Influence radius of gas extraction borehole in an anisotropic coal seam: Underground in-situ measurement and modeling

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Abstract
Coal seam degasification by in-seam drilling borehole is one of the popular techniques for coal mine methane (CMM) control. How to address the conflict between borehole numbers and drainage durations always arouses researchers' interests. Furthermore, since coal has anisotropy structures, how the anisotropy feature of coal associated with bedding and cleat structure affects the influence radius of the drainage borehole has rarely been considered. In order to address the above-mentioned issues, this work not only conducted underground in-situ measurement of the borehole influence radius within 200 days in an anisotropy coal seam at Jiulishan coal mine in China, but also modeled the influence radius evolvement around borehole in an anisotropy coal seam using finite-element based COMSOL package. The underground in-situ measurement revealed an anisotropy feature of borehole influence radius associated with coal bedding and cleat structures. The influence radius of borehole parallel to the bedding plane in butt cleat direction is much larger than that perpendicular to the bedding plane. Ten permeability measurements of coal show that the permeability of coal parallel to the bedding plane in butt cleat direction is higher than that perpendicular to the bedding plane. Simulation results of the gas transport model in coal are consistent with underground in-situ measurement in determining the influence radius of drainage borehole in the anisotropy coal seam. Based on modeling results, the ellipse influence area of borehole in an anisotropy coal seam is proposed, and the relationship between the influence radius of borehole and drainage time is obtained. On the basis of these findings, the proper in-seam borehole arrangements for a specific mining panel at different drainage durations are determined. The finding of this work will be fundamental for addressing the conflict between minimizing the cost of borehole arrangement and increasing coal mining productions by adjusting CMM drainage durations.

Keywords
anisotropy permeability, borehole arrangement, coal mine methane, drainage, gas transport
1 | INTRODUCTION

Methane (CH$_4$), the second most prevalent greenhouse gas, is estimated to have a global warming potential (GWP) of 28-36 over 100 years.$^1$ It accounts for 14% of global anthropogenic greenhouse gas emissions. Methane-rich gases (80% to 95% methane) occur naturally in coal seams and are released during and after mining activities.$^2$ Coal mines have become a significant emission source of methane where coal mines constitute 6% of methane emissions.$^{1,3,4}$ Therefore, controlling methane emissions in coal mines becomes very important for controlling the greenhouse emission in coal industry. On the other hand, coal mine methane (CMM) can act as a valuable source of energy, which adds additional value to the mining operations.$^2$ Potential usage of the CMM exists in the following areas such as fuel in boilers, steel furnace, and turbines for power generation, injection gas to natural gas pipelines, and vehicle fuel.$^{1,5,6}$ Furthermore, there is a plethora of benefits from CMM control for coal mining safety and mine management. A proper CMM control system can not only enhance coal productions because of less frequent mining downtime and production slowdown caused by a higher methane concentration in underground entries and working face but also improve the mining safety by eliminating the coal and gas outburst risk of coal seam from a lower CMM content (pressure) in coal seams.$^{7-12}$ When the concentration of methane is in the explosive range between 5% and 15% in underground roadways, the CMM can be easily ignited resulting in methane explosions.$^6$ Collectively, the CMM control in underground coal mines is an important step to meet the challenge of climate change, diverse energy supplies and enhance the safety performance and mining management.

Generally, CMM control techniques for a specific underground coal mine depend on the geological and mining conditions. For a typical coal mine, methane in ventilation air may contain 0.1%-15% methane, and drained methane via different gas drainage techniques contains 60%-95% methane depending on the gas generation and storage properties of methane in coal seams.$^6$ CMM drainage techniques using drilling boreholes therefore become the most effective techniques for controlling methane in underground coal mines. Since methane emission usually comes from mining panels, adjacent (above and below) coal seams, and gob area (caved zone after mining), a variety of techniques, such as in-seam horizontal and cross borehole drainages, vertical borehole drainage, and gob gas venthole drainage, have been developed and applied for CMM drainage.$^{1,6}$ Among these techniques, in-seam methane drainage in mining panels via horizontal borehole from underground entries is one of the most widely used methods in China because of its low cost and higher efficiency.$^{8,13,14}$ Therefore, how to design a proper borehole arrangement for panels to degas CMM at a specific drainage duration becomes extremely important for mining management. Generally, the more the number of the drainage boreholes, the closer the space among boreholes, the higher the gas drainage efficiency and the shorter the drainage time. However, increasing the number of boreholes would increase the cost of CMM drainage. Shortening the drainage duration may lead to an insufficient gas reduction of coal seam and thus result in frequency mining downtime or production slowdowns.$^{6,15}$ Therefore, a balance must be achieved between the borehole arrangement and drainage duration for both mining safety and mining management.

In order to tackle the issue between the borehole arrangement and gas drainage duration for CMM drainage, the straightforward way is to determine the relationship between the influence radius of borehole and drainage time. The influence radius of borehole refers to how far the gas can be drained around the borehole with drainage time at a specific sucking gas pressure in the borehole (as shown in Figure 1). Generally, the longer the gas drainage durations are, the larger the influence radius of borehole is. This feature in nature is related to the CMM transport behavior in coal where the permeability of coal plays a significant role. Therefore, the permeability of coal needs an extensive study in order to clarify the relationship between borehole arrangement and gas drainage duration for CMM drainage.

Coal is an anisotropy heterogeneous natural material containing both bedding and cleat structures. This unique

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**FIGURE 1** Schematic diagram for influence radius of borehole in an isotropic coal seam; the different influence area (radius) of borehole is attributed to different drainage times and the larger the circle the longer the drainage duration.
feature makes coal to show anisotropy permeability, which was shown in extensive studies. Koenig and Stubbs reported for Pratt A coal seam, the direction permeability goes up to 17:1 oriented parallel to the face cleat direction of coal, and the face cleats dominate the directional permeability. Gash studied the effect of cleat orientation effect on gas permeability and relative permeability of coal. Their test results revealed that gas permeability is largest parallel to the bedding plane in the face cleat direction and is lowest perpendicular to the bedding plane. Massarotto et al confirm and extend the range of horizontal permeability anisotropy ratios (PARs) from previous researchers: the PARFB varied from a low of 1.35 to a high of 19. The PARFV varied from 0.11 to 4.0, while the PARBV varied from 0.17 to 1.8. Li et al tested coal samples associated with cleat pattern and showed that Kushiro coal is anisotropic with respect to gas permeability, where the permeability parallel to bedding plane and face cleat is larger than that perpendicular to the bedding plane and the permeability perpendicular to the bedding plane is larger than that parallel to the bedding plane and butt cleat. Li Yong et al and Zhao Junlong et al drill three columned cores from one source samples of different drilling directions for the investigation of permeability difference between coal cores, and the nature of helium permeability change was measured on different rank coal cores. The experimental results showed that the coal permeability declined exponentially with the rise of effective stress. Wang et al quantitatively studied the fracture structure characteristics in directions through the given parameters of the Fukang mining area, China. The coal reservoir permeability in parallel bedding plane direction is 1.33-12.91 larger than that in vertical direction according to Darcy’s law and the plate law. Chen et al measured the anisotropic gas permeability of coal, which showed an increase in the bedding plane angle of the specimen, expanding the length and area of the contact surface during the adsorption-desorption process. Kumar et al discussed the pore pressure and permeability of cleat structure that regulates the production of coal bed methane. From previous studies, it can be concluded that an in-depth understanding of the directional feature of coal permeability associated with cleats and bedding patterns is critical for the coalbed methane recovery. This also implies that if the directional permeability of coal around drainage boreholes is obtained, the best methane drainage borehole can be designed, which would not only improve the drainage efficiency but also minimize the drainage cost.

In order to clarify whether the influence radius of drainage borehole shows anisotropy feature and the relationship between the borehole arrangement and drainage durations, this work first presents an underground in-situ test for determining the influence radius of boreholes in Jiulishan coal mine in China. Then, the anisotropic permeability of coal associated with bedding planes is measured using pure methane under five different gas pressures from 0.5 to 2.5 MPa. Finally, a theoretical model is developed and numerically solved using the finite-element based COMSOL package to predict the relationship between the influence radius and drainage time, which is compared with the in-situ test data. The influence area of borehole in anisotropic coal seams is also discussed, and the empirical relationship between the anisotropy influence radius and drainage time is obtained. A simplified case study for designing borehole arrangement for a mining panel is finally discussed.

2 UNDERGROUND IN-SITU TEST FOR BOREHOLE INFLUENCE RADIUS MEASUREMENT

2.1 Test drilling borehole layout

The test site is located at Second-1 coal seams in Jiulishang coal mine, Jiaozuo, China. The coal seams are 450 m

![Figure 2](image-url)
The average thickness of coal seam is 7.2 m, and the CMM pressure of the coal seam is around 1.21 MPa. The in-situ stress of the coal seams is around 9.6 MPa. Both the bedding plane and cleat patterns are observed in the panel, and the drilling borehole arrangement is shown in Figure 2. Both the observation and drainage boreholes are 40 m deep into the coal seam and the borehole diameter is 94 mm. The influence radius of drainage borehole in two directions is considered; one is parallel to bedding plane in butt cleat direction (borehole 1, 2, 3, 4) and the other is perpendicular to the bedding plane (borehole 5, 6, 7, 8).

### 2.2 Test approach

The influence radius measurement of borehole involves the following steps. First, eight observation boreholes (1-8) are drilled. Seal the borehole and install the pressure

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**FIGURE 3** Schematic diagram of prepared observation boreholes

**FIGURE 4** In-situ measurement of influence radius of borehole in anisotropy coal seam with different distances from the gas drainage hole: (A) 0.7 m, (B) 1.0 m, (C) 1.3 m, and (D) 1.5 m
gauge, flow meter, and valve (keep the valve open at this moment). When the sealing material in the borehole is solidified after a short period, close the valve and wait for the pressure getting stable to obtain the gas pressure of the coal seam. Second, when all pressures of the boreholes show a stable value, the drainage boreholes (A and B) are drilled with the same approach. Third, once both the observation borehole and drainage borehole are ready, the influence radius measurement is initiated and the sucking pressure in the drainage borehole is 30 kPa. In the first 3 days, the pressure values are recorded thrice a day. After the first 3 days, the value of the manometer is recorded once a day. The test process continues up to 200 days. The schematic diagram of the observation borehole is shown in Figure 3.

2.3 Test results and discussion

Figure 4 shows the pressure builds up and finally reaches 1.21 MPa in all eight observation boreholes in the first 25 days. Once the drainage process in drainage boreholes (A and B) is initiated, the pressure of the observation borehole starts to drop and the drop behavior of each observation borehole is different. Borehole 1 shows the sharpest decreasing trend while borehole 8 shows the slowest decreasing trend. This can be attributed to the different distances and location of boreholes 1 and 8 between observation boreholes and drainage boreholes in the coal seam. It is also clear that the pressure drop in the butt cleat direction is always sharper than that perpendicular to the bedding planes when the distance between the drainage borehole and observation borehole is the same. When the observation borehole is closer to the drainage borehole, the pressure of the borehole drops easily.

Both the gas pressure and gas content of coal seam are indicators for outburst-prone risk in coal seams. 29,30 Generally, a coal seam with a gas pressure >0.74 MPa or a gas content >8 m³/t is considered to have the coal and gas outburst potential. 31,32 Therefore, 0.74 MPa is set as the criterion for judging whether coal seams are out of outburst-prone risk. When the pressure of the observation borehole in a coal seam is below 0.74 MPa, the degassed area between the drainage borehole and observation borehole is out of outburst-prone risk. The distance between this observation borehole and drainage borehole is therefore renamed as the effective influence radius of drainage borehole. The introduction of the effective borehole serves two purposes; one is to make sure the coal seam area around the drainage borehole is out of outburst-prone risk and the other is to ensure a sufficient drainage time for the CMM drainage process. The effective influence radius of drainage borehole depends on both drainage time and the distance to the drainage borehole. As shown in Table 1, in the butt cleat direction, the effective influence radius of boreholes is 0.7 m (borehole 1), 1 m (borehole 2), 1.3 m (borehole 3), and 1.5 m (borehole 4) at drainage time 15, 46, 98, and 150 days, respectively. In the direction perpendicular to the bedding plane, the influence radius of boreholes is 0.7 m (borehole 5), 1 m (borehole 6) at drainage time 40 and 113 days, respectively. After drainage time 175 days, the gas pressure in boreholes 7 and 8 is still higher than 0.74 MPa and the distance is too far for the drainage borehole to obtain an effective influence radius. This also means an outburst risk around boreholes 7 and 8 still exists. From the above discussion, it can be concluded that both coal structure associated with cleat and bedding structure and drainage time (borehole space) affect the effective influence radius of the borehole.

3 PERMEABILITY MEASUREMENT OF COAL ASSOCIATED WITH BEDDING STRUCTURE

3.1 Sample preparation

Block coal samples are obtained from the same coal seam in Jiulishan coal mine, which is anthracite. Two coal samples are prepared in two different directions (X and Z) from coal blocks, as shown in Figure 5. The X direction of sample No. X is parallel to bedding plane in the butt cleat direction. The Z direction of sample No. Z is perpendicular to the bedding plane. The prepared coal is 50 mm in diameter and 100 mm in height.

| TABLE 1 | Setup parameters for the in-house built permeability measurement instrument |
|----------|---------------------------------|
| Parameters | Test range | Precision |
| Confining pressure | 0-30 MPa | ±0.1 MPa |
| Gas pressure | 0-10 MPa | ±0.1 MPa |
| Axial compression | 0-70 MPa | ±0.1 MPa |
| Gas flow | 0-700 mL/min | ±2.0 mL/min |
| Temperature | 25-100°C | ±0.1°C |

3.2 Test apparatus and procedure

The permeability of coal samples was measured using the in-house built gas permeability instrument at the State Key Laboratory Cultivation Base for Gas Geology and Gas Control in Henan Polytechnic University, China. Pure methane (99.99%) is used to measure the gas
permeability. The test system is composed of six main parts, which are coal sample holder, stress loading system, gas tank, vacuum degassing system, temperature control system, and data acquisition system, as shown in Figure 6. The setup parameters of the test system are shown in Table 1.
Gas permeability test follows the procedures which are given as follows:

1. The tightness of the system is double-checked prior to testing. Then, the prepared specimen is loaded into the sample holder.

2. In order to avoid temperature influence, the temperature of the test system is set at 30°C. Hydrostatic pressure (confining pressure equals axial loading) applied on the coal samples is set to predefined value using the high pressure oil pump and axial loading.

3. To avoid the gas adsorption effect on permeability measurement, the sample is first saturated with methane to reach sorption equilibrium at predefined gas pressures; when the change of pressure is <0.01 MPa within 2 hours, the system is treated as having equilibrium status.

4. Once the methane-coal sorption system reaches equilibrium, the valve in the downstream of the system opens and the gas flow in the downstream is recorded. When the gas flow in the downstream reaches steady state, the gas permeability of coal is calculated using Darcy's law equation. The average permeability of coal sample is calculated according to the gas flow rate and the pressure difference between the upstream and downstream of coal sample, which is expressed in equation (1).

\[
k = \frac{2 \mu p_0 Q L}{S (p_1^2 - p_2^2)}, \tag{1}
\]

where \( Q \) is the quantity of methane gas seepage, cm\(^3\)/s; \( p_0 \) is a standard atmospheric pressure, Pa; \( \mu \) is the gas dynamic viscosity, Pa.s; \( L \) is the coal sample length, cm; \( p_1 \) and \( p_2 \) are gas inlet and outlet pressures of the coal sample, respectively, Pa; \( S \) is the cross-section area of the coal sample, cm\(^2\).

5. Replace coal samples and repeat the above steps (1-4) until the gas permeability of prepared coal samples is measured.

### 3.3 | Test results

According to the in-situ stress condition of the coal seam, the confining and axial pressure is set at 9.6 MPa to measure the permeability of coal. Five different gas pressures from 0.5 to 2.5 MPa are used to measure the methane permeability in coal. Figure 7 shows the methane permeability of coal decreases with increasing gas pressures. The permeability of coal parallel to the bedding plane in the butt cleat direction is around 1.5 times higher than that perpendicular to the bedding planes. The power-law relationship is used to describe the relationship within the test ranges from 0.5 and 2.5 MPa, as shown in equations (2a) and (2b).

\[
X \text{ direction: } k_X = 1.094p^{-0.529} \quad (R^2 = 0.9981) \tag{2a}
\]

\[
Z \text{ direction: } k_Z = 0.675p^{-0.373} \quad (R^2 = 0.9989) \tag{2b}
\]

### 4 | GAS TRANSPORT MODEL IN COAL SEAMS

#### 4.1 | Governing and constitutive equations

In order to develop the gas transport model in coal seams, the following assumptions are made: the floor and roof of the coal seam are airtight where the coal seam is dry, homogeneous, anisotropic, and elastic continuum; the system is isothermal, and gas viscosity is constant under isothermal conditions; gas flow through the coal matrix is assumed to be of the viscous type obeying Darcy's law equation within the coal seam; the CMM is treated as pure methane in the coal seam.

#### 4.1.1 | Adsorbed and free gas in coal

Coal mine methane (CMM) in coal seams existed in two statuses: free gas and adsorbed gas. The Langmuir equation is used to calculate the adsorbed methane content, as shown in equation (3).

\[
Q_1 = \frac{ab p_0 \rho_s M_{ad}}{1 + b p_0 \rho_s (1 + 0.31 M_{ad}) (1 - A_{ad} - M_{ad})}, \tag{3}
\]

where \( Q_1 \) is the adsorbed CMM content in unit coal, kg/m\(^3\); \( p \) is the gas pressure of coal seam, MPa; \( a \) and \( b \) are the Langmuir constants, \( M_{ad} \) is the moisture content in coal, \( A_{ad} \) is the ash content in coal, %, and \( \rho_s \) is the density of coal, kg/m\(^3\); \( \rho_0 \) is the density of methane, kg/m\(^3\). It is worth pointing out that the unit of \( Q_1 \) (kg/m\(^3\)) is different from conventional...
dimensional of adsorption content (cm$^3$/g), which is to meet the requirement of the constitutive equation.

Free CMM in a coal seam follows the ideal gas law, and the free gas content is shown in equation (4):

$$Q_2 = \frac{\rho_f \Delta p}{\rho_f}$$  \hspace{1cm} (4)

where $Q_2$ is the free gas content in unit coal, kg/m$^3$; $\rho_f$ is the methane density, kg/m$^3$; $p_0$ is the gas pressure of coal seam, MPa; $\phi$ is the porosity of coal.

Combining equations (3) and (4), the total CMM content of unit coal can be obtained, as shown in equation (5)$^{33}$:

$$Q = \frac{abp}{1+bp} \rho_f \phi f + \frac{1}{1+0.31M_{ad}} \frac{1-A_{ad} - M_{ad}}{1} + \frac{\rho_0}{\rho_0} \rho p \phi f$$  \hspace{1cm} (5)

### 4.1.2 Permeability evolvement of coal

During the CMM drainage process, the gas pressure of coal seam decreases, which results in the change of the coal porosity and permeability. The porosity of coal is the ratio of the space volume between coal particle ($V_p$) and total coal volume ($V$):

$$\phi = \frac{V_p}{V}. \hspace{1cm} (6)$$

Equation (6) can be rewritten in the following form:

$$\phi = \frac{V_{ad} + \Delta V_p}{V_{ad} + \Delta V} = 1 - \frac{V_{ad} + \Delta V_p}{V_{ad}(1+\Delta V/V_{ad})}$$

$$= 1 - \frac{1-\phi_0}{1+\varepsilon_v}(1 + \Delta V_p/V_{ad}), \hspace{1cm} (7)$$

where $V_{ad}$ is the original volume between coal particle, m$^3$/kg; $\Delta V_p$ is the volume change of coal particle space, m$^3$/kg; $\Delta V$ is the volume change of the total volume, m$^3$/kg; $V_0$ is the original total volume, m$^3$/kg; $V_{ad}$ is the original skeleton volume of coal, m$^3$/kg; $\phi_0$ is the original porosity of coal, %; and $\varepsilon_v$ is the volume strain of the coal.

Since coal seam is in an isothermal condition and coal is linear elastic, the volume strain of the original skeleton volume of coal, $\Delta V_p/V_{ad}$, is caused by the pressure change ($\Delta p$) of the coal seams:

$$\Delta V_p/V_{ad} = -\Delta p/k_v, \hspace{1cm} (8)$$

where $k_v$ is the volume modulus of coal, MPa; $\Delta p = p - p_0$ is the gas pressure change of coal seam, and $p_0$ is the initial gas pressure of coal seams.

Combining equations (7) and (8), the dynamic porosity during gas drainage process is obtained:

$$\phi = 1 - \frac{1 - \phi_0}{1 + \varepsilon_v} \left(1 - \frac{1}{\Delta p / k_v} \right) \hspace{1cm} (9)$$

The relationship between the permeability of porous media and porosity follows the cubic rule:

$$k = k_0 \left[1 + \varepsilon_v + \frac{\phi_0}{\phi} + \frac{\sigma(1-\phi) + \phi_0}{p} \right]^3, \hspace{1cm} (10)$$

Combining equations (9) and (10), the permeability evolvement of a coal seam during gas drainage process can be obtained$^{34}$:

$$k = k_0 \left[1 + \varepsilon_v + \frac{\phi_0}{\phi} + \frac{\sigma(1-\phi) + \phi_0}{p} \right]^3, \hspace{1cm} (11)$$

where $k_0$ is the intrinsic permeability of coal, m$^2$.

### 4.1.3 Governing equation

The loading of the coal seams is supported by two parts; one is the gas pressure and the other is coal structure. According to the elastic theory, the governing equation for loading and displacement relationship is shown in equation (12):

$$G \sum_{j=1}^{3} \frac{\partial^2 \sigma}{\partial x_j^2} + \frac{G}{2} \sum_{j=1}^{3} \frac{\partial^2 \sigma}{\partial x_i \partial x_j} = \frac{\partial p}{\partial x_i} + \frac{\sigma(1-\phi) + \phi_0}{p} \frac{\partial \sigma}{\partial x_i} + F_i = 0, \hspace{1cm} (12)$$

where $G$ and $\lambda$ are the Lamé constants; $s$ is the displacement, m; $\nu$ is the Poisson ratio of coal; $F_i$ is the body force; $\sigma$ is the total stress, MPa.

### 4.1.4 Constitutive equation

Considering the Klinkenberg effect, the velocity of gas in coal is shown in equation (13):

$$v_p = -\frac{k}{\mu} \left(1 + \frac{\nu}{p} \right) \nabla p \hspace{1cm} (13)$$

where $v_p$ is the gas velocity, m/s; $\mu$ is the gas dynamic viscosity, Pa.s; $c$ is the Klinkenberg coefficient, MPa, and $\nabla p$ is the pressure gradient, MPa/m. The gas flow in coal follows equation (14)$^{35}$:

$$\nabla \cdot (\rho_p v_p) + \frac{\partial Q}{\partial t} = 0. \hspace{1cm} (14)$$

Combining equations (5), (11), (12), and (14), the gas transport model considering the permeability evolvement and Klinkenberg effect can be described by equation (15)$^{36,37}$:

$$abp + \phi + \frac{\phi_0(1-\phi)}{k_v} \frac{\partial p}{\partial t} - \frac{1}{2} \nabla \left[ \frac{k}{\mu} (1 + \frac{\nu}{p}) \nabla p^2 \right] + p \frac{\partial \phi}{\partial t} = 0, \hspace{1cm} (15)$$

where $f = \frac{\rho_f - 1}{1+0.31M_{ad}} (1-A_{ad} - M_{ad})$, $\alpha = \frac{\sigma(1-\phi)}{p} + \phi$. 

4.2 Boundary condition

In order to solve the coupling equations for the gas transport model in coal, the initial condition and boundary conditions are set below:

1. Initial condition: Pressure: \( p \big|_{t=0} = p_0 \); stress: \( \sigma \big|_{t=0} = 0 \); displacement: \( u \big|_{t=0} = u_i \); velocity: \( \frac{\partial u}{\partial t} \big|_{t=0} = v_i \);
2. Boundary condition: Gas pressure: \( p \big|_{t=0} = p_0 \); boundary displacement: \( u \big|_{\text{boundary}} = u_i \); boundary loading: \( \sigma_{ij} \cdot \mathbf{n} \big|_{\text{boundary}} = \sigma_0 \).

4.3 Physical model configuration

The coupled equations for gas transport model in coal seams described in Sections 4.1 and 4.2 are implemented within COMSOL Multiphysics. The COMSOL Multiphysics software is an efficient and powerful finite element-based platform for simulating and analyzing coupled physical phenomena. The geometry of the gas drainage model is shown in Figure 8. The length and thickness of the coal seam are 20 and 7 m, the borehole diameter is 94 mm, the overburden stress is 9.6 MPa, and the initial CMM pressure is 1.21 MPa (Table 2). Coal permeability is calculated using equations (2a) and (2b), where \( k_{X0} = 0.9891 \times 10^{-16} \text{ m}^2 \) and \( k_{Z0} = 0.6287 \times 10^{-16} \text{ m}^2 \). Other parameters of the physical model are shown in Table 3. Modeling results in five directions (OA, OB, OC, OD, OE) are monitored and analyzed to investigate the influence area of drainage boreholes. The gas drainage pressure of the borehole is set as 30 kPa during the drainage process.

5 Modeling results and discussion

5.1 Simulation results

Figure 9 shows the gas pressure distribution around drainage borehole at different drainage durations. The influence area of the drainage borehole increases with increasing drainage time. The influence radius of the borehole also shows an anisotropy feature around the drainage borehole where the gas pressure distribution along OA, OB, OC, OD, and OE directions is different. The influence radius in the OA direction is larger than that in the OE direction from visual observations. As shown in Figure 10, when gas drainage time is 30 days, the effective influence radius is 0.85, 0.78, 0.73, 0.70, and 0.67 m in OA, OB, OC, OD,
and OE direction, respectively. When gas drainage time is 120 days, the effective influence radius is 1.41, 1.28, 1.19, 1.10, and 1.03 m in OA, OB, OC, OD, and OE direction, respectively. And the simulation results are in perfect agreement with the test results in OA and OE directions. This does support the time-dependent and anisotropy feature of the effective influence radius of the drainage borehole in an anisotropic coal seam.

Figure 11 shows modeling results fit the in-situ test data obtained in Section 2 (OA and OE directions only) very well. The effective influence radius of drainage borehole increases in OA, OB, OC, OD, and OE directions at different drainage times. However, the increasing rate of the effective influence radius decreases as drainage time goes on. In order to obtain the relationship between the effective influence radius and drainage time, the power function is used to fit the results as shown in equations (16a-16e). Table 3 shows the relative error is within 16% between the in-situ measured value and the predicted results using equations (16a) and (16e).

| Distance from gas drainage holes (m) | Gas drainage time (d) as gas pressure decreases below 0.74 MPa |
|-------------------------------------|--------------------------------------------------------------|
|                                     | Test results | Simulation results | Absolute error (d) | Relative error |
| Parallel to bedding                  |             |                  |                    |                |
| 0.7 (No. 1)                         | 15          | 17.4             | 2.4                | 16%            |
| 1.0 (No. 2)                         | 46          | 48.6             | 0.6                | 1.3%           |
| 1.3 (No. 3)                         | 98          | 96.5             | −1.5               | −1.53%         |
| 1.5 (No. 4)                         | 150         | 143.4            | −6.6               | −4.4%          |
| Perpendicular to bedding            |             |                  |                    |                |
| 0.7 (No. 5)                         | 40          | 34.7             | −5.3               | −13.25%        |
| 1.0 (No. 6)                         | 113         | 108.2            | −4.8               | −4.25%         |
| 1.3 (No. 7)                         | —           | 249.9            |                    |                |
| 1.5 (No. 8)                         | —           | 394.5            |                    |                |

5.2 | Effective influence area of drainage borehole

In order to design a borehole arrangement for a mining panel, the conflict between the influence area of the drainage borehole and the drainage time must be reasonably addressed to minimize the total drilling borehole numbers (cost) and maximize the drainage efficiency for enhancing coal production. As mentioned earlier, the more number of the boreholes, the closer the space between boreholes and the longer the drainage time, the higher the gas drainage efficient. However, the more number of the boreholes would increase the cost of CMM drainage and the longer drainage time usually leads to a low coal mining efficiency which finally results in a low mining profit. It can be imagined that if the relationship between effective influence area of borehole and drainage time is obtained, the CMM drainage arrangement can be designed in a flexible way by balancing the borehole drilling cost and drainage duration.

As in Figure 8, the initial gas pressure is same around the drainage, and the coal body is assumed that other factors have the same effect. Therefore, the effective drainage area in coal body is considered to be symmetrical with A’A axis and E’E axis, so is the influence radius of the drainage borehole. Figure 12 shows the effective influence radius increases with drainage time around the drainage borehole. At each drainage time, the effective influence area can be treated as an ellipse phenomenologically. If the A’A and E’E directions are treated as the major and minor axes of the ellipse, the effective influence distance to the borehole center \((x_t, z_t)\) at each drainage time \((t)\) follows equation (17):

\[
\frac{x_t^2}{r_{ht}^2} + \frac{z_t^2}{r_{mt}^2} = 1.
\]

In order to validate the phenomenological idea of the ellipse-shaped area at different drainage durations, equation (17) is used to fit the simulation results presented in Figure 12. It is clear that the proposed model (equation 17) fits simulation results very well as shown in Figure 13. This, on the other hand, supports that the effective influence area of the drainage borehole in an anisotropic coal seams is an ellipse at different drainage durations.
In order to ensure the outburst-prone risk of the coal seam is fully eliminated, the gap area between the influence area of each drainage borehole must be eliminated through a proper borehole arrangement within a sufficient gas drainage time. This means the coal seam must be fully covered by the effective area of drainage boreholes. If the local area in the coal seam is out of the effective influence area of drainage boreholes, it is hard to determine whether this area is out of outburst-prone risk and the retreat mining thus cannot be initiated. Usually, anisotropic permeability of coal seam is neglected in the study of gas drainage, many researchers consider that the permeability of coal seam is isotropous, so the circular effective extraction area is obtained, as shown in Figure 14A,B. If the layout of drainage holes is applied as given in Figure 14A, it exaggerates the effective extraction area, which leads to blind area of gas drainage in coal seam. If the layout of drainage holes is applied as given in Figure 14B, it would cause more drainage holes and give rise to more cost. So this problem can be simplified as per the following mathematical problem: how to fully cover a rectangular panel area using minimum number of the same ellipse, where the ellipse size depends on time. Considering the symmetric feature in the problem, a simplified diagram is shown in Figure 14C for a specific mining panel.

FIGURE 9 Gas pressure isogram in coal seam at different drainage times in an anisotropy coal seam: (A) 30 d, (B) 60 d, (C) 90 d, (D) 120 d, (E) 150 d, and (F) 180 d
Gas drainage borehole

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This means the product of \((x_0, z_0)\) must be the maximum and the \((x_0z_0)^2\) will also be the maximum. The \((x_0z_0)^2\) term can be expanded as equation (19):

\[
(x_0z_0)^2 = \frac{r_{st}^2}{r_{rlt}^2} \left[ \left( \frac{r_{rlt}}{r_{st}} \right)^2 - (r_{st} - z_0)^2 \right] z_0^2
\]

When the area \((ABCD)\) is the maximum, the product of \((x_0z_0)\) must be the maximum and the \((x_0z_0)^2\) will also be the maximum. The \((x_0z_0)^2\) term can be expanded as equation (19):

\[
\frac{x_0^2}{r_{rlt}^2} + \frac{(r_{rlt} - z_0)^2}{r_{st}^2} = 1.
\]

Assuming the coordinate of the first drainage borehole is at \((0, 0)\), the effective influence area of the borehole is an ellipse with major axial \((r_{rlt})\) and minor axial \((r_{st})\), as shown in Figure 14. One of the nearest neighbor drainage boreholes is at \((x_0, z_0)\). In order to get the best borehole arrangement, the intersection rectangular area \((ABCD)\) between the effective influence area of borehole \((0,0)\) and \((x_0, z_0)\) must be the maximum. This means the product of \((x_0z_0)\) is the maximum. In order to meet this criterion, the point \((0, r_{st})\) must be in the ellipse: \(\frac{(x-r_{rlt})^2}{r_{rlt}^2} + \frac{(z-z_0)^2}{r_{st}^2} = 1\) and \(0 < x_0 < r_{rlt}, r_{st} < z_0 < 2r_{st}\). The criterion can be rewritten as equation (18):
That means:

\[ \frac{r_{in}^2}{r_{st}^2} (2r_{st} - z_0) \leq \frac{r_{in}^2}{r_{st}^2} \cdot \frac{1}{2} \left( (2r_{st} - z_0)^2 + (z_0)^2 \right). \]  \tag{20} 

When \((2r_{st} - z_0) = z_0^3\), the term \((x_0z_0)^2\) is the maximum. That means:

\[ z_0^3 + z_0 - 2r_{st} = 0. \]  \tag{21} 

Equation (21) is the typical Cardano equation and its solution \((z_0)\) is given below:

\[ z_0 = \sqrt[3]{Y_1} + \sqrt[3]{Y_2}, \]  \tag{22} 

where \(Y_1 = r_{st} + \sqrt{\Delta}\), \(Y_2 = r_{st} - \sqrt{\Delta}\), and \(\Delta = \left( \frac{-2r_{st}}{2} \right)^2 + \left( \frac{1}{5} \right)^3 \).

As shown in Figure 11 and equations (16a-16e), the effective influence radius \((r_{in}, r_{st})\) of the drainage borehole can be calculated at a specific drainage time \(t\). Once the effective influence radius \((r_{in}, r_{st})\) is known, the arrangement of the drainage boreholes for a specific mining panel is set. Figure 15 and equations (23a) and (23b) show the relationship between the effective influence radius \((r_{in}, r_{st})\) and time. From this relationship, it is certain that when the gas drainage time is set, the effective influence radius can be determined and the proper borehole arrangement will be set for the mining panel.

\[ x_0 = \frac{1.41t}{13.21 + t} \]  \tag{23a} 

\[ z_0 = 0.19t^{0.41} \]  \tag{23b} 

### 5.3 Case study

Here, a decent panel dimension (7 × 120 m, coal thickness is 7 m and panel length is 120 m) is used to design the borehole arrangement for CMM drainage in the Jiulishan coal mine. As mentioned earlier, to ensure the outburst risk of coal seams is eliminated, the panel area must be fully drained using boreholes. Figure 16 shows the concept of the borehole arrangement within the mining panel. Under this circumstance, the whole panel is fully covered by the influence area of each drainage borehole, and there is no gap area among drainage boreholes in the panel.

Using the relationship between the effective influence area and drainage time in Section 5.2, the total borehole number for degassing the mining panel of 7 × 120 m can be obtained at different drainage durations, as shown in Figure 17. When the drainage time is 10 days, 1140 drainage boreholes are needed to eliminate the outburst-prone risk of the panel. When the drainage time is 180 days, 85 drainage boreholes can meet the requirement. Therefore, if the drainage plans for mining panels are planned ahead, the methane drainage cost will be minimized by prolonging the drainage duration and decreasing the number of drainage boreholes. It can also be seen that when the number of drainage boreholes is <300,
increasing the drainage duration is not very helpful for increasing the drainage efficiency. Figure 17 therefore becomes fundamental for balancing the drainage borehole number and drainage durations for a specific mining panel.

6 | CONCLUSIONS

In this work, the influence radius of drainage borehole is measured in an anisotropy coal seam at in-situ condition within 200 days in Jiulishan coal mine, China. Then, the permeability of coal-associated bedding and cleat structures from the same location is measured under different gas pressures from 0.5 to 2.5 MPa. Next, the gas transport model in coal is developed considering the anisotropy feature of coal permeability, which lays the foundation for investigating the influence radius evolvement of drainage borehole at different drainage times. On the basis of the in-situ measurements and modeling results, the influence area of drainage borehole in an anisotropy coal seam is determined, and the proper drainage borehole arrangements are designed at different drainage times.

1. The underground in-situ measurement reveals a distinguishable difference of borehole influence radius associated with coal bedding and cleat structures. The
influence radius of borehole parallel to the bedding plane in butt cleat direction is much larger than that perpendicular to the bedding plane.

2. Ten permeability measurements of coal samples associated with bedding and cleat structure under different gas pressures show that the permeability of coal parallel to the bedding plane in butt cleat direction is much larger than that perpendicular to the bedding plane. The higher the gas pressure from 0.5 to 2.5 MPa, the lower the measured coal permeability.

3. Gas transport model in coal is developed by considering the permeability evolvement caused by gas pressure change, Klinkenberg effect, and the anisotropy permeability of coal. The influence radius and area of drainage borehole are investigated. Modeling results are consistent with underground in-situ measurement which supports the robustness of the proposed model.

4. The ellipse influence area of borehole in anisotropy coal seams is proposed based on the modeling results, and the relationship between the influence radius of borehole and drainage time is obtained. Based on these findings, the proper in-seam borehole arrangement for a specific mining panel duration can be obtained at different drainage durations. The finding of this work will be helpful for addressing the conflict between minimizing the cost of borehole arrangement and increasing coal mining profits by adjusting CMM drainage durations.

CONFLICT OF INTEREST

None declared

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