Decline in gas pressure influences the deformation and permeability of coal-containing methane

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Abstract

The development and utilization of coal-bed methane, as an unconventional gas, is not only beneficial to the reduction of environmental pollution caused by fossil fuels, but also conducive to the prevention of disasters during coal mining. In this paper, a dynamic permeability model of coal body is established and discussed by means of experimental tests, which measure the deformation and gas permeability of coal-containing methane in the process of gas pressure reduction under different temperatures. The results show that, when gas pressure decreases, the strain of coal-containing methane increases linearly. With temperature increases, the variation of radial strain decreases. Under the same temperature, the permeability of coal decreases first and then increases again during gas pressure reduction. The changing point of gas pressure is approximately 1.2 MPa in the study. In the initial stage of gas pressure decrease, the radial strain of coal-containing gas has a significant effect on its permeability.

Keywords: Gas Pressure, Gas Permeability, Coal Deformation, Dynamic Permeability Model

1 Introduction

The “fog” has recently swept through nearly half of China. This occurrence indicates that environment problems are becoming increasingly serious. The energy consumption structure must be reformed; therefore, the exploration and application of natural gas, coal-bed methane (CBM), and shale gas should be strengthened. Among these resources, CBM is an unconventional clean energy that is symbiotic with coal, and it is abundant in China. Furthermore, the reasonable development and utilization of CBM can effectively reduce the risks associated with coal mining.

At present, the United States, Canada, Australia, and China are the main countries engaged in the exploration and development of CBM and have realized CBM industry. During the extraction of CBM, gas pressure of the coal reservoir gradually decreases, which affects reservoir permeability, thus further affects the output of CBM. On the other hand, with the increase in extraction depth, the geothermy is playing an increasingly important role in the extraction of CBM [1]. Therefore, study on deformation and permeability variations in the coal reservoir during the reduction process of gas pressure under different temperatures is significant in the effective exploitation of CBM. Thus far, most of the studies on dynamic deformation and permeability variations during the extraction of CBM are conducted are numerical simulation based on mathematical model. Based on the P&M model, DENG Ze [2] simulated permeability variations in the reduction process of reservoir pressure, with the background of No. 3 coal reservoirs of Qinshui CBM Field. The results showed that, with the decrease in gas pressure, permeability firstly decreases and then increases. ZHOU Junping [3-4] established a fluid-solid coupling model for CBM considering the matrix shrinkage effects and simulated the changes of permeability during the primary production of CBM. By measuring the macroscopic fracture, mechanical parameters, stress and permeability of the main coal seam in the south-central Qinshui Basin, FU Xuehai [5] established a numerical model to simulate the dynamic change of permeability during the production of CBM. With regard to the physical simulation experiment, the permeability and deformation of coal seam influenced by gas pressure and temperature have been the focus of many studies. ZHAO Yangsheng [6–8] concluded that coal and rock permeability changed parabolically with gas pressure through experiments by keeping the axial pressure and confining pressure constant and increasing the gas pressure and then proposed the concept of critical gas pressure. ZHAO Yangsheng also observed the trend that lignite permeability firstly decreased, then increased significantly, and finally decreased in the experimental study under the condition of different temperatures. CAO Shugang [9] derive a quadratic polynomial relationship between gas pressure and permeability by studying the influence of gas pressure on coal permeability characteristics, whereas the gas pressure range in his study was only confined from 0.3 MPa to 1.5 MPa.

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LIANG Bing [10] analysed the mechanical and nonmechanical mechanisms of the influence of gas on coal and rock deformation by conducting experiments on triaxial compression under the condition of different confining pressures and gas pressures. LI Zhiqiang [11-12] concluded that the relationship between coal permeability and coal temperature was not monotonically increasing or monotonically decreasing under the condition of different effective stresses. A transition zone existed through coal and rock permeability change under the condition of different temperatures and stresses. And the location of the transition zone depended on the ratio of effective stress to thermal stress. XU Jiang [13] conducted coal and rock seepage experiments and mechanical tests under different temperatures and concluded that permeability decreased with the increase in temperature. In addition, the influence of temperature on permeability would decrease with the increase in effective stress and gas pressure. Moreover, XU Jiang concluded that the coal and rock deformation increased with the increase in temperature and that the dependent variables had different changing trends under different temperature ranges. So far, studies regarding the deformation and seepage evolution of CBM reservoir are conducted mostly using numerical simulation. The physical simulation is conducted in the method of increasing gas pressure, ignoring the fact that gas pressure decreases around the borehole in the coal reservoir during the CBM extraction process, which certainly leads to some errors because of adsorption and desorption irreversibility [14-15]. What is more, temperature in those studies was rarely considered. Therefore, this paper focuses on the deformation and permeability evolution of coal-containing methane when gas pressure decreases under different temperatures. The relationship between deformation and permeability could provide support for the CBM extraction program.

2 Experimental work

2.1 SAMPLE PREPARATION

In this paper, coal specimens were obtained from the Songzao Colliery, Chongqing, China. The thin coal seam exhibits high gas content, as well as relatively developed joints and fissures.

Firstly, the raw coal was crushed into powder and sieved to get pulverized coal with particle diameters between 60 mesh and 80 mesh.

Secondly, the pulverized coal was mixed with enough water and then placed in a mold.

Thirdly, the mixture was formed into a cylindrical specimen (Φ50 mm × 100 mm) with forming pressure of 100 MPa by using the material testing machine.

Finally, samples were dried in a drying basin and desiccated in the vessel.

2.2 EXPERIMENTAL APPARATUS

The self-developed triaxial servo-controlled seepage equipment for thermal–hydrological–mechanical coupling of coal-containing methane [16] was used to implement these experiments. This apparatus could test the mechanical properties as well as the flow characteristics of CBM under different axial pressures, confining pressures, gas pressures and temperatures.

2.3 TEST PROCEDURE

Seepage experiments under different temperatures (20°C/ 30°C/ 40°C/ 50°C/ 60°C/ 70°C) and different gas (CH_4) pressures are conducted. The experiments were conducted strictly in accordance with the following test procedures:

1) Before the experiments, the coal specimen was fitted into the triaxial pressure chamber, which was lifted into the heated waters to keep the ambient temperature predetermined.
2) Applying the axial pressure and confining pressure to 6.0 MPa. And then applying the CH4 injecting pressure to 3.5 MPa, the status was maintained steady until the coal specimen adsorbed gas sufficiently. Then, the deformation and flow data were recorded.
3) The CH4 gas pressure was adjusted as follows: 3.5→3.0→2.5→2.1→1.8→1.5→1.2→0.9→0.6→ 0.3 MPa. At each point of the gas pressures, the corresponding data were recorded after sufficient desorption that was directly implied by constant deformation and flow data.
4) Each test condition was conducted repeatedly to confirm the reliability of the test results.

3 Results and model analysis

3.1 THE DEFORMATION CHARACTERISTIC

The strain evolution curves of coal-containing methane with gas pressure decrease under different temperatures (from 20°C to 70°C) are shown in Figure 1. Under constantly external stress (axial stress and confining pressure), the coal sample is gradually compressed while gas pressure decreases. The axial strain and radial strain show a linear relationship with the gas pressure. Under the 20°C condition, the axial strain and radial strain of coal-containing methane increase in a similar way on account of the decrease in gas pressure, and their variations are similar when per unit pressure decreases. As the temperature increases, the variations of axial strain and radial strain with gas pressure show a significant difference. This is because the ability to resist deformation of coal-containing methane is decreased with the increase in temperature. Meanwhile, with the decrease in gas pressure, the effective stress applied to coal-containing methane is increased, which leads to compressive deformation gradually in the axial orientation and expansion deformation in the radial orientation of the coal sample due to anisotropic mechanics property. Therefore, under the 70°C condition, a slight decrease in the radial strain is observed when the gas pressure decreases.

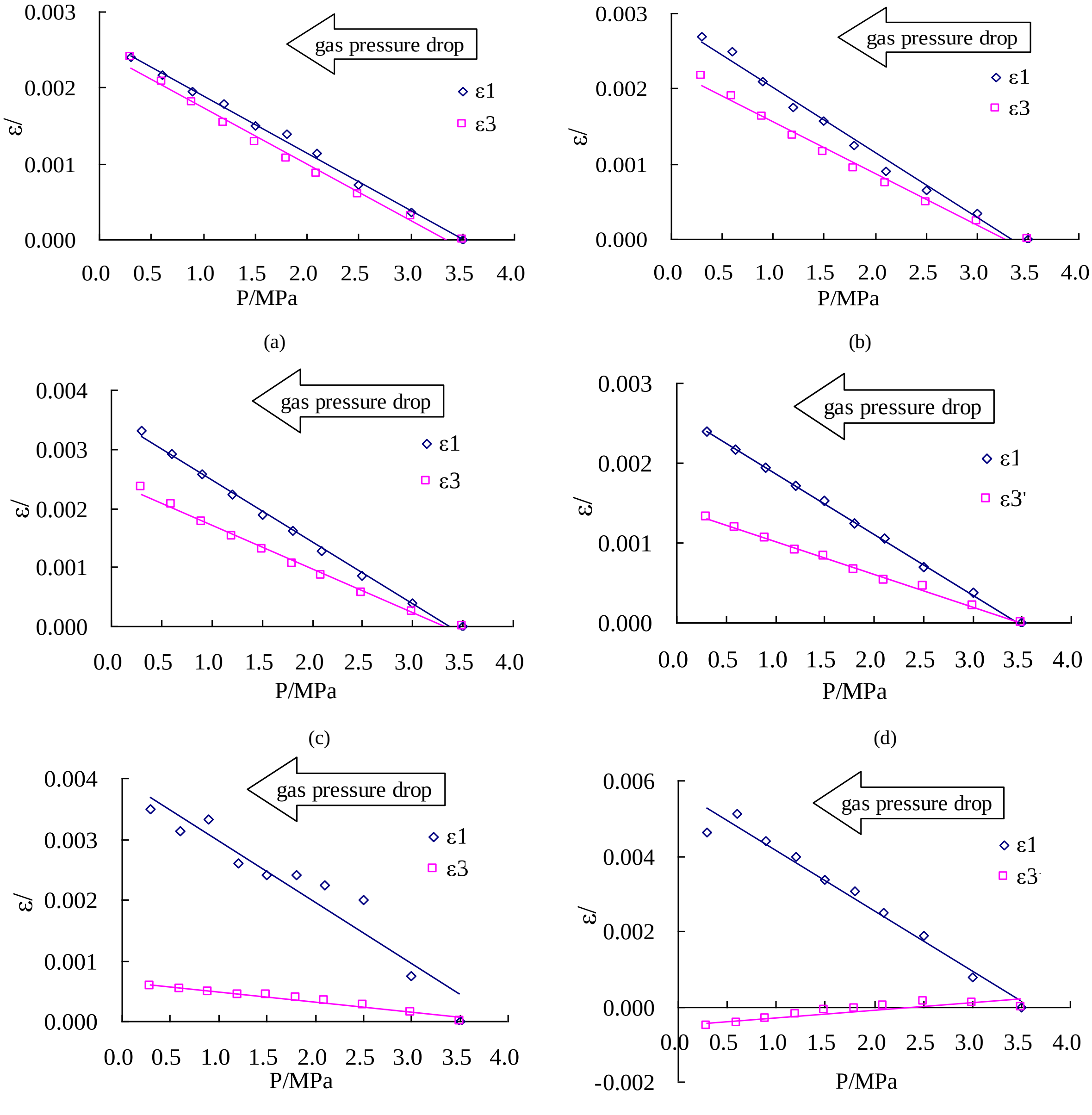

FIGURE 1 Evolutions of strain with gas pressure under different temperatures: (a) 20°C, (b) 30°C, (c) 40°C, (d) 50°C, (e) 60°C, (f) 70°C

Stress-strain relationships for an isothermal gas adsorbing coalbed may be written as [17]:

$$\varepsilon_{ij} = \frac{1}{2G}\sigma_{ij} - \left(\frac{1}{6G} - \frac{1}{9K}\right)\sigma_{kk}\delta_{ij} + \frac{\alpha p}{3K}\delta_{ij} + \frac{\varepsilon_p}{3}\delta_{ij}, \qquad (1)$$

where ε_{ij} is the component of the total strain tensor, σ_{ij} denotes the component of the total stress tensor, $\alpha = 1 - K/K_S$, is the Biot coefficients, p denotes gas pressure, δ_{ij} is the Kronecker delta, K denotes the bulk modulus of coal and fissure system, K_S represents the bulk modulus of coal matrixes, $\sigma_{kk} = \sigma_i + \sigma_j + \sigma_k$, is the total bulk stress, ε_p is matrix/system strain on account of gas adsorption/desorption. Grey [18] used a linear relationship between the swelling strain ε_p and pressure in his permeability model. Eq. (1) indicates a linear relationship between the total strain tensor ε_{ij} and gas pressure p when total stress σ_{ij} remains constant, just as shown in the Fig.1. The otherness of deformation at different temperatures is caused by changes and anisotropy of mechanical properties induced by temperature change.

3.2 THE DYNAMIC PERMEABILITY MODEL AND ITS DISCUSS BY TEST

According to J. Liu [19], the permeability for coal matrix system can be given as:

$$k_{\infty}=\left(1+\frac{\alpha}{\phi_0}\cdot\frac{\left(\Delta\sigma_m+\Delta p\right)}{K}\right)^3\cdot k_0\,, \quad (2)$$

where the mean compressive stress σ_m is denoted by $\sigma_{kk}/3$, φ_0 indicates initial porosity, k_0 denotes initial Klinkenberg permeability, which could be determined by actual test in the lab, k_{∞} is the real-time Klinkenberg permeability.

According to Klinkenberg [20], effective gas permeability at a finite pressure is calculated by the following formula:

$$\begin{cases} k_p = k_{\infty}(1+b/P_m) \\ b = 4c\lambda P_m / r \end{cases}, \quad (3)$$

where k_p is the real-time gas permeability, b is the Klinkenberg factor, dependent on the pore structure of the medium and temperature for the given gas, c denotes Klinkenberg coefficient acquired by fitting the experimental data observed in the lab, λ is the mean free path of gas molecular, Pm shows the average gas pressure; r indicates the effective pore radius; κ is Boltzmann gas constant, 1.3806505×10-23 J/K; T expresses coal temperature, d is the gas molecular diameter.

Combining Eqs (2) and (3), the following relationship is achieved as:

$$k_p=\left(1+\frac{\alpha}{\phi_0}\cdot\frac{\left(\Delta\sigma_m+\Delta p\right)}{K}\right)^3\cdot k_0(1+b/P_m)\,. \quad (4)$$

Eq (5) is the dynamic permeability model and reveals that it is a complicated relation between gas permeability and gas pressure, and that the Klinkenberg permeability lessens with the decrease of gas pressure. However, at a finite pressure, the slippage effect gradually dominants gas permeability. Therefore, the gas permeability decreases with the decrease of gas pressure, and then increases, which will be mainly elaborated by means of experimental test.

For the measurement of coal permeability, Darcy's law (Eq (6)) was used to interpret the experimental result [21]:

$$k=\frac{2qp_0\mu L}{A(p_1^2-p_2^2)}, \quad (5)$$

where K is the permeability (m^2), q is the gas permeation rate (m^3/s), μ is the gas kinematic viscosity (Pa·s), L is the length of the coal specimens (m), A is the cross-sectional area of the coal specimens (m^2), p_1 is the gas pressure at the upper stream or inlet of the specimens (Pa), p_2 is the gas pressure at the downstream or outlet of the specimens (Pa), and p_0 denotes the standard atmosphere.

The permeability of coal-containing methane under different gas pressures and temperatures are shown in Table 1. The table shows that, when temperature is less than 40°C, the permeability of coal-containing methane shows a tendency to decrease firstly and then increase during the decrease process of gas pressure. If the temperature is greater than 40°C, the change in permeability is not evident in the initial stages of gas pressure decrease. Nevertheless, the permeability increases significantly when gas pressure further decreases. The turning point of gas pressure for the permeability is approximately 1.2 MPa. When gas pressure is constant, the permeability of coal-containing methane shows an overall trend that increases firstly and then decreases with the increase in temperature.

TABLE 1 The permeability of coal under different temperatures

Gas pressure	k_p (10^{-3} μm^2)					
(MPa)	**20°C**	**30°C**	**40°C**	**50°C**	**60°C**	**70°C**
3.5	0.431	0.368	0.287	0.418	0.385	0.511
3.0	0.423	0.365	0.267	0.430	0.388	0.517
2.5	0.404	0.340	0.265	0.437	0.391	0.524
2.1	0.382	0.316	0.216	0.441	0.399	0.530
1.8	0.372	0.286	0.189	0.451	0.383	0.543
1.5	0.366	0.286	0.181	0.430	0.367	0.534
1.2	0.358	0.278	0.202	0.428	0.357	0.519
0.9	0.359	0.279	0.262	0.446	0.423	0.538
0.6	0.383	0.294	0.338	0.600	0.553	0.724
0.3	0.407	0.397	0.344	0.908	0.936	1.100

To analyse the evolution of permeability with gas pressure in an intuitive way, the permeability of coal-containing methane was normalized, using the dimensionless K/K_0 in the analysis, where K_0 is the permeability of coal-containing methane while gas pressure is equal to 3.5 MPa at the corresponding temperature. The contrast curves of radial strain–gas pressure and dimensionless permeability-gas pressure are shown in Figure 2.

As shown in Figure 2, in the initial stage of gas pressure decrease, the radial strain of coal-containing methane reveals a trend of increase, whereas the dimensionless permeability shows an evidently opposite trend under the 20°C and 40°C conditions. The decrease in gas pressure leads to an increase in effective stress when the external stress is constant at the initial stage. As such, the gas flow channel is contractive because of the increase in radial strain, which eventually leads to the decrease in permeability. When the temperature is 60°C or 70°C, at the initial stage of gas pressure decrease, we observed little change in the radial strain and dimensionless permeability of coal-containing methane. At the initial stage of gas pressure decrease, the radial strain of coal-containing gas has a significant effect on its permeability. The relationship curve between dimensionless permeability and radial strain when gas pressure exceeds 1.2 MPa is shown in Figure 3. As shown in Figure 3, at the initial stage of gas pressure decrease, the permeability of coal-containing methane decreases linearly with the increase in radial strain.

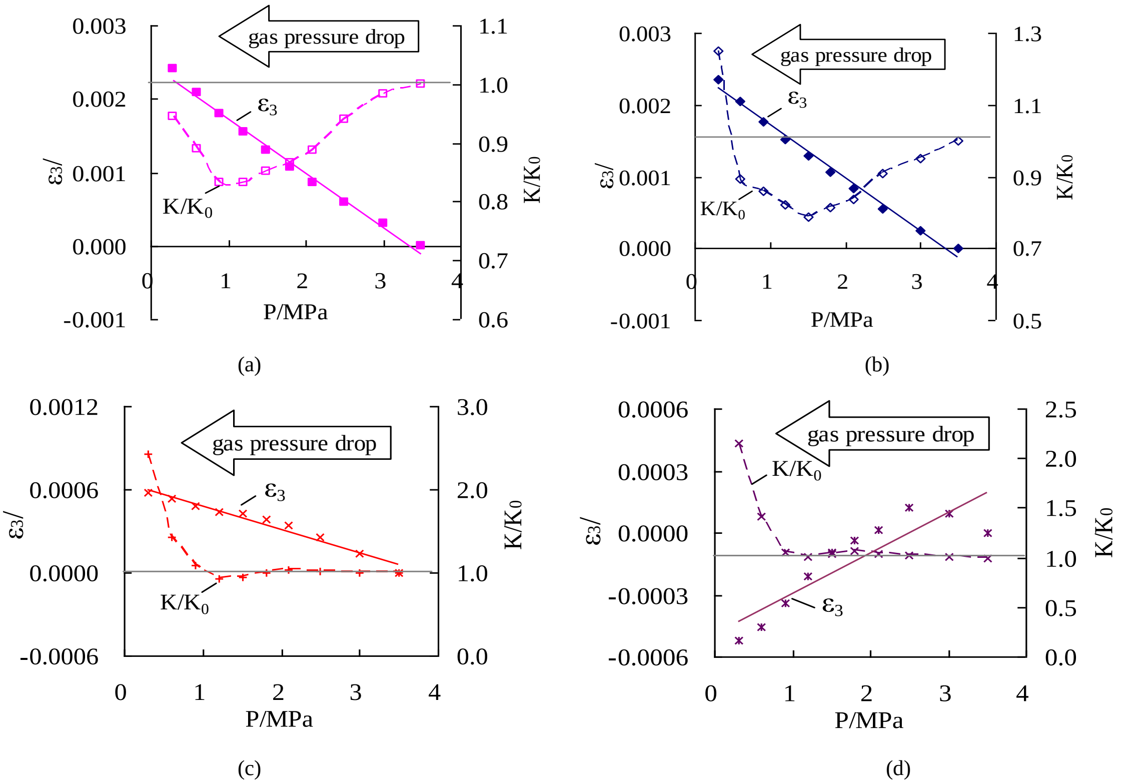

FIGURE 2 Contrast curves of radial strain-gas pressure and dimensionless permeability-gas pressure: (a) 20 °C, (b) 40 °C, (c) 60 °C, (d) 70 °C

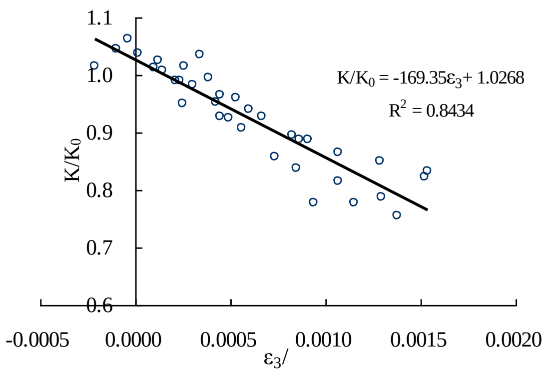

FIGURE 3 The relationship curves of K/K_0 and ε_3 ($P \geq 1.2$ MPa)

With further decrease in gas pressure, radial strain continues to show a linear increase. However, the permeability of coal-containing methane increases correspondingly because of the increased permeability caused by the slippage effect as shown in the Eq (4). This because the radial strain reflects only the structure deformation of coal-containing methane. Instead of structural deformation, the intensive slippage effect dominants permeability change when the gas pressure decreases less than 1.2 MPa.

With the decrease in CBM pressure, the permeability of coal-containing methane decreases first and then increases because of reservoir compression deformation caused by effective stress and intensive slippage effect. While the temperature increases (more than 40°C in this paper), reservoir compression deformation decreases and desorption enhances, thus improving the permeability of the coal reservoir.

4 Conclusions

The deformation and permeability characteristics of CBM reservoir are important factors that affect CBM recovery. By means of the experimental study on the deformation and permeability of coal-containing methane by decreasing gas pressure under different temperature conditions, the following conclusions are achieved:

(1) With the decrease in gas pressure, the strain of coal-containing methane shows a linear increasing trend. As temperature increases, the variation in radial strain has a decreasing tendency with the decrease in gas pressure.

(2) Under the constant temperature, the permeability of coal-containing methane shows a tendency to decrease firstly and then increase with the decrease in gas pressure. The turning point of gas pressure is approximately 1.2 MPa, less than which the intensive slippage effect dominants permeability change. At the initial stage of gas pressure decrease, the radial strain of coal-containing gas significantly affects its permeability because of effective stress change.

(3) Elevated temperature within a certain range can alleviate the reservoir compression deformation caused

by gas extraction, as well as promote desorption to improve the extraction efficiency of CBM.

(4) To simplify the test process, gas pressure changes linearly and discontinuously with time, which is different from the gas pressure changes of during actual extraction of CBM. Nevertheless, some predictable rules are obtained through the test results, and more detailed studies on the actual problem will be considered in future work.

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