

Nonlinear Motion Law of Coalbed Gas Seepage under the Combined Effects of Stress and Temperature

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Abstract

The shrinkage and swelling of the coal matrix due to the effects of temperature were investigated through the performance by Henan Province Key Lab of Gas Geology & Gas Control of a permeability test of loaded coal under various temperature and working conditions using its own seepage equipment for thermo-fluid-solid-mechanical coupling of methane-containing coal. The variation of coal permeability under the combined effects of stress and temperature was investigated, and the gas motion law in the coal samples was tested. The variation equations of coal permeability under the combined effects of stress and temperature, as well as the motion equations describing the nonlinear gas seepage law in coal seams were established. The established equations were proved to fit well with the experimental data, which demonstrated that the motion equations and the research methods were both reasonable. Study on the seepage nonlinear motion law of gas in the coal seam is great significance to mineral gas extraction.

Keywords: Stress field, Temperature field, Nonlinear, Permeability, Pore pressure gradient, Effective stress

1. Introduction

More than 50% of coal seams in China are rich in gas. The total amount of mineral gas resource is estimated at 35 trillion m³, the third largest coalbed methane store in the world behind Canada and Russia. The calorific value of the gas is in the range 33.5...36.8 MJ/m³, and each cubic meter is equivalent to the calorific value of 1.3 kg of standard coal.

How to quickly and efficiently extract coal seam gas is becoming a key problem in the development and utilization of energy [1, 2]. Coal seam permeability is an important parameter reflecting the ease of gas seepage in the coal seam and coal and gas outburst. Much research has been done into the factors influencing permeability. Notably, the temperature of the ground, which affects permeability, usually increases with depth. Many researchers have studied the relationship between the permeability of coal and temperature. For example, refs. [3] and [4] studied the influence of temperature on permeability, but ob-

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tained the opposite results; ref. [5] performed experiments at room temperature and 50°C respectively, and noted that permeability increased as the temperature rose; refs. [6] and [7] studied the features of gas seepage in stress and temperature fields, and proposed relations between stress, temperature and permeability; refs. [8] and [9] studied the relationship between stress, temperature and permeability of the rock, but they did not explicitly point out the relationship between temperature and permeability under the action of stress; refs. [10, 11] did seepage experiments under conditions of different temperatures and stresses by making kerosene, water, air and other fluids flow through limestone, sandstone, etc., but got different conclusions. From this brief review, we can see that much more research into the effect of temperature on permeability is still required. However, the actual condition of gas-bearing coal under the influence of stress and temperature, namely studying the characteristics of gas flow in original coal, could be of more practical use for underground coal mining. Therefore, this paper focuses on the variation relationship of coal permeability and the flow rule of gas in coal samples under the combined effects of stress and temperature, which could provide insight for gas extraction and coalbed methane mining.

2. Experimental contents

2.1. Experimental system

The authors designed a Heat-Flow-Solid-Force coupled experimental apparatus for coal containing methane to simulate the methane gas permeability test for coal samples under different crustal stresses and pore pressures. As shown in Fig. 1, this apparatus was comprised of a loading system, triaxial cell, pore pressure control system, data measurement system, temperature control system, and a table controlled by a computer and control program, including the record of data acquisition to ensure that the test data are accurate and reliable.

The sample was obtained from the 2nd coal seam of the ZhaoGu 2nd mine of the Coking Coal Group, the coal from the coal seam was mainly semibright-bright coal, the firmness coefficient f of the coal seam was high, and the endogenous fracture was not well

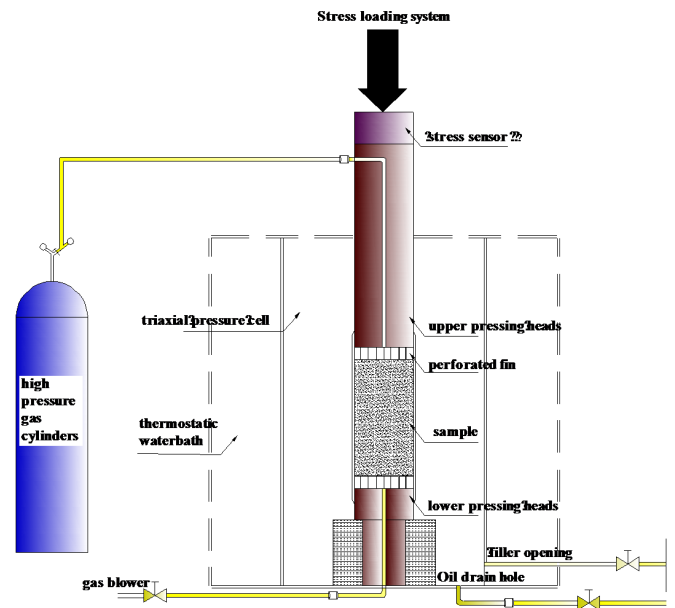


Figure 1: Experimental system structure schematic diagram



Figure 2: Raw coal specimens

developed. The physical parameters of the coal sample for the experiment are listed in Table 1. The experimental samples are shown in Fig. 2.

2.2. Methods

1. To check the air tightness of the experimental system, a cylindrical stainless steel piece with the same size as the sample of $\Phi 50 \text{ mm} \times 100 \text{ mm}$ was put into the coupled experimental device containing coal gas heat-flow-solid-force, and then scheduled axial pressure and confining pressure were applied. After-

Table 1: Basic physical parameters of experimental coal samples

$M_{ad},$ %	$A_{ad},$ %	$V_{daf},$ %	absorption constant a m^3/t	absorption constant b, MPa^{-1}
0.96	16.00	8.20	48.773	1.054
true den- sity, g/cm ³	appar- ent density, g/cm ³	elastic modu- lus, $E,$ MPa	volume com- press- ibility K_Y	poisson ratio ν
1.53	1.46	19200	5.16×10^{-4}	0.36

wards, some nitrogen was pumped at pressure into the vessel to ensure that the pore pressure gas was under confining pressure. After stabilizing for a period of time, a check was made to determine if there was a gas exhaust side flow. If there was no outflow, the gas path system and samples between the walls were proved to have good air tightness.

- To exclude any effect by gas impurities on the result of the experiment, the whole test system was vacuum-pumped for more than 24 h until the system vacuum degree was close to 0 Pa. After that, the vacuum pump system was shut down. If the degree of vacuum remained stable for 2 h, the vacuum degassing process could be considered complete.
- The coal specimen was filled with methane gas at a predetermined pressure, and the outlet valve opened after adsorption equilibrium was reached with the coal samples. When the gas flow was stable, one could start recording the test data. To study the seepage law under different stress conditions and temperatures, the pressure from inlets and outlets should be kept constant during the whole test in order to exclude the impact of pressure fluctuation.

2.3. Experimental design

Our experiment design takes full account of permeability characteristics of loaded coal under various temperature and working conditions.

2.3.1. Experiments with different effective stress under the same temperature conditions

Taking full account of the permeability characteristics, confining pressure and axial pressure of loaded coal under different working conditions, progressive loading increasing by the amplitude of 0.6 MPa with effective stress as a variable was adopted at the temperatures of 10°C, 20°C, 30°C and 40°C. Meanwhile, in order to study the permeability of coal under different loading stages, the methane gas pressure of inlet was set at 0.6 MPa and the outlet pressure was set at 0.1 MPa in order to eliminate the influence of pore pressure change on the experiment results. Under a predetermined temperature condition, we first fixed the pore pressure, and then progressively increased the confining pressure and axial pressure to a certain load in order to measure permeability under the stress state. After that, we increased the confining pressure and axial pressure to a larger load so as to simulate the coal loading stress conditions. We repeated the above procedures to better understand the influence of effective stress on coal seam permeability at different loading stages.

2.3.2. Experiments with constant effective stress under variable temperature conditions

Under the same working conditions, the CH₄ permeability of coal under different effective stress was measured with the temperature increasing from 10°C to 40°C, respectively (temperature gradient was 2°C). Under fixed confining pressure and pore pressure, we loaded a certain axial pressure and changed the environment temperature in order to study the influence of thermal expansion on coal permeability under constant effective stress.

2.3.3. Nonlinear seepage experiment of coal gas under constant temperature condition

Under constant temperature condition, we loaded a certain confining pressure and axial pressure while changing the pore pressure to study nonlinear seepage of gas under a different pore pressure gradient.

3. Results

The gas permeability of the coal sample is calculated by the following formula [12]:

$$k = \frac{2qp_2\mu L}{A(p_1^2 - p_2^2)} \quad (1)$$

In the formula: k is the permeability (mD); q is the gas transfusion flow under standard conditions (cm^3/s); μ is the gas kinetic viscosity equal to $1.08 \cdot 10^{-5} \text{ Pa}\cdot\text{s}$; L is the long of sample; A is the cross sectional area of sample (m^2); p_2 is the gas pressure of the outlet that is equal to atmospheric pressure; p_1 is the pressure of the inlet (MPa).

The calculation formula for methane dynamic viscosity is as follows:

$$\mu = 1.36 \times 10^{-4} T^{0.77} \quad (2)$$

where: T is the thermodynamic temperature (K).

Experiments were conducted according to 2.3.1 and 2.3.2, and the results are shown in Figs 3–5.

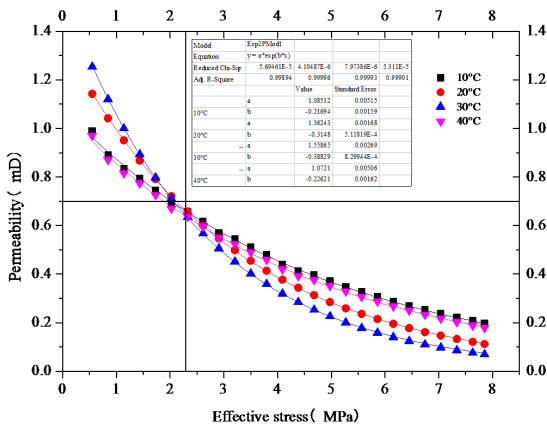


Figure 3: Variation curves of effective stress and permeability under the condition of constant temperature

4. Experimental results analysis

Fig. 3 shows the permeability of loaded coal that contains gas under different working conditions under constant temperature. It can be seen that loaded coal containing gas has the following characteristics:

1. The permeability of coal gradually decreases with the increase of effective stress under different temperature conditions, showing a clear

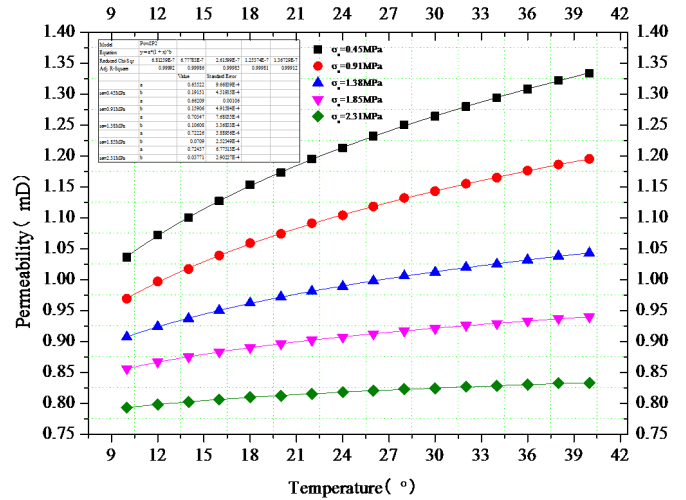


Figure 4: Relationship between CH₄ permeability and temperature under the condition of low effective stress

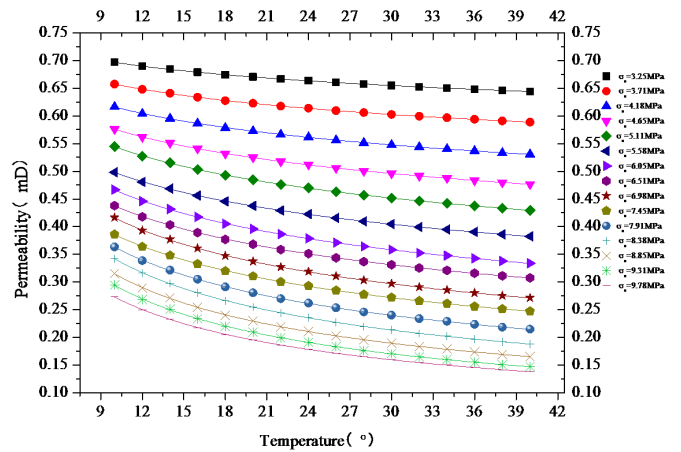


Figure 5: Relationship between CH₄ permeability and temperature under the condition of high effective stress

negative exponential relationship. At the initial stage of effective stress, the permeability declines rapidly, but with the effective stress increasing again, the downward slope of seepage curve gradually decreases. At the initial loading stage, the original pore volume of coal body shows a gentle declining trend first, which is mainly due to the strong cohesion between coal particles caused by the strong compressive ability of the skeleton structure of the raw coal. However, the pore volume gradually closes with the continuing increase of the effective stress, and the internal compressible pore volume gradually shrinks when the effective stress gets higher. Thus, the coal body

presents the compaction stage, and the downward slope of seepage curve varies little and gradually stabilizes.

2. In Fig. 3, comparing the seepage curves under the same coordinates, the downward slope at 40°C is larger than those at 10°C, 20°C and 30°C in the smaller effective stress range, and that at 30°C is larger than that at 20°C, while that at 10°C is the smallest. In contrast, in the larger effective stress range, the seepage downward slope at 10°C is larger than those at 20°C, 30°C and 40°C, and that at 40°C is the smallest. That is to say, there exists a turning point in the variation process of permeability. The permeability coefficient of the coal sample mainly depends on the pore-fissure distribution characteristics, and the thermal swelling deformation of coal matrix occurs with the rise in temperature, which can be formulated as [13] $\varepsilon_F = 1/3 \times \beta\Delta T$. Based on the generalized Hooke's law, the stress σ_F caused by the thermal swelling deformation can be formulated as: $\sigma_F = 1/3 \times \beta\Delta T \times E$. From this formula, it can be seen that the wider the temperature change range is, the greater the thermal deformation. In the lower effective stress range, the wider temperature variation range leads to greater deformation stress, and the coal deformation is bigger under the same load, which means the deformation stress of coal caused by the increase in temperature is larger than the effective stress, and the coal pore opens to swell outwards, causing permeability to rise with the increasing temperature. At the same time, the rise in temperature leads to an increase in plasticity and a decrease in coal strength, and the coal matrix deformation becomes bigger. Hence, the coal matrix would shrink to coal pore when the thermal deformation stress is smaller than the effective stress, and the inward expansion narrows the seepage channel, which leads to a decrease in permeability as the temperature rises. Thus, the turning point of coal permeability will present in the seepage curve.
3. Fig. 4 shows the relationship between CH₄ permeability and temperature under the condition of lower effective stress ($\sigma_e < 3.25$ MPa), and

the permeability presents a clear upward trend with the rise in temperature under this condition. Thermal deformation stress occurs in all directions as the coal temperature rises, and the coal skeleton particles may swell outward with the pore-fissure opening outward when the thermal deformation stress is bigger than the effective stress, which causes increasing permeability. Notably, the lower effective stress area should be the effective stress minus the thermal deformation stress when considering the influence of the thermal deformation stress on the effective stress.

4. Fig. 4 shows the relationship between CH₄ permeability and temperature under the condition of higher effective stress ($\sigma_e \geq 3.25$ MPa), and the permeability presents a decreasing trend with the rise in temperature under this condition. When the thermal deformation stress is smaller than the effective stress, outward expansion of coal is blocked and only the inward expansion can occur, which narrows the pore-fissure space and decreases the seepage channel, thus decreasing the permeability. Notably, the higher effective stress area should be the sum of the effective stress and the thermal deformation stress when considering the influence of the thermal deformation stress on the effective stress.

5. Coal permeability under the combined effects of stress and temperature

5.1. Coal permeability equation under the influence of temperature

By regression analysis of the experimental data from Figures 4 and 5, the relationship between temperature t and permeability k can be expressed as follows [3]:

$$k(T) = k_t(1 + t)^n \quad (3)$$

where $k(T)$ is the permeability function under temperature, (mD); and k_t and n are regression constants.

5.2. Coal permeability equation under the influence of effective stress

A large number of experimental studies demonstrate a relationship between permeability and effective stress as follows:

$$k(\sigma_e) = \alpha \exp(-b\sigma_e) \quad (4)$$

where $k(\sigma_e)$ is the permeability function under the influence of effective stress, (mD); α and b are fitting constants; and σ_e is average effective stress, which can be calculated using the following formula [14]:

$$\sigma_e = \frac{(\sigma_1 + \sigma_2 + \sigma_3)}{3} + \alpha p \quad (5)$$

Where α is Biot effective stress coefficient [15] and σ_1 , σ_2 and σ_3 are three components of principal stress.

5.3. Coal permeability equation under the combined influence of stress and temperature

The above analysis shows that coal permeability is a function influenced by the combined effects of stress and temperature. By virtue of variable separation method, the permeability function $k(\sigma_e, T)$ under combined influence of stress field and temperature field can be expressed as [16]:

$$k(\sigma_e, T) = k(\sigma_e)k(T) = k_t(1+t)^n \times \alpha \exp(-b\sigma_e) \quad (6)$$

Assuming $k_m = \alpha k_t$, then it would seem as:

$$k(\sigma_e, T) = k_m(1+t)^n \exp(-b\sigma_e) \quad (7)$$

Based on the above analysis, when considering the influence of thermal expansion stress on the effective stress, low effective stress should be the difference between the effective stress and thermal expansion stress, while high effective stress should be the sum of effective stress and thermal expansion stress. Combined with formula (7), permeability calculation formulas under the combined influence of stress and temperature can be obtained as:

$$\begin{cases} k = k_0(1+t)^n \exp[-\beta(\sigma_e - \sigma_F)] \\ \quad \text{for } \sigma_e \leq 3.25 \\ k = k_0(1+t)^n \exp[-\beta(\sigma_e + \sigma_F)] \\ \quad \text{for } \sigma_e \geq 3.25 \end{cases} \quad (8)$$

where k_0 is permeability when $t = 0$ and $\sigma_e = 0$.

6. Nonlinear flow equation under the influence of different temperatures

Assuming coal seam gas presents a laminar flow in accordance with Darcy's law under the pressure gradient in a permeable space, the coal seam gas flow velocity considering Klinkenberg effect [17] can be expressed as:

$$v = -\frac{k}{\mu} \left(1 + \frac{m}{p}\right) \cdot \nabla p \quad (9)$$

where v is seepage velocity, m/s; m is the Klinkenberg coefficient, Pa; and ∇p is pressure gradient, MPa/m.

Substituting formula (8) into Eq. (9), the following can be obtained:

$$\begin{cases} v = -\frac{k_0(1+t)^n \exp[-\beta(\sigma_e - \sigma_F)]}{\mu} \left(1 + \frac{m}{p}\right) \cdot \nabla p \\ \quad \text{for } \sigma_e \leq 3.25 \\ v = -\frac{k_0(1+t)^n \exp[-\beta(\sigma_e + \sigma_F)]}{\mu} \left(1 + \frac{m}{p}\right) \cdot \nabla p \\ \quad \text{for } \sigma_e \geq 3.25 \end{cases} \quad (10)$$

Substituting the coefficient ζ for $\frac{k_0}{\mu} \left(1 + \frac{m}{p}\right)$, formula (10) can be simplified as:

$$v = -\zeta(1+t)^n \exp[-\beta(\sigma_e \pm \sigma_F)] \cdot \nabla p \quad (11)$$

When $\Delta t = 0$, $\beta = 0$ and $m = 0$, the above formula is just Darcy's law.

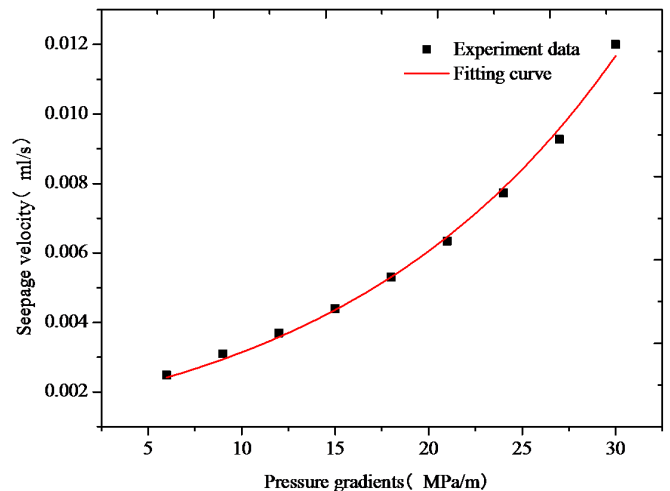


Figure 6: Nonlinear percolation feature curve of methane under low effective stress

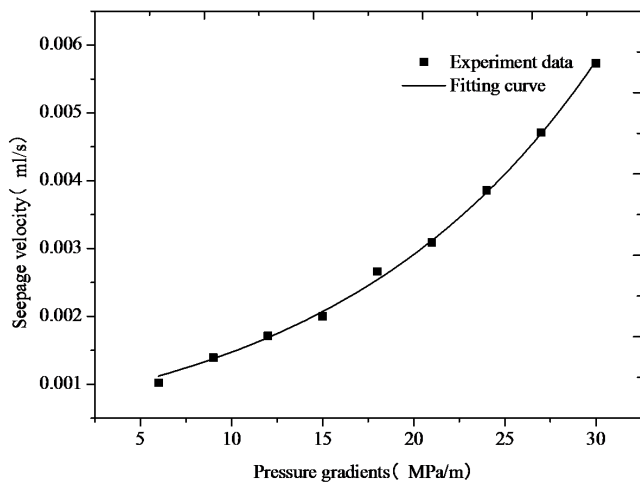


Figure 7: Nonlinear percolation feature curve of methane under high effective stress

By virtue of formula (11), regression analysis with experimental data was carried out, and the results are shown as Figs 6 and 7. The curves show obvious nonlinear characteristics, and the fitting coefficients are 0.9981 and 0.9958 respectively, which indicates that the curve fitting and experimental data coincide with each other well. Namely, this equation can accurately describe the coal seam gas nonlinear percolation process under the combined influence of stress and temperature.

7. Conclusions

1. This paper investigated the permeability variation rules under different temperature and effective stress by virtue of methane seepage experiments, and the results indicated that the influence of temperature on permeability mainly depended on the relationship with the effective stress and thermal deformation stress.
2. Considering the inward (outward) deformation caused by temperature effect, two different rules about the influence of temperature change on coal permeability were analyzed. At lower effective stress, the thermal deformation stress would result in outward opening of the pore-fissure, and cause a rise in permeability; at higher effective stress, the thermal deformation stress results in pore-fissure shrinkage, and causes a decrease in permeability. Based on the

analysis, the permeability equation under the combined effects of stress and temperature was established by the variable separation method.

3. Under different pore pressure gradients with constant thermal deformation stress, the law of methane seepage was studied and the methane seepage speed presented the feature of non-linear flow. In accordance with Darcy's law, the non-linear equation of methane seepage under different temperature was put forward and the equation was fitted with the experimental data at the same time. The experimental results were consistent with the fitting results, and the equation clearly describes the methane seepage non-linear equation under the combined effects of stress and temperature.

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