boreholes, m²; \( \mu \) is the dynamic viscosity coefficient of gas, Pa·s; \( \frac{\partial P}{\partial r} \) is the pressure gradient of gas along the radial direction around boreholes.

The state equation of gas can be expressed as follows:

\[
\rho = \frac{M_g P}{RT} = \frac{\rho_n P}{P_n}
\]  
(14)

where \( M_g \) is the molecular weight of gas; \( R \) is the ideal gas constant, J/(mol·K); \( T \) is the absolute temperature of coal seam, K; \( P \) is the gas pressure of coal seam, MPa; \( P_n \) is the standard atmospheric pressure, MPa; \( \rho_n \) is the gas density at gas pressure \( P_n \), kg/m³.

The total gas content equation of adsorbed gas and free gas can be simplified as follows:

\[
W = \left( \frac{abcP_n}{1 + bP} + n \right) \rho
\]  
(15)

where \( \rho \) is the gas density at gas pressure \( P \), kg/m³.

With Equations (13), (14), (15), and (12) combined, the governing differential equation for the gas pressure function in the gas flow field of coal seam can be obtained, which varies with time and space.

\[
g(P) \cdot \left( \frac{\partial^2 P^2}{\partial t^2} + \frac{2}{r} \frac{\partial P^2}{\partial r} \right) = \frac{\partial P^2}{\partial t}
\]  
(16)

\[
g(P) = \frac{2P_n P \lambda}{n + \frac{abcP(2 + bP)}{(1 + bP)^2}}
\]  
(17)

Equation (16) is the dynamic governing equation for the unsteady radial seepage of gas flow around boreholes during borehole extraction. \( g(P) \) is a function of variable \( P \) where \( \lambda \) is the permeability coefficient of coal seam, \( \lambda = k/2\mu P_n \).
The permeability coefficient of coal seam around gas extraction boreholes can be expressed by the following equations:

\[ \lambda = (R_0 - r_0)\lambda_0(r_0 - r) \]  

(18)

where \( \lambda_0 \) is the initial permeability coefficient, m²/MPa²·d; \( R_0 \) is the maximum influence range of gas extraction from coal seam boreholes, m.

The equation for calculating the influence range \( R_0 \) of gas extraction from coal seam boreholes is as follows:

\[ R_0 = r_0 e \left( 2 \pi \lambda_0 \frac{P_0^2 - P^2}{q_0} \right) \]  

(19)

where \( P_0 \) is the original gas pressure, MPa; \( P_1 \) is the negative pressure of borehole extraction, kPa; \( q_0 \) is the initial gas flow rate per unit length of borehole, m³/d.

With the initial value condition and the boundary condition, the dynamic governing equation for the unsteady radial seepage of gas flow around borehole is obtained as follows:

\[
\begin{align*}
g(P) \left( \frac{\partial^2 P}{\partial r^2} + \frac{2}{r} \frac{\partial P}{\partial r} \right) &= \frac{\partial P^2}{\partial t}, \quad (t > 0, r_0 < r < R_0), \\
P^2 (r, t) \bigg|_{t=0} &= P_0^2 \quad (r_0 < r < R_0), \\
P^2 (r, t) \bigg|_{r=r_0} &= P_1^2 \quad (t \geq 0) \\
\frac{\partial P}{\partial r} \bigg|_{r=R_0} &= 0 \quad (t \geq 0)
\end{align*}
\]  

(20)

This equation is a second-order binary nonlinear partial differential equation, which is difficult to be solved. In order to obtain its approximate analytical solution, the variable substitution simplification is carried out. By using the Laplace integral transformation and complex variable function theory, the analytical solution of Equation (20) can be obtained:

\[
P(r, t) = \sqrt{P_1^2 + (P_0^2 - P_1^2) \text{erf} \left[ \frac{\ln \left( \frac{r}{r_0} \right)}{2 \sqrt{2 P_0 P_1 R_0 (r_0 - r)} + \sqrt{\frac{4 P_1^2 - P_0^2}{r_0 (r_0 - r)} \ln \left( \frac{r}{r_0} \right)}} \right]} \quad (0 \geq 0, \ r \geq r_0)
\]  

(21)

where \( \text{erf}(u) \) is a probability integral function whose value can be found from a number table.

Equation (21) is an expression of gas pressure distribution law in the radial flow field around extraction boreholes where the gas pressure \( P \) varies with the radius \( r \) of the radial flow field and the extraction time \( t \).

### 3.3 Theoretical calculation results

The calculation parameters in Equation (21) are determined according to the actual situation of the #43 coal seam in the 5004301 working face of Wudong Coal Mine, as shown in Table 2. The parameters in Table 2 are substituted into Equation (21), and the corresponding curves are calculated and plotted by the software Mathematica. These curves are used to analyze the variation of the gas pressure (\( P \)) with the extraction time (\( t \)) and the distance from the borehole center (\( r \)), and also used to find the effective extraction radius of boreholes, as shown in Figure 7.

From Figure 7, it can be concluded that the gas pressure increases with the increase of the distance from the borehole when the extraction time is fixed and that the gas pressure decreases with the increase of the extraction time when the distance from the borehole is fixed. As mentioned in Section 2, mining operations should not be performed in coal seams where outburst hazards have not yet been eliminated, and a gas pressure criterion of 0.441 MPa is used to determine whether there are outburst hazards. After calculation, the results show that when the extraction time is 20, 40, 60, 80, 100, and 120 days, respectively, the effective extraction radius is 0.91, 1.31, 1.74, 2.26, 2.77, and 3.02 m, respectively. Moreover, the fitting equation for the effective extraction radius and the extraction time is \( y = 0.02207x + 0.4567 \), and the goodness of fit is 0.9934, which is very close to 1. This indicates that the effective extraction radius has a linear relationship with the extraction time.

In order to study the effect of gas extraction under different original gas pressure conditions, the original gas pressure of coal seam is selected to be 0.4, 0.8, 1.2, 1.6, and 2 MPa with other parameters unchanged, as shown in Figure 8. Figure 8A,B shows the relationship between the distance from the borehole and the gas pressure for different original gas pressures for the extraction time of 60 days; Figure 8C,D shows the relationship between the extraction time and the gas pressure for different initial gas pressures for the distance from the borehole of 2 m. From Figure 8, it can be seen that the gas pressure around the borehole for coal seam extraction decreases with the decrease of the original gas, and the reduction range remains stable. For different original gas pressures, the curves for the relationship between the gas pressure of coal seam and the distance from the borehole, as well as those for the relationship between the gas pressure of coal seam and the extraction time, are basically consistent. According to the criterion of effective extraction radius in Section 2 (\( \{ P_e < 0.49 \ P_0 \ \text{when} \ P_0 < 1.08 \ \text{MPa} \} \) and \( \{ P_e < 0.53 \ \text{MPa when} \ P_0 > 1.08 \ \text{MPa} \} \), the effective extraction radius of boreholes increases first and then decreases as the original gas pressure of the coal seam increases. Therefore, the effective influence range of gas extraction through boreholes increases first and then decreases as the original gas pressure increases. In addition, the greater the original gas pressure,
the greater the gas content in coal seams, and the greater the amount of gas extracted. In order to study the effect of gas extraction for different borehole diameters, the borehole diameters are selected to be 93, 113, 133, 153, and 173 mm, respectively, as shown in Figure 9. Figure 9A,B shows the relationship between the distance from the borehole and the gas pressure for different borehole diameters for the extraction time of 60 days. Figure 9C,D shows the relationship between the extraction time and the gas pressure for different distances from the borehole of 2 m. Figure 9 indicates that the gas pressure around the borehole for coal seam extraction decreases with the increase of the borehole diameter, while the range of gas pressure relief remains basically unchanged.54 When the extraction time is fixed, with the increase of the borehole diameter, the overall trend of the effective extraction radius shows an increase, and the growth rate also shows an increase. At this time, the effective influence range of the borehole and the content of gas extracted increase gradually. Therefore, if the diameter of the borehole for gas extraction is within the range of 93-173 mm and the conditions permit construction, the diameter of the borehole for gas extraction can be increased to increase the gas extraction effect.

In order to study the effect of gas extraction under different negative pressure conditions, the negative pressure of borehole extraction is selected to be 11, 22, 33, 44, and 55 kPa with other parameters unchanged, as shown in Figure 10. Figure 10A,B shows the relationship between the distance from the borehole and the gas pressure under different negative pressure conditions for the extraction time of 60 days; Figure 10C,D shows the relationship between the extraction time and the gas pressure under different negative pressure conditions for the distance from the borehole of 2 m. As can be seen from Figure 10, with the increase of the negative pressure in the extraction borehole, the gas pressure decreases gradually while the gas pressure relief range increases gradually. When the negative pressure is increased from 11 kPa to 22 kPa, the pressure relief range of the gas in the extraction borehole is very small, and the gas pressure hardly changes. When the negative pressure is increased from 22 kPa to 33 kPa, 44 kPa, and 55 kPa the range of gas pressure relief increases, but the increase is very small. This indicates that the range of gas pressure relief cannot be increased simply by increasing the negative pressure of extraction. At the same time, with the increase of the negative pressure for extraction, the effective extraction radius increases gradually, that is, the

| Parameter                                      | Value       | Source       |
|------------------------------------------------|-------------|--------------|
| Initial permeability coefficient of coal seam $\lambda_0$ (m$^2$/MPa·d) | 0.0698      | Site data    |
| Maximum value of adsorbed gas $a$ (m$^3$/t)       | 30.7856     | Laboratory data |
| Constant amount of adsorbed gas $b$ (MPa$^{-3}$)  | 1.176       | Laboratory data |
| Ash content $A_d$ (%)                             | 5.59        | Laboratory data |
| Water content $M_{ad}$ (%)                        | 3.26        | Laboratory data |
| Borehole radius $r_0$ (mm)                        | 113         | Site data    |
| Negative pressure of borehole extraction $P_1$ (kPa) | 22          | Site data    |
| Initial gas flow rate per unit length of borehole $q_0$ (m$^3$/d) | 2.5         | Site data    |
| Maximum influence range of gas extraction from coal seam boreholes $R_0$ (m) | 29.25       | Equation (19)|
| Initial permeability $k_0$ (m$^2$)                | $2.5 \times 10^{-18}$ | Site data |
| Porosity of coal seam $n$ (%)                     | 6.34        | Site data    |
| Original gas pressure $P_0$ (MPa)                 | 0.9         | Site data    |
| Gas dynamic viscosity coefficient $\mu$ (MPa·d)   | $1.258 \times 10^{-16}$ | Site data |
| Standard atmospheric pressure $P_n$ (MPa)         | 0.101325    | Constant parameter |
| Initial gas density at standard atmospheric pressure $\rho_n$ (kg/m$^3$) | 0.717       | Kong et al$^{32}$ |
| Constant temperature of coal seam $T$ (K)         | 291         | Site data    |
| Young’s modulus of coal $E$ (GPa)                 | 2.71        | Site data    |
| Young’s modulus of coal grains $E_s$ (GPa)        | 8.43        | Laboratory data |
| Poisson’s ratio $\nu$                             | 0.32        | Laboratory data |
| Molar mass of coal gas (L/mol)                    | 22.4        | Liu et al$^{15}$ |
| Gas constant $R$ (J/mol·K)                        | 8.4135      | Liu et al$^{15}$ |
| Molar mass of methane $M_g$ (kg/mol)              | 0.016       | Liu et al$^{15}$ |
effective influence range of the extraction borehole increases gradually, and the content of gas extracted also increases. Therefore, with equipment allowed and mine safety, economy and other aspects considered, the negative pressure for gas extraction can be properly increased to increase the content of gas extracted.

4 | NUMERICAL SIMULATION OF EFFECTIVE EXTRACTION RADIUS OF BOREHOLES IN GAS EXTRACTION

4.1 | Mathematical model

Coal has a typical structure of natural porous media. It is widely accepted by researchers that coal consists of both coal matrix and fracture.55,56 The gas in the coal matrix and the fracture are independent of each other. The gas in coal contains adsorbed and free gas, which is mainly transported through fracture in the coal. Both free and adsorbed gas is controlled by the mass conservation equations57-59:

\[
\frac{\partial f}{\partial t} + \nabla \cdot (\rho f) = -\nabla m - \nabla (\rho v)
\]  

(22)

where \( f \) is the quantity of adsorbed gas per volume of coal matrix, kg/m³; \( \rho \) is the gas density, kg/m³; \( n \) is the fracture porosity, \( m \) is the mass diffusion flux of the adsorbed gas, kg/(m³·s); and \( v \) is the gas velocity of the free gas, m/s.

For the coal matrix system, the value of \( c \) can be calculated using the Langmuir equations60,61:

\[
f = \frac{P v_{\text{dle}} M_f}{P + P_L} v_m \rho_c
\]  

(23)

where \( v_{\text{dle}} \) denotes the maximum adsorption capacity of coal with a value of 0.0228 m³/kg; \( P_L \) denotes the Langmuir pressure constant with a value of 1.41 MPa; \( P \) is the gas pressure of coal, MPa; \( v_m \) is the molar volume of methane under standard conditions, m³/mol; \( \rho_c \) is the coal density, kg/m³; and \( M_f \) is the molar mass of methane with a value of 0.016 kg/mol.

The control equation of the gas flow field can be derived by the combination of Equations (13-14) and (22-23).

4.2 | Physical model and boundary conditions

The solid mechanics module and PDE module in the finite element computer program COMSOL Multiphase are used in this paper, which were also used by Zhang et al.32 To simplify the calculation, a two-dimensional model is established based on the plane strain assumption, as shown in Figure 11. This model is divided into roof stratum, coal seam, and floor stratum. The coal seam has a thickness of 2 m and a length of
20 m. The only gas extraction borehole is located at the center of the coal seam. By the triangular meshing method, the mesh is finely defined with 10,716 mesh elements, and further the mesh near the borehole is refined. The boundary and initial conditions for the solid deformation model and the gas flow model are set separately. For the solid deformation model, the right and left sides and bottom are set as roller boundaries, and the top side is set as a stress boundary with a normal stress of 12.25 MPa. For the gas flow model, a constant pressure of 22 kPa is applied to the wall of the borehole, and no flow conditions are applied to the other boundaries. The parameters in the simulation are listed in Table 2. Most parameters are selected from the measured results in the laboratory or the field. In addition, a monitoring line (x: 0-20 m; y: 0 m) is set in the coal surrounding the borehole in the simulation process.

4.3 | Numerical simulation results

In Figure 12, the gas pressure distribution directly reflects the variation of gas pressure of coal seam around the borehole. It can be seen that the gas pressure of coal seam around the borehole is small, while the gas pressure of coal seam far away from the borehole is large. With the prolongation of the coal seam gas extraction time, the coal seam gas far from the borehole is concentrated gradually near the borehole, since it is driven by the negative pressure of extraction and the gas pressure difference of coal seam itself. With the continuous extraction, the gas pressure of coal seam around the borehole decreases gradually. The gas pressure gradient near the borehole is relatively large, and the gas pressure decreases rapidly while the gas pressure gradient far from the borehole is relatively small and the gas pressure decreases slowly, which is basically consistent with the results from other researchers.\(^{26,32}\) According to Section 2, a gas pressure criterion of 0.441 MPa is used to determine whether there are outburst hazards. In Figure 13, the simulation results show that the effective extraction radius is 0.82, 1.25, 1.53, 1.81, 2.32 and 2.79 m, respectively, when the extraction time is 20, 40, 60, 80, 100, and 120 days, respectively. Furthermore, the fitting equation for the effective extraction radius and the extraction time is \(y = 0.01906x + 0.4193\), and the goodness of fit is 0.9879, which is very close to 1. This indicates that the effective extraction radius has a linear relationship with the extraction time.

Figure 14 shows the effect of original gas pressure, borehole diameter, and negative pressure on gas extraction for...
the same extraction time (60 days). With the increase of the distance from the borehole center, the gas pressure of coal seam rises gradually and finally tends to be the original value. Moreover, the gas pressure rises slowly at both ends and rapidly in the middle (the gas pressure varies with the distance from the exposed wall), which is in good agreement with the results obtained by Zhou and Lin through numerical calculation and field measurement. As shown in Figure 14, the distribution curves of gas pressure of coal seam around the boreholes for different borehole diameters almost coincide, and they are similar for negative extraction pressures. As the analysis indicates in Section 3, when the borehole diameter is in the range of 93-173 mm and the negative pressure is in the range of 11-55 kPa, the effect of gas extraction is not obvious. The effective radius of gas extraction cannot be increased by increasing the negative pressure and the borehole diameter. In general, the influence of the original gas pressure on the gas extraction volume of boreholes is more obvious. The larger the original gas pressure is, the smaller the coal deformation caused by gas adsorption expansion is, the smaller the porosity and permeability are, the larger the gas content is, and the bigger the gas extraction volume is. Therefore, the first thing to do is to extract the gas from the coal seam where the original gas pressure is relatively high and the production of underground coal is threatened tremendously. Effective measures such as hydraulic fracturing, protective layer mining, and loosening blasting are needed to improve the efficiency of gas extraction.

5 | FIELD TEST

5.1 | Test design

A group of boreholes for the field test are arranged in the track roadway of the 5004301 working face in the northern area of Wudong Coal Mine. As shown in Figure 15A, there is one extraction borehole and five observation boreholes, which are located on the right side of the extraction borehole with a diameter of 113 mm and a depth of 25 m. According to the design, the observation boreholes are constructed at the test points and the location of the extraction borehole is reserved. The test points are selected in the places not affected by faults where rock mass is relatively complete and cracks are not developed. According to the requirements for the test points, the layout of boreholes is designed so that the observation boreholes and the extraction hole are distributed...
in parallel in the same plane. During the construction for extraction, the phenomenon of “reaming” is easy to occur, that is, the enlargement of boreholes leads to the intersection of boreholes or the reduction of borehole spacing, which is not conducive to an accurate inspection of the extraction radius. Therefore, the spacing between boreholes should not be set too small. In this test, the spacing is set to a reasonable 0.5 m. The reaming schematic is shown in Figure 15B. The observation boreholes are sealed by the comprehensive cement sealing method based on polyurethane foaming.

**FIGURE 10** Influence of negative extraction pressure on gas extraction: (A and B) variation of coal seam gas pressure with distance from borehole; (C and D) variation of coal seam gas pressure with extraction time

**FIGURE 11** Geometry model and boundary conditions
The length of the sealing boreholes is within 20 m of the orifice, as shown in Figure 15C. In addition, D10.8 mm seamless steel pipes are used for grouting pipes, D10.8 mm PPR pipes for back grouting pipes, and D8 mm high-pressure nylon pipes for pressure pipes. After 48 hours of solidification, a pressure gauge is connected to each hole, and the nitrogen gas at a pressure of 1 MPa is added. For the gas extraction boreholes, polyurethane sealing is used with a sealing depth of 12 m, and D60 mm dual-reactor tubes are adopted as sealing tubes. After each observation borehole is sealed, a pressure gauge is installed. Then, the pressure gauge reading is observed and recorded faithfully every day. The actual construction on site is shown in Figure 15D.

### 5.2 Results and discussion

The pressure data of the five observation boreholes are shown in Figure 16A. From the variation trend of the gas pressure measured in the field, it can be seen that with the increase of the extraction time, the gas pressure of the #1, #2, and #3 observation boreholes decreases, and the rate of pressure drop slows down gradually. When gas has been extracted from the #1 observation borehole for 9 days, the gas pressure decreases from 0.9 to 0.441 MPa (critical gas pressure), and the effective extraction radius of coal seam is considered to be 0.5 m. When gas has been extracted from the #2 observation borehole for 28 days, the gas pressure drops from 0.9 to 0.441 MPa with a decrease by more than 51%, and the effective extraction radius of coal seam is considered to be 1 m. When gas has been extracted from the #3 observation borehole for 54 days, the gas pressure decreases from 0.9 to 0.441 MPa, and the effective extraction radius of coal seam is considered to be 1.5 m. The gas pressure of the #4 observation borehole remains stable until 25 days of extraction. After that, the gas pressure of the #4 observation hole begins to decline slowly. After 60 days of extraction, the gas pressure is decreased from 0.9 to 0.7 MPa, and thus, the required
extraction criterion is no longer satisfied. For the #5 observation borehole, the gas pressure basically does not change and it fluctuates up and down around 0.9 MPa with a basically horizontal trend line. This indicates that the distance between the designed #5 observation borehole and the extraction borehole is too large, and thus, the extraction effect is not obvious.

Furthermore, fitting equation for the effective extraction radius and the extraction time is $y = 0.02204x + 0.3313$, and the goodness of fit is 0.9920, which is very close to 1. This indicates that the effective extraction radius has a linear relationship with the extraction time. Therefore, the effective extraction radius of 20, 40, 60, 80, 100, and 120 days can be

**Figure 14** Multi-factor analysis of gas extraction from borehole: (A) factor of original gas pressure, (B) factor of borehole diameter, and (C) factor of negative extraction pressure.
reasonably predicted by this equation, which is 0.77, 1.21, 1.65, 2.09, 2.53, and 2.98 m, respectively.

The effective extraction radius measured in the field is compared with that from theoretical calculation and numerical simulation, as shown in Figure 17. It can be seen that the effective extraction radius from theoretical calculation is slightly larger than that measured in the field while the effective extraction radius from numerical simulation is slightly larger than that measured in the field only for the extraction times of 20 and 40 days and slightly smaller for the other extraction times. Compared with the field measurement results, the theoretical calculation results have an average relative error of 8.477%, and the numerical simulation results have an average relative error of 7.542%. Both average relative errors are less than 10%. This indicates that the research work in this paper can provide a theoretical basis for underground borehole gas extraction.

### 6 CONCLUSIONS

In this paper, the gas flow around boreholes for gas extraction is studied through theoretical calculation, numerical simulation, and field measurement; the variation of gas pressure is analyzed, and the effective gas extraction radius of boreholes is obtained. After analysis and discussion, the main conclusions are drawn as follows:

1. According to the two relevant criteria stipulated by the Chinese government for evaluating the effect of gas
extraction of coal seam, the distance from the borehole center is defined as the effective gas extraction radius when the gas pressure in coal seams is reduced to 0.441 MPa. In this paper, the unit model of gas seepage around boreholes is established, and the theoretical expression of the variation of gas pressure around boreholes with the radial distance and extraction time is derived. After the fitting, it is indicated that the effective extraction radius has a linear relationship with the extraction time. Furthermore, the influence of original gas pressure, borehole diameter, and negative pressure on gas extraction effect is analyzed. It is found that the effective radius of gas extraction by drilling increases first and then decreases as the original gas pressure increases. In addition, the borehole diameter and negative pressure are proportional to the effective extraction radius. With equipment allowed, and mine safety, economy, and other aspects considered, the borehole diameter and negative pressure for gas extraction can be properly increased to increase the effect of gas extraction.

2. The solid mechanics module and PDE module in the finite element computer program COMSOL Multiphasic are used to simulate the influence of extraction time, original gas pressure, borehole diameter, and negative pressure on gas extraction. With the prolongation of the coal seam gas extraction time, the gas far from the borehole is concentrated gradually near the borehole since it is driven by the negative pressure of extraction and the gas pressure difference of coal seam itself, resulting in the phenomenon that the gas pressure around the borehole is “large in the middle and small on both sides.” When the borehole diameter is in the range of 93-173 mm and the negative pressure is in the range of 11-55 kPa, the effective gas extraction radius of boreholes does not change significantly. However, the gas extraction quantity of boreholes is obviously influenced by the original gas pressure of coal seam and the extraction time. The fitting for the results obtained by numerical simulation indicates that the effective extraction radius has a linear relationship with the extraction time.

3. According to the variation of gas pressure around boreholes measured in situ, the effective extraction radius for the extraction time of 9, 28, and 54 days is 0.5, 1, and 1.5 m, respectively. The measured effective extraction radius is also linear with the extraction time. The effective extraction radius obtained by the theoretical calculation and numerical simulation is consistent with that from the field measurement, and the average relative error of the two methods is relatively small (less than 10%).

When gas is extracted from boreholes in underground mine, the effective extraction radius can be obtained by theoretical calculation or numerical simulation in advance, and the designed distance between boreholes can be determined accordingly. Therefore, the above findings can provide a theoretical basis for gas extraction.

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CONFLICT OF INTEREST
The authors declare there is no conflict of interest.
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