INTRODUCTION

As an unconventional natural gas attached to the coal seam, coalbed methane (CBM) has aroused wide public attention. CBM is also a gas, whose main component is methane. CBM is not only a disaster factor and greenhouse gas in coal mining but also a source of clean energy. Therefore, the development of CBM will not only effectively reduce the emission of methane and slow down the greenhouse effect but will also be an effective measure to prevent disasters such as coal and

Abstract

The permeability characteristics of gas-containing coal under different radial stress, different axial stress, and gas pressure were studied by orthogonal experiments, using a self-developed three-axis servo fluid infiltration system with a gas-solid coupling of gas-containing coal, on the basis of a single-factor influence on the permeability of gas-containing coal. By considering the effective stress, three kinds of relationships between permeability and radial stress, permeability and axial stress, as well as permeability and gas pressure were established. The results show that radial stress, axial stress, and gas pressure have a great influence on the permeability characteristics of gas-containing coal: (a) The influence of radial stress on gas permeability is significant, whereas the influence of axial stress is negligible. The degree of influence of radial stress, gas pressure, and axial stress on the permeability decreases in turn; (b) The permeability decreases following a power function with the increase of the radial stress; (c) The permeability gradually increases with the increase of axial stress. With the increase of axial stress, the permeability increases following a power function; (d) The increase in gas pressure will reduce the effective stress on the coal, and the number of pores and cracks inside the coal body will decrease. This will increase the effective seepage flow and gas flow rate of the gas and eventually lead to the increase of coal permeability. There is a quadratic function relationship between the permeability and gas pressure.

KEYWORDS

axial stress, gas pressure, gas-containing coal, influencing factors, permeability, radial stress
gas outbursts in mines. Moreover, the occurrence of gas accidents in coal mines is still very frequent. The gas disasters in a coal seam can be attributed to the flow of gas in the coal seam, that is, the seepage of gas in the coal seam. Therefore, the seepage characteristic of CBM has been increasingly becoming an important research direction in the field of gas disaster prevention. Coal seam permeability is one of the important parameters reflecting the difficulty degree of gas seepage in a coal seam and the outburst of coal and gas.

In terms of the influencing factors of permeability, domestic and overseas scholars have done considerable research work and achieved fruitful research results. Harpalani et al. conducted experiments on the conventional permeability of coal and established a coupling relationship between effective stress and coal rock mass. Zhang et al. indicated that the flow rate of gas in the coal sample gradually decreases with the nonlinear loading of axial pressure and increases with the nonlinear unloading of axial stress and confining pressure. McKee et al. established the relationship among permeability, porosity and density of coal, effective stress and buried depth, and validated it using field data. Hema et al. used carbon dioxide as seepage gas and studied the effect of confining pressure on the permeability characteristics of coal. Somerton et al. used nitrogen and gas as seepage gas to study the permeability of coal under triaxial stress. Xu et al. conducted a study on the permeability characteristics of coal samples under a full stress and strain process, and obtained the equation of the relationship between coal sample permeability and principal stress difference, axial strain and volumetric strain. However, the effects of gas adsorption and temperature effects are not considered. Tang et al. simulated the occurrence and migration of CBM under complex geostress conditions, and verified through experiments that gas molecules enter the coal matrix during gas adsorption and seepage, causing coal matrix expansion. It affects the seepage law of gas in the coal seam and reduces the gas permeability of the coal seam. Zhao et al. pointed out that gas adsorption and deformation have an important influence on gas seepage in coal seams, and the permeability changes with pore pressure, denoting the existence of a critical value. When the pore pressure is less than the critical value, the permeability of the coal seam is attenuated, and vice versa. Han et al. studied the effect of temperature on the permeability of coal, and concluded that the permeability increases with the increase in temperature and has a positive exponential relationship. Gilman et al. studied the effects of the ground stress and geoelectric field on CBM migration, and applied the basic principles of seepage theory to derive coalbed methane seepage equations considering the ground stress and geoelectric field. The study considered that the gas seepage flow increases approximately linearly with the increase of electric field intensity. He et al. concluded that the permeability of coal seams is exponentially related to the ground stress.

Zheng et al. conducted experiments and simulations on the permeability characteristics of different coal ranks.

It can be seen that the permeability of CBM is affected by many factors. However, the studies above only consider a single factor and have not reflected the degree of influence of various factors on the permeability of CBM. Therefore, it is necessary to study the influence of multiple factors on the permeability of CBM to provide more scientific guidance for selecting coal samples and accurately measuring the permeability of coal samples.

In addition, the underground coal is in a loaded gas state, and therefore, it is more meaningful to study the characteristics of the gas seepage in the original coal, which is more practical for the underground coal mining. Therefore, in this paper, a self-developed three-axis servo fluid infiltration system with a gas-solid coupling of CBM is used, through the orthogonal experimental study of gas seepage in the raw coal sample of Lubanshan North Mine (LBS), and the permeability of gas-containing coal under different radial stress, different axial stress and different gas pressure conditions is studied. The seepage characteristics of CBM are fitted to the equations of motion of gas-bearing nonlinear seepage in coal seams, which provides a theoretical basis for gas drainage and CBM recovery in mines.

2 | EXPERIMENT

2.1 | Experimental principle

During the experiment, the gas flow in coal samples complies with gas seepage theory. That is, gas migration in a coal seam is basically in accordance with the law of linear infiltration—Darcy’s law, and the permeability of gas-containing coal gas is obtained according to the flow of the coal sample and the osmotic pressure at both ends of the coal sample.
Calculate the coefficient of permeability, \( k \), at each mean pressure, as follows\(^{27} \):

\[
k = \left[ \frac{(2Q_e\mu_L)}{\left( \frac{P_i^2 - P_e^2}{A} \right)} \right],
\]

where \( k \) is the coefficient of permeability, mD. \( Q_e \) is the exit flow rate of air, m\(^3\)/s. \( P_e \) is the exit pressure of air, Pa. \( L \) is the length of the specimen, m. \( A \) is the cross-section area of the specimen, m\(^2\). \( P_i \) is the entrance pressure of air, Pa, and \( \mu \) is the viscosity of air at the temperature of the test, Pa·s.

Compute the mean pressure of each test for each specimen, and then calculate the reciprocal of each mean pressure, as follows:

\[
2/(P_i + P_e).
\]

Plot the coefficient of permeability vs the reciprocal of the mean pressure for each test of a specimen, see Figure 1. Draw a straight line through at least three points and extrapolate the line to intersect the ordinate line at the zero reciprocal mean pressure. The value of \( k \) at the intersection is the equivalent liquid permeability of the specimen.

2.2 | Experimental equipment

The test equipment is an independently developed triaxial servo fluid-solid coupling system with gas, coal, and heat. The device mainly includes a hydraulic system, gas supply, and acquisition system, triaxial infiltration system, stress-strain acquisition system, and constant temperature water bath heating system. All the data in the system are automatically collected by the computer, as shown in Figure 2. This system can simulate the gas permeation characteristics under different ground stresses and different temperature fields and therefore provide better results.

The main performance parameters of the test system are as follows:

1. Confining pressure: 0 to 25 MPa with a precision of ± 0.1 MPa.
2. Gas pressure: 0 to 6 MPa with a precision of ± 0.1 MPa.
3. Axial pressure: 0 to 70 MPa, with a precision of ± 0.1 MPa.
4. Gas mass flow meter: 100 sccm (standard-state cubic centimeter per minute), 15 slm (standard liter per minute) and 2 slm, which can automatically switch.
5. Constant temperature water bath: −25°C to 95°C, with a precision of ±0.1°C.

2.3 | Preparation of coal samples

The coal samples were obtained from the LBS of South Sichuan Coal Luzhou Co., Ltd., which is located in Yibin City, Sichuan Province. The coal mine contains several minable coal seams, whose geological conditions are simple. As shown in Figure 3, the coal samples were collected from coal seam #2, and marked as N-2. Each raw coal sample was taken from the same site, and prepared according to “Methods for determining the physical and mechanical properties of coal.
and rock-Part 1: General requirements for sampling.”28 In addition, the gas pressure and the temperature of N-2 coal seams were also measured.

The outburst risk of the N-2 coal seam of LBS is evaluated in accordance with “Specification for identification of coal and gas outburst mine”29 and “Prevention and Control of Coal and Gas Outburst (2009).”30 In addition, as shown in Table 1, the outburst risk evaluation index measured results of N-2 coal seams were compared with the coal and gas outburst identification thresholds. Then, it can be concluded that the N-2 coal seam has the risk of a coal and gas outburst.

In addition, as shown in Table 2, some of the basic parameters and proximate analysis of N-2 coal were tested. True and false densities were measured by an MDMDY-300 automatic density instrument (China Shanghai Grows Precision Instrument Co., Ltd, Shanghai, China). Proximate analysis was determined in accordance with “Proximate analysis of coal.”31 The coal classification index (Rºmax) was conducted in accordance with “Method of determining microscopically the reflectance of vitrinite in coal.”32 According to the measured parameters shown in Table 2, it can be concluded that N-2 coal is highly metamorphic, low-ash and low-sulfur anthracite.

In the laboratory, coal samples are prepared in accordance with the “Method for preparation of coal sample (GB/T 482-2008).”33 First, select the large block and raw coal with good

| Term        | $D_{cf}$ | ΔP (mm Hg) | $f$  | $P$ (MPa) | $W$ (m³/t) |
|-------------|----------|------------|------|-----------|-------------|
| Thresholds  | III, IV, V | ≥10        | ≤0.5 | 0.74      | W ≥ 8       |
| N-2         | V        | 20.5       | 0.492 | 1.61      | 15.6377     |

$D_{cf}$ is the degree of coal fracturing, dimensionless; ΔP is the initial gas diffusion velocity of coal, mm Hg; $f$ is the coal hardiness coefficient, dimensionless; $P$ is the coal seam gas pressure, MPa; $W$ is the coal seam gas content, m³/t.

Table 1 Comparison between outburst risk evaluation index and identification thresholds

Table 2 Basic parameters and proximate analysis of N-2 coal sample

| Proximate analysis indexes | Basic parameters |
|---------------------------|------------------|
| $M_{ad}$ (%) | $A_{ad}$ (%) | $V_{daf}$ (%) | $C_{daf}$ (%) | $R^\text{max}$ (%) | TRD (g/cm³) | ARD (g/cm³) | n (%) |
| 1.62 | 9.07 | 6.29 | 92.52 | 3.03 | 1.59 | 1.56 | 1.89 |

$M_{ad}$ is the moisture content on an air-dry basis, %; $A_{ad}$ is the ash content on an air-dry basis, %; $V_{daf}$ is the volatile matter content on a dry-ash-free basis, %; $C_{daf}$ is the carbon content on a dry-ash-free basis, %; $R^\text{max}$ is the vitrinite group maximum reflectance, %; TRD is the true relative density, g/cm³; ARD is the apparent relative density, g/cm³; n is the ratio of the total volume of tiny voids in the coal to the total volume of coal, %.
integrity. Second, core the coal sample using a Φ50 mm core barrel. Third, cut the coal core samples into a standard length using a cut machine. The standard coal samples’ size is Φ50 mm × 100 mm, as shown in Figure 4. Fourth, the prepared coal samples are dried and placed in a drying oven.

Due to the close wave speed characteristics of the coal samples, the development of internal cracks is similar. Therefore, in order to prevent different crack developments from affecting seepage results, it is necessary to check the standard coal samples before the seepage test. Therefore, the wave speed detector HS-FSB4C is used to choose the standard coal samples with a close wave speed. The wave speed of standard coal samples for the seepage test is shown in Figure 5.

2.4 | Experimental procedure

During the experimental process, methane gas with a purity of 99.99% is used for the seepage flow of gas-containing coal under different stress loading paths. Since adsorption/desorption is extremely sensitive to temperature, the entire container was placed into the constant temperature water bath with the water temperature kept the same as the N-2 coal seam temperature during the entire set of experiments.

Experimental steps are as follows:

1. Obtain the number marks of coal samples. Install the rubber boot, coal sample, and loading indenter onto the cylindrical underhead in the sealed cylinder of the gas seepage device, keeping the axis of the coal sample perpendicular to the plane of the underhead.

2. To prevent the flow of gas from the gap between the coal sample wall and rubber cover, it is necessary to wipe a layer of silicon rubber with a thickness of approximately 1 mm on the surface of the standard coal sample wall.

3. Tighten the external sealing screw cylinder, check and connect all the pipes and instruments, and ensure that the test equipment is airtight.

4. Start the hydraulic pump; then, allow the hydraulic oil to fill the cylinder so that the triaxial pressure chamber reaches the predetermined confining pressure value.

5. After the confining pressure is stable, apply a predetermined axial pressure on the coal sample and fill the gas to a certain pressure to check the airtightness of the device. After the airtightness inspection is done, open the gas valve and inject gas with a preset pressure into the coal sample. After the gas flow rate is stabilized, record the initial gas flow.

6. After the above five steps are completed, the seepage experiments can be performed successively.

2.5 | Experimental design

The influencing factors of the permeability of gas-containing coal are mainly investigated, which include axial stress, radial stress, and gas pressure. Each factor is selected at three levels for testing. The level of experimental factors is shown in Table 3. The purpose of this paper is to study the influence mechanism of gas coal permeability and determine the degree of influence of each factor. Three levels of testing were conducted for all three factors without considering the interaction among these factors, and therefore, a table of \( m = 3 \) was chosen.

3 | EXPERIMENTAL RESULTS AND ANALYSIS

3.1 | Experimental results

According to the experimental procedure, the factors affecting the permeability of gas-containing coal are tested based
on the experimental design. A total of nine tests are performed, and the experimental results are shown in Table 4. After the experiment is completed, the permeability of gas-containing coal in different experimental schemes is calculated according to equation (1). From Table 4, it can be seen that the permeability of gas-containing coal is at the maximum when the radial stress is at the minimum, the axial stress and gas pressure both being the largest. The experimental data are the smallest when the radial stress is at the maximum, the axial stress is 3 MPa, and the gas pressure is at the minimum.

3.2 Range analysis

Orthogonal experimental results are usually processed with two methods: range analysis and variance analysis. First, the range analysis method is used to analyze the influence of various factors on the change of the permeability of gas-containing coal under many factors. Then, the significance of each factor is analyzed by means of variance.

The analysis of the range of each factor is shown in Table 5. $K_i$ in the table indicates the sum of the experimental results corresponding to the horizontal number in any column. $k_i = K_i/S$, where $S$ is the number of occurrences at each level in any column; therefore, $k_i$ is the arithmetic mean value of the experimental results obtained when the factor at any level is taken at level $i$. $R$, known as the range, on any column is $R = \max\{K_1, K_2, K_3\} - \min\{K_1, K_2, K_3\}$.

In general, the range of each column is not equal, indicating that the change in the level of each factor has a different effect on the experimental results. The greater the range difference is, the more significant the change in the value of the column within the test range will be. The index of the experiment has a greater change in value, so the column with the maximum range is the factor that has the most influence on the experimental result, which is the most important factor. From Table 5, it can be concluded that $R_A (0.0158) > R_C (0.0036) > R_B (0.0018)$, so the order from primary to secondary of each factor is: A (radial stress) → C (gas pressure) → B (axial stress).

The trend chart of the experimental data clearly shows the optimal level of each factor, and it is also possible to compare the influence of various factors on the experimental indicators. Taking the level of every factor in Table 5 as the abscissa, and taking the average of $K_i$ as the ordinate, the relationship between the factors and permeability is drawn. The influence trend of each factor on the permeability of gas-containing coal is shown in Figure 6.

From Figure 6, it can be found that the permeability of gas-containing coal decreases obviously with the increase of radial stress, and the larger the radial stress is, the greater the decrease will be. The permeability increases with the increase of axial stress, and increases significantly with the increase of gas-containing coal under many factors. Then, the significance of each factor is analyzed by means of variance.

### Table 3 Experimental scheme

| Number | Radial stress (A) (mm) | Axial stress (B) (%) | Gas pressure (C) (MPa) | Empty column (Ec) | Scheme |
|--------|------------------------|---------------------|------------------------|------------------|--------|
| 1      | 2                      | 2                   | 0.5                    | 1                | $A_1B_1C_1$ |
| 2      | 2                      | 3                   | 1.0                    | 2                | $A_1B_2C_2$ |
| 3      | 2                      | 4                   | 1.5                    | 3                | $A_1B_3C_3$ |
| 4      | 3                      | 2                   | 1.0                    | 3                | $A_2B_2C_3$ |
| 5      | 3                      | 3                   | 1.5                    | 1                | $A_2B_3C_3$ |
| 6      | 3                      | 4                   | 0.5                    | 2                | $A_2B_1C_1$ |
| 7      | 4                      | 2                   | 1.5                    | 2                | $A_2B_1C_3$ |
| 8      | 4                      | 3                   | 0.5                    | 3                | $A_2B_1C_1$ |
| 9      | 4                      | 4                   | 1.0                    | 1                | $A_2B_2C_2$ |

Columns that do not place factors or interactions in them are called empty columns (Ec). Empty columns are also called error columns in the analysis of variance in orthogonal designs. It is generally best to leave at least one empty column.
TABLE 4  Experimental results

| Number | A  | B  | C  | Ec | k (mD) |
|--------|----|----|----|----|--------|
| 1      | 2  | 2  | 0.5| 1  | 0.0175 |
| 2      | 2  | 3  | 1  | 2  | 0.0163 |
| 3      | 2  | 4  | 1.5| 3  | 0.0234 |
| 4      | 3  | 2  | 1  | 3  | 0.0069 |
| 5      | 3  | 3  | 1.5| 1  | 0.0102 |
| 6      | 3  | 4  | 0.5| 2  | 0.0068 |
| 7      | 4  | 2  | 1.5| 2  | 0.0036 |
| 8      | 4  | 3  | 0.5| 3  | 0.0030 |
| 9      | 4  | 4  | 1  | 1  | 0.0033 |

TABLE 5  Analysis of various factors

| Term   | A    | B    | C    | Ec   |
|--------|------|------|------|------|
| $K_1$  | 0.0572 | 0.0280 | 0.0274 | 0.0310 |
| $K_2$  | 0.0240 | 0.0295 | 0.0265 | 0.0267 |
| $K_3$  | 0.0099 | 0.0335 | 0.0372 | 0.0334 |
| $k_1$  | 0.0191 | 0.0093 | 0.0091 | 0.0103 |
| $k_2$  | 0.0080 | 0.0098 | 0.0088 | 0.0089 |
| $k_3$  | 0.0033 | 0.0112 | 0.0124 | 0.0111 |
| Range $R$ | 0.0158 | 0.0018 | 0.0036 | 0.0022 |
| Factor principal | A→C→B |
| Factor secondary  | A→C→B |
| Optimal scheme    | A₁B₁C₃ |

The orthogonal experimental data were fitted by linear regression. The actual measured points and fitting points of the permeability under radial stress are shown in Figure 7. From Figure 7, it can be seen that the measured data of gas-containing coal permeability are in good agreement with the fitted data. However, from Figure 7, it can be seen that the permeability decreases with the increase of radial stress.
shows that the permeability of gas-containing coal has a non-linear function relationship with the increase of radial stress.

With 0.5 and 1.0 MPa of gas pressure and 2.0 MPa of axial stress kept unchanged, the variation in the gas permeability of gas-containing coal with radial stress is shown in Figure 8. According to the experimental data of Figure 8, the fitting equation between the permeability and radial stress under constant experimental conditions can satisfy formula (3).

\[ k = a \sigma_3^b, \]

where \( k \) is the permeability, mD; \( \sigma_3 \) is the radial stress, MPa; \( a \) and \( b \) are fitting constants, dimensionless.

It can be seen from the fitting equation between the permeability and radial stress in Table 7 that the correlation coefficient \( R^2 \) between the permeability and the radial stress fitting equation is >0.99 under different gas pressures, which shows that the fitting curve is in good agreement with the measured data and the fitting curve is also good. This can accurately reflect that the permeability of gas-containing coal decreases with the increase of radial stress and has a power function relationship.

From Figure 8, it has been seen that the permeability of coal decreases with the increase of radial stress under the condition of fixed axial stress and gas pressure, and the trend of the permeability gradually slows down with the increase of radial stress. The reason for this is that, as the radial stress increases, the coal sample is compacted, the porosity decreases, and it becomes more difficult for the gas to pass through the coal sample. At the same time, the fitting equations of equation (3) and Table 7 show that, with the increase of radial stress, the permeability of coal samples decreases by a power function, which is consistent with previous research results.\(^{24}\) According to the effective stress principle proposed by Terzaghi,\(^{38}\) the effective stress of gas-containing coal can be approximated as:

\[ \sigma' = \sigma - P, \]

where \( \sigma' \) is the effective stress, MPa. \( \sigma \) is the total stress, MPa. According to the force state of the coal sample, it can be inferred that \( \sigma_1' = \sigma_1 - P \) in the axial direction, where \( \sigma_1' \) and \( \sigma_1 \) are the effective stress and total stress in the axial direction, respectively. In addition, it can be inferred that \( \sigma_3' = \sigma_3 - P \) in the radial direction, where \( \sigma_3' \) and \( \sigma_3 \) are the effective confining pressure and total confining pressure in the radial direction of the coal sample, respectively. It can be seen that, under the condition of keeping the axial stress and gas pressure unchanged, the axial effective stress remains unchanged, and the increase of radial stress is equivalent to the increase of radial effective stress.

### 4.2 Relationship between permeability and axial stress

The orthogonal experimental data were fitted by linear regression. The real measured points and fitting points of the permeability under axial stress are shown in Figure 9.
it can be seen that the measured data and the fitting data of the permeability are generally consistent; however, from Figure 9, the trend indicating that the permeability of gas-containing coal increases with the increase of axial stress can be predicted, showing that the permeability of gas-containing coal and the axial stress has a nonlinear function relation.

With 0.5 and 1.0 MPa of gas pressure and 2.0 MPa of radial stress kept unchanged, the variation in the gas permeability of gas-containing coal with axial stress is shown in Figure 10. According to the experimental data in Figure 10, it can be seen that the permeability and axial stress satisfy formula (3) under the constant test conditions, and the constants of the fitting equation are shown in Table 8.

From the fitting equation between the coal permeability and axial stress in Table 8, it can be seen that the correlation coefficients between the permeability and axial stress fitting equations under different gas pressures are all greater than 0.97, indicating that the fitting curve is in good agreement with the measured data and the fitting curve is good. These findings can accurately reflect that the permeability of gas-containing coal increases with the increase of axial stress and has a power function relationship.39,40

With the increase of axial stress. Because the permeability of gas-containing coal increases with the increase of axial stress, it reveals a macroscopic manifestation of the change in the effective stress of specimens and the continuous expansion of internal cracks in coal.25,26 Based on the principle of effective stress, with the continuous increase of axial stress on coal samples, the microcracks begin to expand, and the expansion of microcracks increases the gas flow channels. At the same time, it can be known from the fitting equations of equation (3) and Table 8 that, with the increase of axial stress, the permeability increases as a power function.

4.3 | Relationship between permeability and gas pressure

The linear regression fitting is applied to the orthogonal experimental data. The actual measurement points and fitting...
points of the coal gas permeability under gas pressure are shown in Figure 11. It can be seen from Figure 11 that the measured data of the permeability of gas-containing coal are in good agreement with the fitted data. However, Figure 11 can predict the trend of the increase in the permeability of gas-containing coal with the increase of the gas pressure, which indicates that the permeability of gas-containing coal and the gas pressure increase follow a nonlinear function relation.

Under the condition that the axial stress is 2 MPa and the radial stress is 2 MPa, the permeability of the coal sample changes with the gas pressure, as shown in Figure 12. According to the experimental data in Figure 12, the fitting equation between the permeability and the gas pressure can satisfy formula (5).

\[ k = aP^2 + bP + c, \]  

where \( k \) is the permeability, mD. \( P \) is the gas pressure, MPa. \( a, b, \) and \( c \) are the fitting constants, dimensionless.

As shown in Figure 12, under the condition that the radial stress and axial stress are kept unchanged, the permeability of gas-containing coal and the gas pressure show an obvious nonlinear relationship, that is, as the gas pressure increases, the permeability also increases. With the increase of the gas pressure at the inlet, the effect of the effective stress on the coal sample and the increase of the radial stress and the axial stress are reversed according to formula (4). The increase of pressure will reduce the effective stress on the coal sample, and the number of pores and cracks inside the coal body will decrease. This will increase the effective seepage flow and gas flow velocity, and eventually increase the permeability of the coal sample. At the same time, as the gas pressure gradients continue to increase, the driving force to push gas through the coal body increases. The more gas flows through the cross-section of the coal sample, the greater the corresponding permeability will be. The Klinkenberg effect is only related to the adsorption capacity and gas pressure of the coal.
itself.\textsuperscript{26,41} The gas content inside the coal sample can be calculated using formula (6)\textsuperscript{18}:

$$W = P^n,$$

where $W$ is the coal gas content, m$^3$/t, $P$ is the gas pressure, MPa. $n$ is a coefficient, dimensionless.

With the increase of gas pressure, the pore pressure gradient increases, and the amount of gas adsorbed on the surface of the coal pore increases. The gas adsorption capacity on the fracture surface of coal samples increases with the increasing gas pressure. In particular, coal is a kind of porous material. The seepage gas flows into the pores to communicate with each other in the coal body.\textsuperscript{11,42} Under the condition that the radial stress and the axial stress remain unchanged, the effective stress of the coal sample decreases with the increase of the gas pressure. The number of closed pores and fissures in the coal body is relatively reduced. At the same time, as the differential pressure increases, the driving force that pushes the gas to penetrate from the coal body increases.

When the effective stress is relatively reduced, the coal is still deformed and the gas migration path is restricted. Therefore, the gas seepage velocity increases with the deformation of the coal body, which is in line with the motion equation describing the nonlinear seepage law of coal seam gas.

\section*{5 | CONCLUSION}

In this paper, a self-designed three-axis servo fluid seepage system with a gas-solid coupling of gas-containing coal is used to determine the permeability under different stress conditions, and the influence of multiple factors on the permeability is discussed. Then, the following conclusions can be drawn:

1. Radial stress, axial stress, and gas pressure have an important influence on the permeability characteristics of gas-containing coal. Different load conditions correspond to different permeability characteristics. The influence of radial stress on the permeability is significant, and axial stress has the smallest impact. The order from primary to secondary of each factor is radial stress, gas pressure, and axial stress in turn.
2. Under the condition of fixed axial stress and gas pressure, the permeability decreases with the increase of radial stress, and the trend of the coal sample permeability gradually slows down. At the same time, the permeability decreases following a power function.
3. Under the condition of keeping radial stress and gas pressure unchanged, the permeability increases with the increase of axial stress, and the trend of permeability gradually slows down. Moreover, the coal microcracks expand, and the propagation of microcracks increases the gas flow channel. The permeability increases as a power function with the axial stress.
4. Under the condition that the radial stress and axial stress are kept unchanged, the permeability and the gas pressure follow a quadratic function. The increase of gas pressure will reduce the effective stress on the coal sample, and the number of pores and cracks inside the coal body will decrease, which will increase the effective seepage flow and gas flow velocity and eventually increase the permeability of gas-containing coal.

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