

Discrimination Method of Gas Pressure Measurement in Coal Seams: Physical Experiment and Model Development

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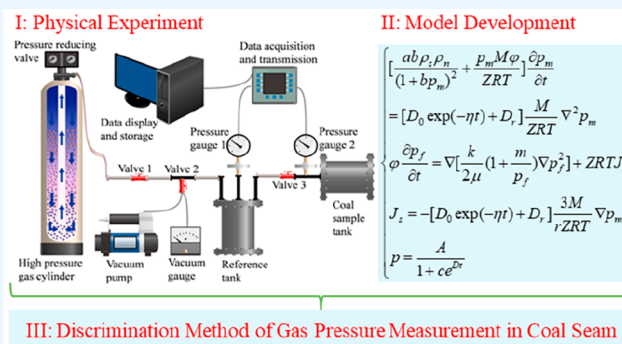
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ABSTRACT: Coal seam gas pressure is a key parameter of gas accident control and gas drainage. At present, there are some problems in field pressure measurement, such as long period, and there is often a need to drill more holes to ensure the reliability of pressure measurement. In this research, a physical gas pressure measurement experiment in a coal sample borehole was carried out, and a mathematical model of gas pressure evolution with time was constructed. Based on the OpenFOAM platform and C++ language, a numerical solver was developed, and the mathematical model was verified by the data of gas pressure in coal seam boreholes. The results show that the evolution process of gas pressure in coal seam boreholes can be divided into two stages. In the first stage, the gas pressure increases rapidly, and the pressure change rate decreases continuously. In the second stage, the gas pressure is slow and stable, and the pressure change rate tends to 0. The correlation coefficients between the mathematical model and the field-measured data are more than 0.94, and the calculation and prediction accuracy are high. Therefore, the model can be used to verify the field data during pressure measurement, which has better field significance and application value.



1. INTRODUCTION

The measurement of gas pressure in coal seams is an important work in mine safety production.^{1,2} Accurate measurement of coal seam gas pressure is of great significance for the prediction and early warning of coal and gas outbursts, the study of the gas desorption and emission law, and the evaluation of the coal seam gas content.^{3–5} At present, the direct method to measure gas pressure in coal seams is one of the most common methods. By drilling and sealing in the coal seam, a closed gas chamber is formed, and the gas in the adjacent coal seam is constantly desorbed and diffused into the gas chamber. Then, the gas pressure in the gas chamber increases gradually, and the final stable value is the coal seam gas pressure.^{6,7} However, the process of pressure measurement is affected by many factors, such as coal seam water, sealing technology, and pressure measurement time,^{8–10} so it is impossible to judge whether the pressure measurement result is accurate. Therefore, an efficient method to determine the accuracy of pressure measurement results is particularly important.

In the process of gas pressure measurement, the construction technology and gas occurrence conditions in the coal seam have an impact on its accuracy. Among them, construction technology involves sealing methods and sealing materials,¹¹ and sealing methods are mainly divided into solid sealing and liquid sealing. The solid sealing method mainly includes the yellow mud sealing method, grouting sealing

method, polyurethane sealing method, and apron capsule sealing device pressure measuring method.^{12–14} The poor fluidity of solid materials may cause incomplete sealing of cracks, resulting in seal failure and inaccurate pressure measurement. The liquid sealing method is mainly designed for the case of soft lithology and developed fractures around the borehole.^{15,16} Zhou proposed the rubber ring-mucus sealing method.¹⁷ The mucus can well fill the cracks around the borehole, thus improving the sealing effect. However, drilling holes with poor lithology easily cause problems such as fluid leakage. In addition to the construction technology, the gas occurrence condition is also a factor affecting the accuracy of pressure measurement. The influence of coal seam water on the gas pressure measurement process was studied, and the pressure measurement method of the water-bearing coal seam was proposed according to the solubility of methane.^{18,19} In addition, the development degree of coal seam pore fissures

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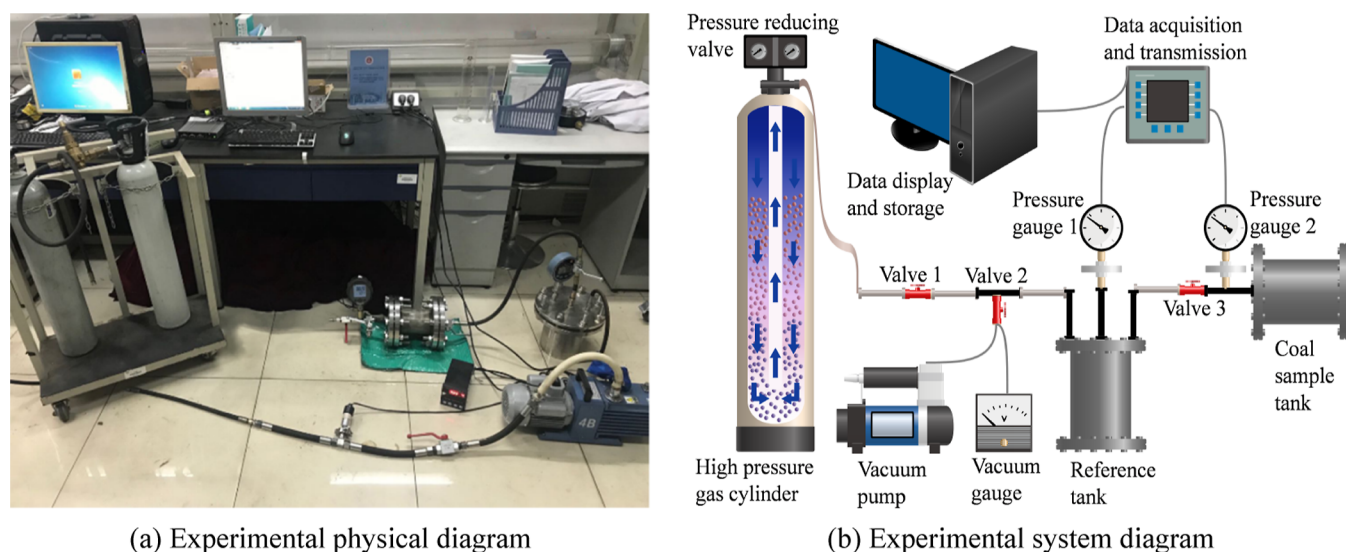


Figure 1. Schematic diagram of the gas pressure measurement experimental system.

affects the process of gas pressure measurement by affecting the permeability of gas migration.^{20,21}

The gas migration characteristic in coal is the theoretical basis for describing the gas pressure measurement process. Based on the gas flow mechanism, the gas pressure calculation and prediction model is established, and then, the accuracy of the gas pressure measurement results is judged. Wang et al.^{22,23} measured the gas pressure in a coal seam by establishing a dynamic inversion model of gas pressure. Chen and Liu²⁴ deduced the prediction equation of gas pressure according to the source of gas emission from the heading face. Wang et al.²⁵ studied the expression of gas flow in spherical and radial flow fields and proposed a method of calculating gas pressure in coal seams. Meanwhile, as the power of gas flow, there is a quantitative mathematical relationship between the gas pressure gradient and gas flow.^{26–28} An et al.²⁹ calculated the coal seam gas pressure by analyzing the theoretical solution of the coal gas diffusion process. Zhang³⁰ combined the occurrence characteristics of coal seams and constructed a pressure recovery curve method for gas measurement in coal seams. In addition, the gas pressure in coal seams can be predicted by experiments and model methods. Through experimental research, Dutka and Godyń.³¹ predicted and analyzed the gas pressure in coal seams with different depths. Skiba et al.³² estimated coal seam gas pressure based on the multilayer perceptron model, and the result error was small.

At present, there are some problems in the process of gas pressure measurement, such as the testing link being more tedious and prone to large errors and repeated testing means being used to ensure the reliability of the test results. In addition, it also includes the shortcomings of a long gas pressure balance time and high measurement time cost. There are many influencing factors in the process of gas pressure measurement, and it is impossible to judge whether the pressure measurement result is accurate. Based on this, an experiment and numerical simulation study on the change law of gas pressure in a coal sample borehole was carried out in this paper, and the dynamic evolution model of gas pressure in the borehole was established. Furthermore, a method for judging the accuracy of the gas pressure measurement result in coal seams was proposed, and the method was verified by experiments in the field.

2. EXPERIMENTAL WORK

2.1. Experimental Devices. The experimental system is shown in Figure 1, including a coal sample tank, reference tank, high-pressure gas cylinder, vacuum pump, vacuum gauge, pressure gauge, and valves. The above-mentioned instruments can be divided into a pressure measuring system, degassing system, inflation system, and data acquisition system. Among them, the pressure measuring system is composed of a coal sample tank and reference tank. The coal sample tank holds the coal sample and carries out the gas adsorption, and there is a metal cylinder in the center of the bottom, which is used to form a drilling hole when pressing the coal sample and taking it out after the pressing is finished. The reference tank is filled with high-pressure gas to provide a stable pressure gas adsorption environment. The degassing system is a vacuum pump and vacuum gauge. A vacuum pump provides the degassing power of the experimental system to form a vacuum environment, and the vacuum gauge is used to measure the vacuum degree of the system. The high-pressure gas cylinder of the charging system contains methane with a purity of more than 99.99%, which provides enough gas for the experimental system. The data acquisition system uses a pressure gauge to measure the internal pressure of the reference tank and the sample tank, with a sampling frequency of 10 Hz.

2.2. Coal Sample Preparation. The coal samples used in the experiment are from the 864 working face of coal seam 82 in the Tongting coal mine. The thickness of the coal seam in this working face is 2.19–3.40 m, with an average thickness of 2.35 m, medium ash, which belongs to high-calorific value fat coal. Raw coal was ground, and granular coal with a particle size of 0–0.25 mm was selected. Industrial analysis of experimental coal samples is carried out, and the specific parameters are shown in Table 1. The selected pellet coal is fully mixed with a certain amount of coal tar, put into the coal

Table 1. Industrial Analysis Parameters of the Experimental Coal Samples

moisture/%	ash/%	volatile/%	calorific value/(MJ/kg)	fixed carbon/%	sulfur/%
1.23	23.97	31.24	26.28	45	0.42

sample tank, and pressed under fixed pressure for 12 h, and the experimental briquette can be obtained. The specification of the experimental coal sample is a cylinder with a diameter of 100 mm and a height of 160 mm.

2.3. Experimental Scheme.

- (1) Adjust the experimental temperature. The temperatures of the experimental environment, experimental equipment, and experimental coal samples are all stable. Through the temperature control device, the temperature set in the experiment is 23 °C.
- (2) Airtightness test. One should inject gas into the coal sample tank and reference tank and keep it still to observe whether the pressure representation is stable. If the indicator does not change, it shows that the airtightness of the system is well, and there is no air leakage.
- (3) Vacuum degassing. The vacuum pump is connected to the coal sample tank and the reference tank to degas the experimental system. When the vacuum indicator is reduced to 20 Pa, pumping is stopped, and the system is kept still. If the number does not change, it indicates that the vacuum of the system is well.
- (4) Charging with methane. A certain volume of methane is filled into the reference tank using a high-pressure gas cylinder, and the reference tank is kept airtight after the filling is completed.
- (5) Adsorbing methane. The reference tank filled with methane is connected to the coal sample tank so that the coal sample in the coal sample tank begins to adsorb methane. One should stand still for a period of time. When the pressure representation number remains stable and no longer changes, it indicates that the coal sample has reached the equilibrium state of gas adsorption and desorption. After that, one should reseal the coal sample tank.
- (6) Simulated borehole pressure measurement. Valve 4 is opened to connect the coal sample tank with the external environment. When the pressure expression is reduced to 0, it means that all the gas in the coal sample drill hole has been discharged, corresponding to the actual working condition when the coal seam drilling is completed. Then, the coal sample tank is resealed so that the gas in the surrounding coal sample begins to spread to the drilling area, and the pressure expression of the coal sample tank is recorded until the pressure reaches a stable state, and the experimental process ends.

3. THEORETICAL MODEL AND NUMERICAL METHOD

3.1. Theoretical Model. Coal is a dual structure composed of coal particles and fissures with pores, which simplifies the coal body to a dual medium model of matrix and fracture.³³ The process of gas flow in pressure-measuring boreholes can be regarded as a continuous process in which gas is first desorbed from the pore surface of coal and then diffused through the coal matrix, and it finally seeps into the borehole from the cracks.³⁴ The following physical assumptions are introduced: (1) The coal matrix can be simplified to the continuum model. (2) The gas content absorbed by the coal body conforms to the Langmuir equation. (3) The coal matrix is isotropic, and the gas flow in the coal matrix conforms to Fick's law. (4) Gas flow in the fracture follows the Darcy seepage law.

Gas generally exists in coal in the adsorption state and free state, and the gas in the two states is transformed into each other. The gas in the pore system of the coal matrix flows in the form of diffusion under the concentration gradient,³⁵ which conforms to Fick's law

$$J_m = -D_m \nabla C_m \quad (1)$$

where J_m denotes the diffusion flux, $m^3/(m^2 \text{ s})$; D_m is the diffusion coefficient, m^2/s ; and C_m is the diffused gas content, m^3/m^2 . Liu and Lin found that the diffusion coefficient D of gas in the matrix varies with the diffusion time,³⁶ and the functions of the dynamic diffusion coefficient and time are as follows

$$D_m = D_0 \exp(-\eta t) + D_r \quad (2)$$

In the equation, D_0 is the initial diffusion coefficient of the coal matrix, m^2/s ; η is the attenuation coefficient, s^{-1} ; t is the residual diffusion coefficient of the coal matrix, s ; and D_r is the residual diffusion coefficient of the coal matrix. The gas content in the coal matrix is the sum of the adsorption state and free state,³⁷ that is

$$q_m = q_a + q_g = \frac{abp_m \rho_s \rho_n}{1 + bp_m} + \frac{p_m M \varphi}{ZRT} \quad (3)$$

where q_a represents the adsorbed gas quantity, m^3/kg ; q_g is the free gas quantity, m^3/kg ; a is the maximum adsorption capacity, m^3/kg ; b is the adsorption constant, MPa^{-1} ; p_m is the coal matrix gas pressure, MPa ; ρ_s is the coal density, kg/m^3 ; ρ_n is the gas density in the standard state, kg/m^3 ; M is the gas molar mass, g/mol ; φ is the porosity of coal, %; Z is the free gas compression factor; R is the gas constant, $\text{J}/(\text{mol K})$; and T is the temperature, K . According to the principle of conservation of mass,³⁸ the change of gas in the matrix is equal to the difference between the mass of the inflow and outflow of the matrix, subtracting the exchange amount from the pore to the fracture, that is,

$$\frac{\partial \left(\frac{abp_m \rho_s \rho_n}{1 + bp_m} + \frac{p_m M \varphi}{ZRT} \right)}{\partial t} + \nabla \cdot (-D_m M \nabla C_m) = 0 \quad (4)$$

Among them, the concentration of gas can be expressed according to the equation of state of ideal gas

$$C_m = \frac{p_m}{ZRT} \quad (5)$$

Equations 1, 2, and 5 can be substituted into 4, which can be obtained as

$$\left[\frac{ab\rho_s \rho_n}{(1 + bp_m)^2} + \frac{p_m M \varphi}{ZRT} \right] \frac{\partial p_m}{\partial t} - [D_0 \exp(-\eta t) + D_r] \frac{M}{ZRT} \nabla^2 p_m = 0 \quad (6)$$

Equation 6 is the pore gas flow equation of the coal matrix. Free gas in coal fissures flows in the form of seepage, and the microelement in the fissures is analyzed. Within a unit time, the difference between the mass of the microfracture elements flowing in and out of the microfissures in all directions, coupled with the exchange capacity J_s that desorbed from the pores and into the fissures, is equal to the mass change of the fracture microelements,³⁹ that is,

$$\frac{\partial(\varphi\rho_f)}{\partial t} = -\nabla(\rho_f v) + J_s \quad (7)$$

where ρ_f is the gas density of coal fissures, kg/m^3 ; J_s is the exchange capacity of pores into the fissures, $\text{m}^3/(\text{m}^2 \text{ s})$; and v is the percolation velocity of gas in coal fissures, m/s . Considering the Klinkenberg effect,⁴⁰ Darcy's law can be expressed as

$$v = -\frac{k}{\mu} \left(1 + \frac{m}{p_f} \right) \nabla p_f \quad (8)$$

In the equation, k is the permeability of coal, m^2 ; μ is the dynamic viscosity coefficient, Pa s ; m is the Klinkenberg coefficient, Pa ; and p_f is the coal fracture gas pressure, MPa . In the process of gas migration, gas density and gas pressure satisfy the following relationship.

$$\rho_f = \frac{Mp_f}{ZRT} \quad (9)$$

By substituting eqs 7 and 8 into 9, the fracture gas flow equation can be obtained.

$$\varphi \frac{\partial p_f}{\partial t} = \nabla \left[\frac{k}{2\mu} \left(1 + \frac{m}{p_f} \right) \nabla p_f^2 \right] + ZRTJ_s \quad (10)$$

According to the above-mentioned analysis, in the process of gas migration, because the seepage velocity of gas in the fracture is much larger than the diffusion velocity of gas in the pore, there is matrix exchange capacity J_s between pores and fractures.⁴¹ The matrix exchange capacity J_s can be expressed as

$$J_s = -\frac{3D_m}{r} \nabla \rho_m = -[D_0 \exp(-\eta t) + D_r] \frac{3M}{rZRT} \nabla p_m \quad (11)$$

where r denotes the radius of the coal matrix, m , and ρ_m is the gas density of the coal matrix, kg/m^3 . According to above-mentioned established pore gas flow eq 6, fracture gas flow eq 10, and matrix exchange capacity eq 11, the gas flow control equations of pore–fracture dual media can be obtained.

$$\left\{ \begin{array}{l} \left[\frac{ab\rho_s\rho_n}{(1+b p_m)^2} + \frac{p_m M \varphi}{ZRT} \right] \frac{\partial p_m}{\partial t} \\ = [D_0 \exp(-\eta t) + D_r] \frac{M}{ZRT} \nabla^2 p_m \\ \varphi \frac{\partial p_f}{\partial t} = \nabla \left[\frac{k}{2\mu} \left(1 + \frac{m}{p_f} \right) \nabla p_f^2 \right] + ZRTJ_s \\ J_s = -[D_0 \exp(-\eta t) + D_r] \frac{3M}{rZRT} \nabla p_m \end{array} \right. \quad (12)$$

Equation 12 is the control equation of gas migration in the coal seam in the process of pressure measurement. The equation set takes the matrix exchange capacity equation as the bridge and connects the pore gas flow equation and the fracture gas flow equation. The above-mentioned partial differential control equations together constitute the flow field migration model in the process of gas pressure measurement, which provides a theoretical basis for subsequent numerical simulation research.

3.2. Numerical Method. In this work, the OpenFOAM platform is used for numerical simulation. OpenFOAM, whose

full name is Open Field Operation and Manipulation, is a computational fluid dynamics (CFD) software package based on the object-oriented methods of the C++ and Linux platforms. The size of the simulation example is consistent with that of the coal sample in the experimental scheme. The diameter is 108 mm, and the length is 188 mm. A borehole with a diameter of 16 mm and a length of 65 mm is set in the middle of one end of the coal sample. In the process of meshing geometry, nonstructural meshes are used, and the number of meshes is more than 30,000 (Figure 2).

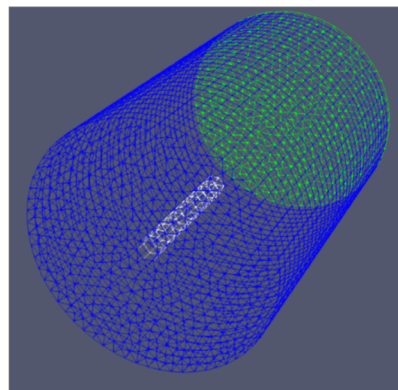


Figure 2. Mesh division of the coal sample.

The initial parameters of the control equation mainly include the original coal seam gas pressure, basic coal parameters, and Langmuir constants. Because there are gas adsorption, seepage, and diffusion in this process, the determination of model parameters has an important influence on the convergence time, convergence rate, and accuracy of the solution process. Combined with the experimental conditions, the equilibrium pressure of methane adsorption on coal samples in the initial state is 0.705 MPa. Referring to the experimental coal sample parameters and reference,^{42–44} other parameter values are set as shown in the table below (Table 2).

Table 2. Parameters of Numerical Simulation

parameter	Value	parameter	value
coal apparent density ρ_s	1350 kg/m^3	coal porosity φ	0.04
coal permeability k	$2.0 \times 10^{-16} \text{ m}^2$	gas viscosity μ	$1.0 \times 10^{-5} \text{ Pa s}$
adsorption constant a	20.12 m^3/t	adsorption constant b	0.52 MPa^{-1}
Klinkenberg coefficient m	$1.44 \times 10^5 \text{ Pa}$	initial diffusion coefficient D_0	1.8×10^{-11}
residual diffusion coefficient D_r	0.9×10^{-11}	standard gas density ρ_n	0.714 kg/m^3
gas attenuation coefficient η	0.9×10^{-7}	gas constant R	8.3143 $\text{J}/(\text{mol}\cdot\text{K})$
gas molar mass M	16 g/mol	temperature T	293 K

In the simulation, the borehole side of the coal sample is a variable boundary condition, the pressure changes in real time with the gas pressure and concentration difference between the gas in the borehole and the coal, and the other end of the coal sample is the zero-flux boundary condition. After the pressure measurement begins, the methane in the coal seam seeps into the borehole due to the action of the pressure gradient, which

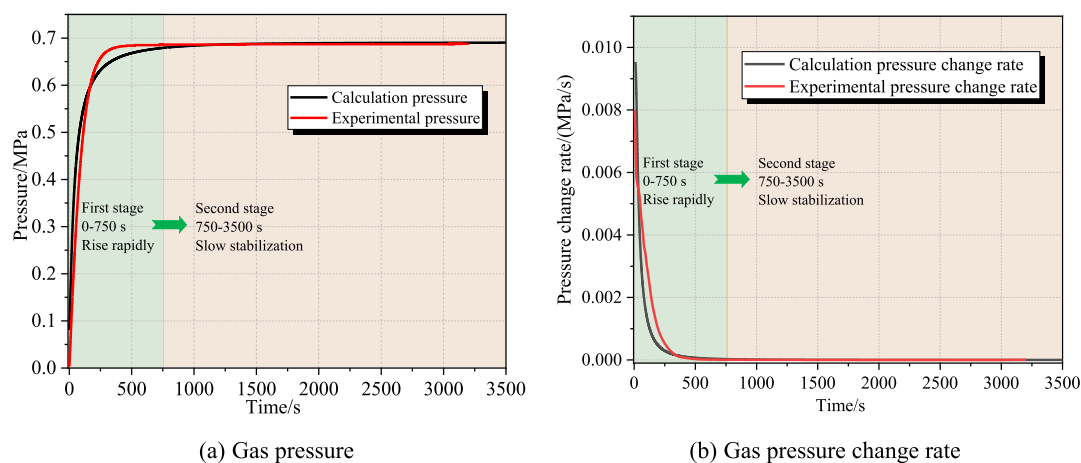


Figure 3. Comparison of simulated and experimental gas pressures and change rates.

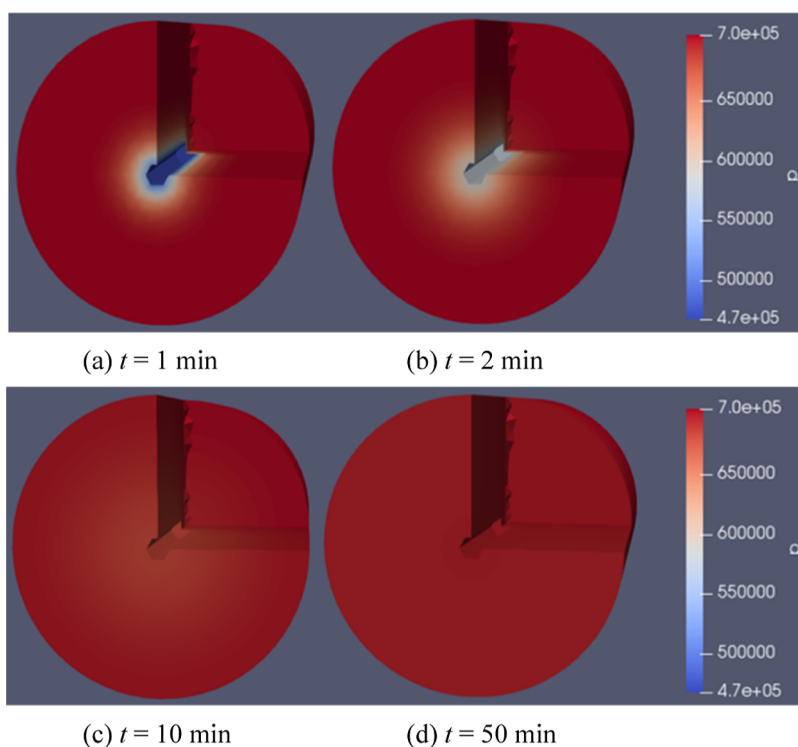


Figure 4. Cloud map of the simulated gas pressure in the borehole.

leads to a continuous increase in the gas pressure in the borehole until the pressure inside and outside the borehole is balanced. Based on the theoretical model, meshing, and the setting of initial and boundary conditions, a numerical solver for simulating the evolution of gas pressure is developed on the OpenFOAM platform based on the C++ language.

4. RESULTS AND DISCUSSION

4.1. Gas Pressure Evolution. The comparison between the experimental results and simulation results of gas pressure in boreholes is shown in Figure 3. The red curve represents the gas pressure change data measured in the experiment, and the black curve represents the gas pressure change data obtained by numerical simulation.

It can be seen from the experimental pressure that after the initial closure of the coal sample tank, the gas pressure increases rapidly from 0 MPa, reaches the peak value in 750 s,

approximately 0.689 MPa, and then basically remains stable. Therefore, the curve can be divided into two stages: In the first stage, the gas pressure rises rapidly, but the rising rate slows down gradually. This is because the gas in the borehole is basically discharged before sealing, and the pressure is basically the same as the ambient atmospheric pressure, while the gas in the coal around the borehole is gradually desorbed and migrates to the borehole, resulting in a rapid rise in pressure. Meanwhile, with the decrease in the pressure gradient and concentration gradient inside and outside the borehole, the rising rate of the gas pressure decreases gradually. In the second stage, the pressure increases slowly and finally becomes stable, and the pressure change rate gradually decreases. The data curve of the numerical simulation results also shows the same trend as the experimental results.

The change in gas pressure near the borehole of the coal sample is also obtained by numerical simulation, as shown in

Figure 4. The gas pressure in the coal borehole increases rapidly from 0 and reaches the equilibrium pressure of the surrounding coal body in a relatively short time.

4.2. Simplified Equation of Gas Pressure. Figure 3 shows that when the gas pressure is low, the growth rate increases, and with increasing gas pressure, the growth rate decreases gradually and finally approaches 0. On this basis, it can be assumed that the change rate of gas pressure Δp is proportional to the gas pressure p and the product of the difference between the gas pressure p and the original gas pressure p_0 , and the proportional coefficient is recorded as k . Then, a differential equation is established according to the above-mentioned conditions

$$\frac{dp}{dt} = kp(p_0 - p) \quad (13)$$

The general solution of the differential equation is obtained by integrating both sides

$$p = \frac{p_0}{1 + ce^{-kp_0 t}} \quad (14)$$

Let $A = p_0$ and $D = kp_0$. The equation is simplified to

$$p = \frac{A}{1 + ce^{-Dt}} \quad (15)$$

In the equation, c is an undetermined constant, and D is affected by the coal seam permeability, borehole diameter, and adsorption constant. This equation is the prediction equation of the borehole gas pressure variation curve. The gas pressure calculated according to eq 15 and the gas pressure obtained by experimental measurement are compared. As shown in Figure 5, the two are in better agreement, and the correlation

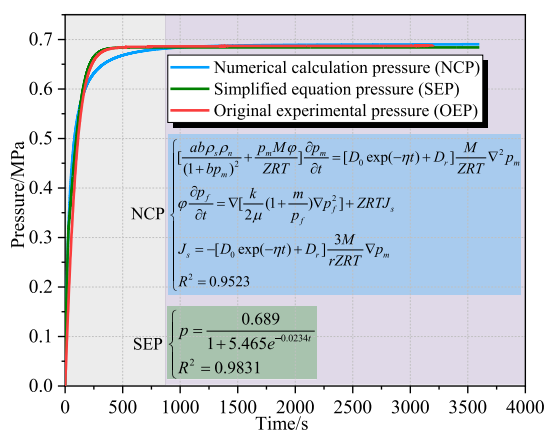


Figure 5. Comparison of the calculated and experimental gas pressures.

coefficient of R^2 is 0.9831. The results show that the equation can better reflect the changing law of gas pressure in coal seam boreholes.

4.3. Field Experimental Verification. Previously, the characteristic law of coal seam gas pressure and the quantitative model equation were obtained through experiment and simulation research. In this section, the rationality of the equation was verified by the field-measured data of the coal mine. This paper used the coal seam hole pressure measurement data of a coal mine in Yilan, Heilongjiang Province. Six drilling holes were selected in the upper 1, upper 2, and middle coal seams, in which the boreholes in the upper 1 coal seam were numbered S1-1 and S1-2, the drilling holes in the upper 2 coal seam were numbered S2-1 and S2-2, and the boreholes in the middle coal seam were numbered Z-1 and Z-2. Using the passive pressure measurement method, the distance between the opening site and the roadway floor is approximately 1.5 m, and the diameter of the drill hole is 94 mm. The specific parameters are shown in Table 3. One should stand still for 24 h after the completion of the drilling construction to ensure that the original gas in the drill hole has been fully discharged. Then, the hole was sealed, and when the hole was sealed for 24 h, the change in pressure expression was observed. When the variation range of borehole pressure within 3 days is less than 0.015 MPa, it is considered that the borehole gas pressure has been stable, and the pressure measurement is over.

The gas pressure data of six boreholes are applied to eq 15, and the measured gas pressure changes are compared with the fitting results of eq 12, as shown in Figure 6. It can be seen that for all six groups of working conditions, eq 15 is in better agreement with the measured results. The Z-1 borehole has the highest degree of fit, with a value of 0.9859. The lowest is also above 0.94. This shows that the fitting degree between the on-site coal seam gas pressure measurement data and the pressure measurement curve equation is relatively high, and the equation can well reflect the law of the field coal seam gas pressure measurement data.

5. CONCLUSIONS

- (1) The experiment of measuring gas pressure in coal seam boreholes was carried out, and the whole process of gas pressure rising until reaching stability after borehole sealing was continuously monitored. The evolution of gas pressure in coal seam boreholes can be divided into two stages. In the first stage, the gas pressure rises rapidly, and the pressure change rate decreases continuously. In the second stage, the gas pressure is slow and stable, and the pressure change rate tends to 0.
- (2) The theoretical process of gas occurrence, migration, and seepage in coal seams was analyzed, the corresponding control equation was constructed, and the solver was

Table 3. Basic Parameters of Drilling

drill hole number	azimuth angle/deg	inclination angle/deg	sealing section/m	expose coal point/m	uncover coal point/m	uncover coal elevation/m	buried depth/m
S1-1	28	42	52	52	58	-545.2	645.2
S1-2	353	45	54	54	58	-541.8	641.8
S2-1	298	37	41	41	51	-555.3	655.3
S2-2	353	36	42	42	53	-555.3	655.3
Z-1	240	40	32	32	45	-519.1	619.1
Z-2	310	38	33	33	43	-516.9	616.9

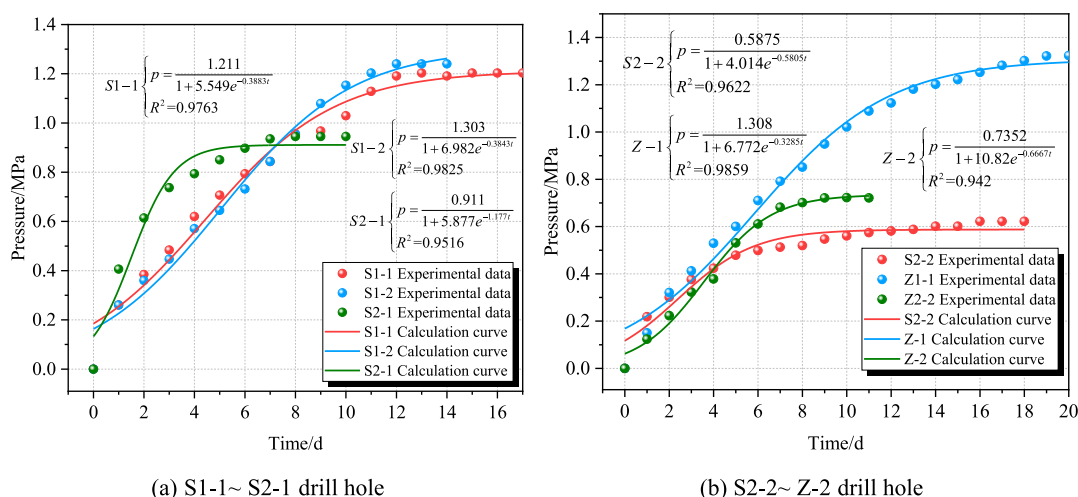


Figure 6. Comparison of gas pressure between the practical measurement and theoretical model.

compiled based on the OpenFOAM platform. The simulation results are in better agreement with the experimental results.

- (3) Based on the experimental and simulation results, the evolution model of gas pressure with time was deduced. Compared with the field-measured data of the coal mine, the correlation coefficient is more than 0.94, which shows that the model can well reflect the evolution law of gas pressure in coal seam boreholes.

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Notes

The authors declare no competing financial interest.

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