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Gas seepage equations of the coal seam under the action of moisture and the stress field

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Abstract

A seepage experiment was conducted in relation to a loaded coal mass with various moisture content and working conditions using self-developed tri-axial gas seepage equipment. A briquette sample was used as the research object. The change in the relationship of coal mass permeability under the combined action of moisture content and effective stress was studied experimentally. The relational function was established between coal mass permeability under this combined action and the seepage equation expressing gas migration in the coal seam. The research showed the following: (1) the moisture content of coal heavily influences effective permeability, as coal mass permeability decreases in a quadratic polynomial relationship with the increase of effective stress at constant moisture content; (2) at constant moisture content in the coal mass, coal mass permeability gradually declines in a negative exponent relationship with the increase of effective stress. Moreover, coal seam gas seepage equations under the combined action of moisture and stress field were put forward based on experimental results, the law of mass conversation and Darcy's law.

Keywords: The rate of moisture content; Effective stress; Permeability; Gas seepage

1. Introduction

The gas seepage law of coal seams is researched in the field of CBM, gas drainage, and gas disaster prevention. Permeability is a key index that reflects the difficulty of gas seepage in coal seam. Many researchers internationally have investigated ground stress field [1], geothermal field [2], electric field [3, 4], sound field [5], pore pressure and slippage effect [6, 7], and coal and rock cleats [8, 9]. However, many of the coal samples used in previous experiments were dried samples. Moisture in the underground working environment is an important component of coal, and the effect of changes in the moisture content on the gas permeability of coal has attracted related research. However, little research has been done on gas migration and seepage equations of the coal seam under the combined action of moisture content and stress field. Moreover, the original stress state in the actual coal seam is disturbed owing to the mining process, and the increase of axial stress makes the fractures or pores compacted. Thus, the path of gas flow becomes narrower and coal permeability declines. The decrease in horizontal stress results in the expansion of fractures and pores in the coal mass, extension of the gas migration path, increase in coal mass permeability and changes in coal mass permeability. Therefore, experimental work into the gas seepage characteristics of the coal mass should be conducted at various working conditions and moisture content rates. Moreover, the seepage equations of gas

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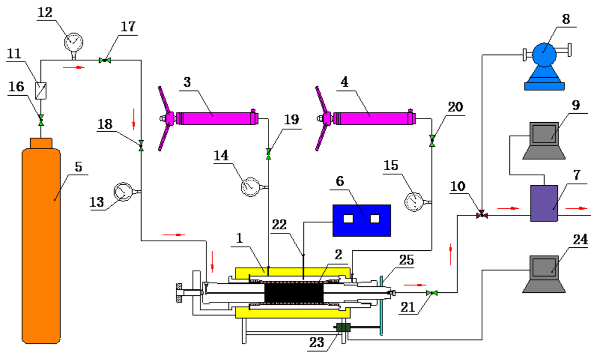

Figure 1: Schematic diagram of the composition of the tri-axial gas seepage experimental system. 1: Coal sample holder; 2: coal samples; 3,4: manual pressure metering pump; 5: high pressure gas tank; 6: thermostat equipment; 7: gas mass flow meter; 8: vacuum pump; 9, 24: computer ; 10: three-way valve; 11: pressure-relief valve; 12–15: gauge; 16–21: valve; 22: temperature sensor; 23: displacement sensor; 25: bezel

Figure 2: Briquette samples for testing

Figure 3: Standard temperature and humidity box

migration in the coal seam under the action of moisture and stress field should be established theoretically. These behaviors contribute to a more comprehensive understanding of the law of gas seepage in the coal seam.

2. Experimental

2.1. Experimental system

This experiment used a self-developed tri-axial gas seepage experimental system of loaded coal mass.

The experimental system can consider the effects of a variety of factors – such as different working conditions (i.e., axial pressure and confining pressure), pore pressure, moisture, and temperature – on coal mass permeability. The components diagram of the experimental system is shown in Fig. 1. The equipment consists of the stress loading device, temperature control device, gas source control device, coal sample holder, degasser, and associated data acquisition device. The stress loading device has two sets of high-pressure pumps with manual increase to ensure the mutual independence of the axial pressure and confining pressure in the experimental process. The temperature of the experiment is adjusted with the temperature control device, using the most peripheral electric heating coil of the holder and the automatic thermostat (the temperature ranges from room temperature to 150°C, and the accuracy is within ± 0.1°C). The pore pressure control system is made up of methane bottles, valves and pipelines, and gas bottles supply CH_4 with a purity of 99.999%. A pressure-relief valve regulates the air inlet pressure. The high-pressure gas cylinder provides the gas pressure of methane as gas source simulating the gas pressure of the coal seam. The data acquisition system consists of the displacement acquisition device, gas mass flow meter and the temperature control device.

The whole process of the experiment is conducted in the test operation bench and controlled by a computer and control programs, which include data collection records to ensure accurate and reliable experimental data.

2.2. Preparation of coal samples

The test coal samples taken from a coal mine in Henan were prepared in strict accordance with the measuring method based on the physical and mechanical properties of coal and rock [10]. Raw coal samples were pulverized. Coal particles in the range of 0.20–0.25 mm were chosen and mixed with an appropriate amount of purified water. Regular coal samples type 50 mm×100 mm were made in the rigid test machine at a pressure of 100 MPa. The prepared coal samples are shown in Fig. 2. The prepared coal samples were placed in a muffle furnace for drying, weighed and put into a humidity chamber (Fig. 3) to achieve the desired moisture content. The moisture content of the coal samples was measured and calculated using the following formula:

$$w = (\frac{M_1}{M} - 1) \times 100\% \tag{1}$$

where w is the moisture content of coal samples, M_1 is the saturated moisture amount absorbed in the coal in the natural state (g), and M is the mass of coal after drying (g).

2.3. Test scheme and procedures

High purity methane was used in this experiment to study the influence of different working conditions and moisture on the seepage characteristics of loaded coal mass. Five sets of coal samples with moisture of 0.00%, 0.92%, 1.82%, 2.72%, and 3.76% at a constant temperature of 30°C and pore pressure of 0.8 MPa were exposed to progressively increased axial pressure and confining pressure. The detailed experimental procedures are as follows:

1. The temperature control device should be adjusted prior to the experiment to keep the whole experimental system maintained at all times at a constant temperature environment of 30°C.
2. The prepared coal samples with the selected moisture content were put in the holder and the desired axial pressure and confining pressure were applied, ensuring that the applied confining pressure was greater than the gas pressure. The system was degassed by a vacuum device to exclude errors caused by the effect of impurity gases on the test results. After degassing, the inlet valve connected to the gas source tank was opened, the outlet valve was closed and the valve regulating the gas pressure was adjusted up to 0.8 MPa to make the coal samples fully adsorb the methane.
3. Axial pressure and confining pressure were applied to a predetermined value. The outlet valve was opened until the coal completed the adsorption. The gas flow was recorded after reaching the stable rate using the mass flow meter.
4. The coal sample was subjected to predetermined stress of the next level. The gas flow was recorded by the mass flow meter after reaching the stable state and until all predetermined stress conditions were completed.
5. Replace the coal sample with a new one of different moisture content, and repeat the above steps. The next set of experiments was then conducted.

The weights of the coal samples were measured again after the experiment. The before-and-after weights of coal samples showed minimal change. Hence, moisture loss was minimal during the experiment, and its impact on the experimental results was very small owing to the low moisture content of coal samples within a relatively closed environment. Therefore, the moisture content of coal samples can be assumed to remain unchanged in the entire course of the experiment.

3. Experimental results analysis

Briquette samples can be regarded as a homogeneous isotropic porous media in this experiment. Given that the gas migration rule follows Darcy's law, the following formula can be used to calculate the permeability K [11]:

$$K = \frac{2qp\mu L}{(p^2 - p_0^2)S} \tag{2}$$

where K is the permeability (mD), q is the flow rate of gas flow under the standard conditions (cm^3/s), μ is the gas dynamic viscosity and equals 1.08×10^{-5} Pa·s, L is the sample length (cm), S is the sample cross-sectional area (cm^2), p_0 is the atmospheric pressure (Pa), and p is the gas pressure at the inlet end (Pa).

Experimental results are shown in Table 1.

3.1. Analysis of experimental results of permeability under the effect of moisture

The change curves (see Fig. 4) of gas seepage characteristic of coal samples with different moisture content under constant stress were obtained using data taken from Table 1.

The test results of Fig. 4 show that the relationship between coal permeability and moisture content at constant effective stress presented a nonlinear downward trend. That is, the reduction of coal permeability with the increase in moisture content presented a quadratic relationship and gave a higher fit value (Table 2). Coal is known to contain some water in actual coal seams. The presence of water in the coal mass can be classified as external moisture, inherent moisture and combined water. External moisture is mainly located in coal pores and fissures and has some mobility. Inherent moisture is mainly located in the coal fracture surface and smaller pores. The liquidity of inherent moisture

Table 1: . Experimental Data

Axial pressure (MPa)	Confining pressure (MPa)	Pore pressure (MPa)	Effective pressure (MPa)	Permeability (mD) Moisture content rate(%) 0.00	0.92	1.82	2.72	3.76
2.0	1.0	0.8	0.88	3.962	1.81	0.946	0.432	0.331
4.0	2.0	0.8	2.22	1.604	0.93	0.484	0.221	0.145
6.0	3.0	0.8	3.55	1.016	0.55	0.253	0.132	0.096
8.0	4.0	0.8	4.88	0.592	0.322	0.168	0.072	0.057
10.0	5.0	0.8	6.22	0.23	0.173	0.09	0.041	0.029

Table 2: Fitting relationship of permeability and moisture content

Effective stress (MPa)	Fitting curve function	Related coefficient (R_2)
0.88	$K = 3.857 - 231.5x + 3711.22x^2$	0.979
2.22	$K = 1.599 - 82.99x + 1180.58x^2$	0.999
3.55	$K = 1.010 - 56.79x + 869.99x^2$	0.997
4.88	$K = 0.587 - 32.17x + 481.32x^2$	0.998
6.22	$K = 0.235 - 9.77x + 110.25x^2$	0.964

is much lower than that of external moisture. External moistures with two kinds of states are the main reason for reduced coal mass permeability. Moisture occupies the large pores of coal and fissures. Thus, the seepage channels are narrowed, flow resistance increases and permeability falls. Given that coal and rock are porous media, part of the coal pores and fractures are compressed and closed in a constant effective stress environment. Inherent moisture and external moisture affect the effective porosity of coal samples too. Part of the space within the coal framework is occupied by water molecules. Thus, the gas migration tunnels are narrowed and gas permeation resistance increases. Permeability declines macroscopically. Moreover, the original porosity of coal as a porous medium is high from a microscopic view. Given the increase of external and inherent moisture, the porosity gradually falls, and the gas permeability decreases.

Table 2 shows that the relationship of coal permeability and moisture content under the five kinds of stress changes with a negative exponential relationship. Permeability decreases and the relationship become negative as the coal moisture content increases. Thus, coal permeability and moisture content at constant effective stress is expressed by the following formula:

$$K(W) = a + b \cdot w + c \cdot w \tag{3}$$

where $K(w)$ is coal permeability (mD); w is the moisture content of coal samples $(w \geq 0)$; a, b, and c are the fit coefficients $(w = 0)$; $K(0)$ is equal to a, which is the coal permeability when the moisture content is 0.00%.

3.2. Experimental results analysis under the effect of effective stress

The seepage experiment with progressive loading under different moisture conditions was carried out to study the change of gas seepage characteristics in different effective stress environments. The experimental results are shown in Fig. 5.

Fig. 5 shows that the permeability of the coal samples decreases as effective stress increases following the negative exponential function, and that the decline gradient of permeability flattens slightly as moisture increases. The pore and fracture space decreases under effective stress, gas migration pathways reduce and the resistance of gas migration increases. Thus, the permeability of the coal sample drops. Moreover, the initial porosity of pore or cracks is high for coal as a porous medium and decreases rapidly under effective stress. The limited porosity is squeezed by the water. Thus, porosity gradually reduces as confining pressure and moisture content increase, and it reaches its minimum at the end of the elastic-plastic stage. Moreover, gas permeability decreases as effective stress and mois-

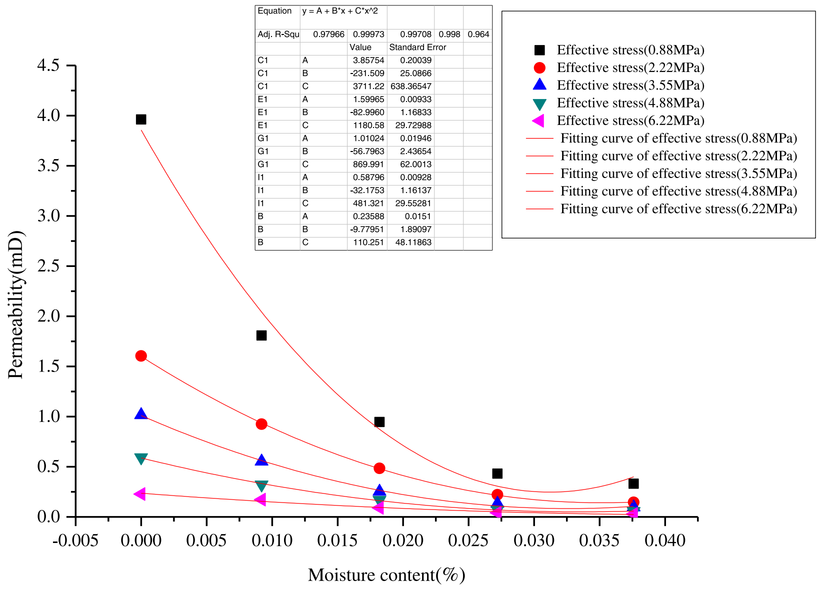

Figure 4: Change curves of permeability under the conditions of different moisture content

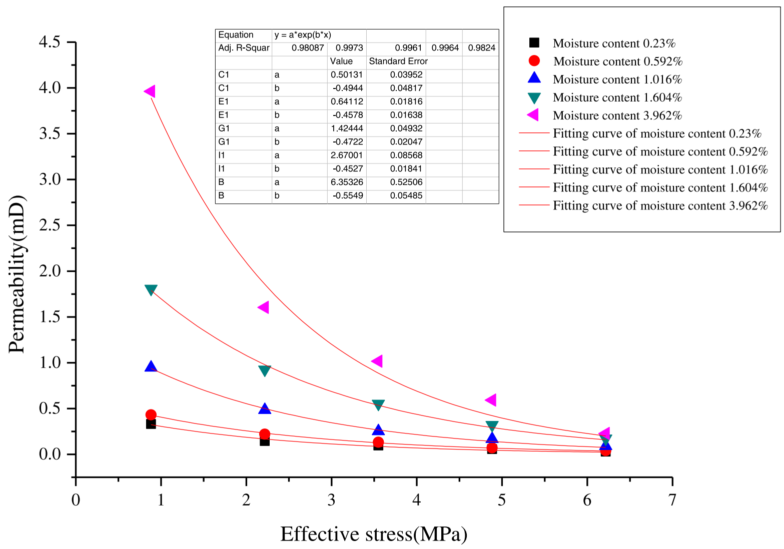

Figure 5: Permeability change curves under different effective stress conditions

ture content increase, and the descent gradient flattens gradually.

Table 3 shows that the relationship between coal permeability and effective stress is a negative exponential relationship in the five kinds of moisture conditions. The change relationship of permeability decreases in a negative exponential relationship as effective stress increases. Thus, coal permeability and effective stress under the condition of the same moisture content can be expressed as follows:

$$K(\sigma_e) = \alpha \exp(-\beta\sigma_e) \tag{4}$$

where $K(\sigma_e)$ is the function of permeability under effective stress (mD), α and β are the fitting constants, and σ_e is the average effective stress (MPa), which can be calculated as follow: [5, 12].

$$\sigma_e = \frac{(\sigma_a + \sigma_c)}{3} - \frac{(p_1 + p_2)}{2} \tag{5}$$

where σ_a is the axial stress (MPa), σ_c is the confining pressure (MPa), σ_e is the average effective stress (MPa), and p_1 and p_2 are the gas pressure in the intake or outlet (MPa), respectively.

3.3. Permeability equation of coal mass under the effect of moisture and stress field

The above analysis shows that coal permeability $K(\sigma_e, w)$ is a function of moisture content and effective stress, which can be deduced by a variable separation method under the combined effect of moisture and stress field.

$$K(\sigma_e, w) = K(\sigma_e)\, K(w) \tag{6}$$

Substitute Equations (3) and (4) into Equation (6),

$$K(\sigma_e, w) = \left[a + b\cdot w + c\cdot w^2\right] \times \alpha \exp(-\beta\sigma_e) \tag{7}$$

4. Gas seepage equations under the action of moisture and stress field

According to the law of mass conservation, the difference between inflow mass and outflow mass along every direction is equal to the change in mass for the microelement unit in unit time [13].

$$\frac{\partial M}{\partial t} + \nabla(\rho V) = 0 \tag{8}$$

where M is the gas content of coal in the unit volume (kg/m^3), ρ is gas density (kg/m^3), and V is gas seepage velocity (m/s).

Langmuir isotherm equation indicates that the adsorbed gas content in unit volume of coal can be expressed as:

$$M_a = \frac{abcp_n p}{1 + bp} \tag{9}$$

where a is the limit adsorption amount per unit mass of coal (m^3/kg), b is the adsorption constants of coal (MPa^{-1}) c is equal to $(1-A-M)$ as the correction factor, A and M are the coal ash and moisture, respectively, p_n is the pressure under standard conditions and equal to 101325 Pa (kg/m^3), p is gas pressure (Pa).

The free gas content in unit volume of coal can be expressed as:

$$M_g = \varphi\rho \tag{10}$$

where φ is the porosity of coal.

Methane can be regarded as an ideal gas. According to the ideal gas equation:

$$\rho = \beta P \tag{11}$$

where β is the gas compression factor (kg/(m^3·Pa)). $\beta = M_g/(RT)$, where M_g is the molecular weight of methane (kg/kmol), R is the gas constant of CBM and equal to 8.3145 J/(kg·K), and T is the temperature of coal (K).

Thus, the gas content in unit volume of coal is:

$$M = M_g + M_a = \beta\left(\varphi p + \frac{abcp_n p}{1 + bp}\right) \tag{12}$$

The gas migration in the coal mass follows Darcy's law.

$$V = -\frac{K}{\mu}\nabla p \tag{13}$$

where K is coal permeability (m^2), and μ is the dynamic viscosity of the gas (Pa· s).

The porosity changes of porous media body in the isothermal process can be expressed as:

$$\frac{\partial\varphi}{\partial t} = (1-\varphi)\left(\frac{\partial\varepsilon_v}{\partial t} + \frac{1}{K_s}\frac{\partial p}{\partial t}\right) \tag{14}$$

where ε_v is the coal volume strain, and K_s is the coal skeleton modulus.

By calculating simultaneous equations from Eq. (8) to Eq. (14), the gas equation can be obtained.

$$\begin{aligned} p(1-\varphi)\tfrac{\partial\varepsilon_v}{\partial t} + \left[\varphi + \tfrac{p(1-\varphi)}{K_s} + \tfrac{abcp_n}{(1+bp)^2}\right]\tfrac{\partial p}{\partial t} + \\ +\nabla\left[\tfrac{K}{2\mu}\nabla p^2\right] = 0 \end{aligned} \tag{15}$$

According to the experimental results of this article, after substituting Eq. (7) into Eq. (15) the gas flow

Table 3: Fitting relationship of permeability and effective stress

Moisture content rate (%)	Fitting curve function	Related coefficient (R2)
0.00	$K = 0.501 \exp(-0.494\sigma_e)$	0.981
0.92	$K = 0.641 \exp(-0.458\sigma_e)$	0.997
1.82	$K = 1.424 \exp(-0.472\sigma_e)$	0.996
2.72	$K = 2.670 \exp(-0.453\sigma_e)$	0.996
3.76	$K = 6.353 \exp(-0.554\sigma_e)$	0.982

equation under the combined effect of moisture and the stress field can be expressed as:

$$p\,(1-\phi)\,\frac{\partial\varepsilon_v}{\partial t} + \left[\phi + \frac{p(1-\phi)}{K_s} + \frac{abcp_n}{(1+bp)^2}\right]\frac{\partial p}{\partial t} + \\ +\nabla\left[\frac{\left[a+b*w+c*w^2\right]\times\alpha\exp(-\beta\sigma_e)}{2\mu}\nabla p^2\right] = 0 \tag{16}$$

5. Conclusions

A self-developed tri-axial experimental system of gas seepage in a loaded coal mass containing gas was utilized in this test. The briquette samples were regarded as the research object. The gas seepage experiments were conducted under different moisture content and working conditions. The conclusions are as follows.

1. The experimental research shows that the moisture content of coal under constant effective stress conditions has an important impact on effective permeability. The permeability of coal decreases as moisture content increases. The increased moisture in the coal occupies the seepage pore channels; thus, gas migration becomes more difficult and the flow of gas is inhibited. Water injection in a coal seam can be regarded as a local prevention measure to prevent coal and gas outbursts andreduce gas emission during the mining process.
2. Five kinds of moisture content were used in the test. The relationship between coal permeability and moisture content in the range of moisture content of the tested coal mass can be expressed as a quadratic polynomial. The general expression is $K(W) = a + b \cdot w + c \cdot w$. Coal permeability shows a negative exponential relationship with the increase of effective stress under conditions of given moisture content.
3. Coal seams of the same moisture level were subjected to similar treatment as in the isothermal process. Methane in a coal seam could be regarded as an ideal gas in line with the Langmuir equation. The gas seepage equation of the coal seam under the action of moisture and stress field was established based on the law of mass conversation and Darcy's law. The equation can be used as a basis for theoretical analysis of the gas migration law under the action of moisture and stress field in the coal seam.

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