STUDY ON SEEPAGE CHARACTERISTICS AND MODEL OF ORTHOTROPIC ANISOTROPY COAL

by

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The extraction of coalbed methane can ensure the safe production of coal mines and the efficient use of resources. According to the anisotropy of coal seam, CT spiral scanning and triaxial gas seepage tests are carried out, the seepage characteristics of orthotropic coal are analyzed, and a coal permeability model considering orthotropic structure is proposed. Results show that: The permeability of parallel bedding direction changes obviously with axial pressure. The confining pressure is 5 MPa, the permeability in the parallel bedding direction is about 1.6 times that of the vertical bedding, and the confining pressure is 13 MPa, the permeability in the parallel bedding direction is about 1.01 times that of the vertical bedding. The coal permeability model with anisotropic structure is verified by the experiment data in both parallel and vertical bedding directions, and shows great applicability. Research results provide references for the efficient development of coalbed methane.

Key words: *orthotropic anisotropy, CT scan, triaxial seepage test, permeability model*

Introduction

Coal reservoir contains a large amount of gas. Coalbed methane extraction and utilization are inseparable from the study of coal, and coalbed methane extraction is closely related to the fracture inside the coal body. Therefore, the study of anisotropic coal permeability is of great significance for coalbed methane extraction. In the process of coal diagenesis, due to the complexity of micro-structure, the structural differences of coal mean that the gas-flow rate in coal has significant directional differences, especially in the direction of bedding and cleat [1, 2]. Zhao *et al.* [3] indicated that vertical and parallel bedding, surface cleat, and parallel bedding and vertical surface cleat have obvious anisotropy by conducting physical property characteristic tests on gas-bearing coal. Deng e*t al*. [4] studied the permeability of different bedding through the triaxial seepage test, and finally found that the inner samples axially loaded with parallel bedding had larger porosity and better permeability. Jia *et al*. [5] studied the anisotropic permeability of coal under low stress by permeability experiment, and obtained the difference

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in permeability between different cleats and bedding. Wang *et al*. [6] found that the anisotropy of permeability of coal-containing gas has dynamic variation properties through seepage experiments, this change is caused by the change of load and the direction of gas-flow also changes. Zang *et al*. [7] established an orthogonal anisotropic permeability model considering the dual effects of effective stress and gas adsorption/desorption, and analyzed the influence of anisotropic permeability on pre-pumping of gas. Based on the theory of rock mechanics, Teng *et al*. [8] established a modified permeability model of shaly sandstone under the condition of coupled fluid mechanics and revealed the relationship between permeability and effective stress.

In this paper, CT scanning and triaxial compression seepage tests were carried out to study the evolution law of permeability in different directions with confining pressure, gas pressure, and axial pressure, and the relationship between permeability anisotropy and fracture was analyzed. A coal permeability model with an orthogonal anisotropy structure was constructed, and the permeability model was fitted and analyzed. The research results provide a reference for the efficient development of coalbed methane

The CT scanning of coal structure and anisotropic permeability characteristics

Coal sample processing and test scheme

In this series of experiments, the coal block is processed into cylindrical coal samples of Ø 25 mm × 50 mm for CT scanning and cylindrical coal samples of Ø 50 mm × 100 mm for triaxial seepage test according to the direction of vertical bedding and parallel bedding. Spiral CT scanning with Cylindscan-1000 series X-ray 3-D microscope was performed. The triaxial compression seepage test was carried out by the rock stress-seepage servo loading testing machine of Beijing Key Laboratory of Coal and Associated Energy Precision Mining, China University of Mining and Technology (Beijing). The seepage test was carried out with CO2, and the confining pressure was loaded with flow rate of 10 mm per minute. The axial pressure is controlled by constant quantity, and the injection rate of the indenter is controlled to 0.05 MPa·s. The confining pressure is loaded to 5 MPa, 9 MPa, and 13 MPa, respectively, and the corresponding air pressure is 1 MPa, 1.5 MPa, and 4 MPa, respectively. The axial pressure ranges from 0-30 MPa. The equipment is drawn in fig. 1.

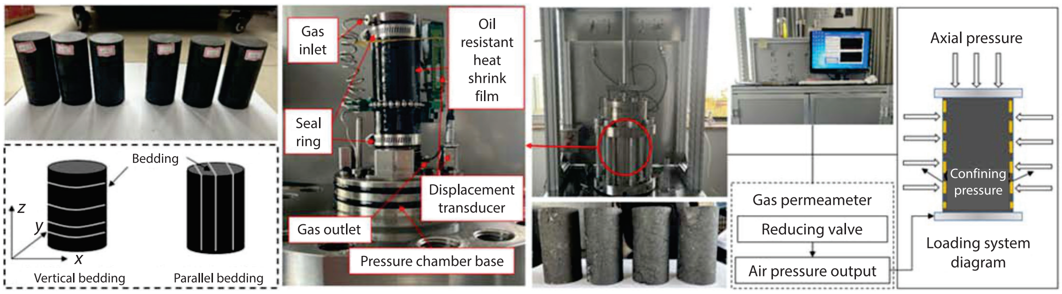


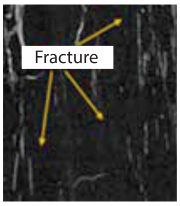
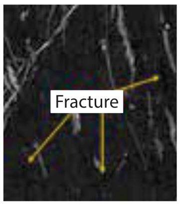
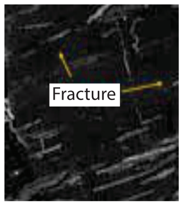
Figure 1. Diagram of triaxial seepage test equipment

Analysis of CT scan results

The images and data of the CT scan test in this paper were analyzed by Avizo. The vertical bedding coal samples are selected for analysis, in which the *X*-direction and *Y*-direction are parallel to the bedding and the *Z*-direction is vertical to the bedding, as shown in fig. 1. With the central long axis of the coal pillar as the z-axis, CT sections in three directions at z = 2500 nm were selected, and the section results are shown in tab. 1. The gray area of the coal samples slice is the coal matrix part of the experimental coal samples, and its particle density is large. The density of pores and fracture is the smallest, and the gray value is also the smallest, which is manifested as a darker part in the image. The white in the images is a high density substance, representing minerals. From the CT images, the distribution of coal matrix, fracture, and minerals is not uniform, which proves the structural anisotropy and heterogeneity of coal samples.

The permeability of the X-direction, Y-direction, and Z-direction is $2.05 \cdot 10^{-3}$ mD, $2.03 \cdot 10^{-3}$ mD, and $6.79 \cdot 10^{-4}$ mD, respectively. The permeability of the X-direction is 3.02 times that of the Z-direction slice and 1.01 times that of the Y-direction slice. By comparing the permeability of the three directions, it can be concluded that the permeability of the coal samples in the X-direction and Y-direction is significantly higher than that in the Z-direction, while the permeability of the coal samples in the X-direction and Y-direction is roughly the same. This is because the X-direction and Y-direction are parallel to the bedding, and the fracture opening parallel to the bedding direction is larger than that vertical to the bedding, and the fracture distribution parallel to the bedding direction is wider, and it can be seen from tab. 1 that the fractures in the X-direction and the Y-direction are more than those in the Z-direction.

Table 1. The CT scan results and permeability caculation in different directions

Slice direction	X-direction	Y-direction	Z-direction
CT scan results			
Permeability	$k_x = 2.05 \cdot 10^{-3}$ mD	$k_y = 2.03 \cdot 10^{-3}$ mD	$k_z = 6.79 \cdot 10^{-4}$ mD

Orthogonal anisotropic coal seepage characteristics

Figure 2 is the permeability comparison diagram of vertical bedding and parallel bedding under different confining pressure, gas pressure, and axial pressure. It can be seen that the permeability of parallel bedding decreases significantly with the increase of axial pressure. In contrast, the permeability of vertical bedding does not change significantly, which is because the fractures of parallel bedding are widely distributed, in contrast, the primary fractures of vertical bedding are closely distributed. The compressible space in the parallel bedding direction is larger than that in the vertical bedding direction, under the effect of axial pressure, the fracture in the parallel bedding direction of the coal sample changes greatly, so the permeability change is more obvious.

It can be seen that when the confining pressure is 5 MPa, the permeability of the coal sample in the parallel bedding is about 1.6 times that in the vertical bedding direction, and when the confining pressure is 13 MPa, the permeability of the parallel bedding is about 1.01 times that in the vertical bedding direction. With the increase of confining pressure, the permeability in two directions gradually approaches. When the confining pressure is 13 MPa and the axial

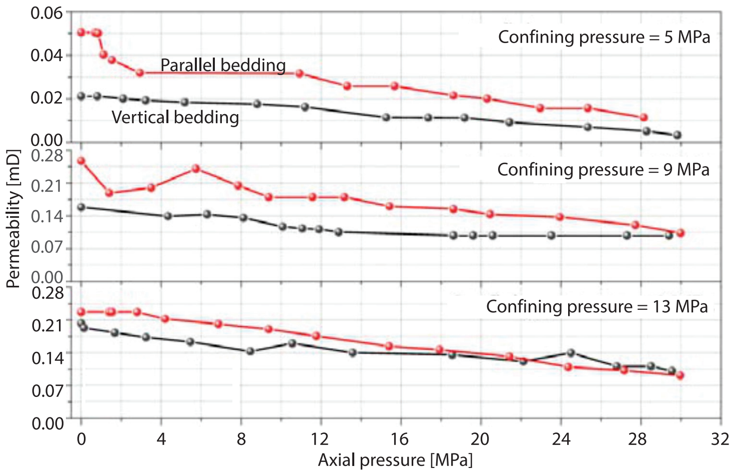


Figure 2. Permeability evolution of coal with axial pressure

pressure is greater than 24 MPa, the permeability in the parallel bedding direction is smaller than that in the vertical bedding direction. The reason is that the higher confining pressure first compacts the fracture of coal samples under the effect of pre-stress. The compressibility of parallel bedding is larger and the sensitivity of parallel bedding direction confining pressure is better, the fracture variation in parallel bedding direction is greater than that in vertical bedding direction, and the fracture in parallel bedding direction is approach to those in vertical bedding direction. So the permeability of the two under high confining pressure is similar and the parallel bedding direction is less than that in vertical bedding direction under high confining pressure and high axial pressure.

Orthogonal anisotropic coal sample seepage model

Permeability model of coal sample based on orthogonal anisotropy

The relationship between permeability and opening degree of coal sample [9-11]:

$$
\begin{aligned}
k_{x0} &= \frac{\mathrm{g} b_{y0}^3}{12\mu s} + \frac{\mathrm{g} b_{z0}^3}{12\mu s} \\
k_{y0} &= \frac{\mathrm{g} b_{z0}^3}{12\mu s} + \frac{\mathrm{g} b_{x0}^3}{12\mu s} \\
k_{z0} &= \frac{\mathrm{g} b_{y0}^3}{12\mu s} + \frac{\mathrm{g} b_{x0}^3}{12\mu s}
\end{aligned} \tag{1}
$$

where b_{x0}, b_{y0}, and b_{z0} are the initial values of the opening in three directions, respectively, s – the joint spacing, g – the acceleration of gravity, and i – the dynamic viscosity of the fluid.

Aiming at the anisotropic characteristics of coal under stress, taking the x-direction as an example, under the action of stress, the crack widths in the x-, y-, and z-directions are compressed Δb_x, Δb_y, and Δb_z, respectively. The permeability in the x direction can be expressed:

$$
k_x = \frac{\mathrm{g} b_y^3}{12\mu s} + \frac{\mathrm{g} b_z^3}{12\mu s} = \frac{\mathrm{g}\left(b_{y0} + \Delta b_y\right)^3}{12\mu s} + \frac{\mathrm{g}\left(b_{z0} + \Delta b_y\right)^3}{12\mu s} = \frac{\mathrm{g} b_{y0}^3 \left(1 + \dfrac{\Delta b_y}{b_{y0}}\right)^3}{12\mu s} + \frac{\mathrm{g} b_{y0}^3 \left(1 + \dfrac{\Delta b_z}{b_{z0}}\right)^3}{12\mu s} \tag{2}
$$

where b_x, b_y, and b_z are the opening degree in three directions, respectively.

The physical and mechanical properties of coal in the vertical and the parallel direction show significant differences. The relationship between the openings of the three directions of coal:

$$b_x : b_y : b_z = 1 : m : n \tag{3}$$

where m and n are the fracture aperture ratio coefficients of coal mass.

Substituting eq. (3) into eq. (2), the permeability in the x direction:

$$k_x = \frac{m^3 k_{x0}}{m^3 + n^3}\left(1 + \frac{\Delta b_y}{b_{y0}}\right)^3 + \frac{n^3 k_{x0}}{m^3 + n^3}\left(1 + \frac{\Delta b_z}{b_{z0}}\right)^3 \tag{4}$$

where k_{x0} is the initial permeability in the x-direction.

According to the deformation of the matrix block as the sum of the deformation of the matrix unit and the opening chance of the fracture, it can be obtained:

$$\Delta b = \Delta s - \Delta s_m = (b + s)\frac{\Delta \sigma_{et}}{E} - s\frac{\Delta \sigma_{et}}{E_m} \tag{5}$$

where E is the elastic modulus of coal, E_m – the elastic modulus of coal matrix, and $\Delta\ \sigma_{et}$ – the effective stress.

The relationship between porosity and fracture aperture [12]:

$$\phi_{f0} = \frac{b_x}{s} + \frac{b_y}{s} + \frac{b_z}{s} = (1 + m + n)\frac{b}{s} \tag{6}$$

Substituting eq. (6) into eq. (5), we have:

$$\frac{\Delta b}{b} = \left[1 + \frac{1 + m + n}{\phi_{f0}}\left(1 - \frac{E}{E_m}\right)\right]\frac{\Delta \sigma_{et}}{E} \tag{7}$$

Substituting eq. (7) into eq. (4), we can conclude that the permeability in the x-direction:

$$\begin{aligned}\frac{k_x}{k_{x0}} &= \frac{m^3}{m^3 + n^3}\left[1 + \left[1 + \frac{1 + m + n}{m\phi_{f0}}\left(1 - \frac{E_y}{E_m}\right)\right]\frac{\Delta \sigma_{ety}}{E}\right]^3 + \\ &+ \frac{m^3}{m^3 + n^3}\left[1 + \left[1 + \frac{1 + m + n}{m\phi_{f0}}\left(1 - \frac{E_z}{E_m}\right)\right]\frac{\Delta \sigma_{etz}}{E}\right]^3\end{aligned} \tag{8}$$

Similarly, the permeability in the y and z directions can be obtained, so the permeability formula in the three directions of the orthotropic coal:

$$\begin{aligned}\frac{k_x}{k_{x0}} &= \frac{m^3}{m^3 + n^3}\left[1 + \left[1 + \frac{1 + m + n}{m\phi_{f0}}\left(1 - \frac{E_y}{E_m}\right)\right]\frac{\Delta \sigma_{ety}}{E}\right]^3 + \frac{m^3}{m^3 + n^3}\left[1 + \left[1 + \frac{1 + m + n}{m\phi_{f0}}\left(1 - \frac{E_z}{E_m}\right)\right]\frac{\Delta \sigma_{etz}}{E}\right]^3 \\ \frac{k_y}{k_{y0}} &= \frac{m^3}{m^3 + n^3}\left[1 + \left[1 + \frac{1 + m + n}{m\phi_{f0}}\left(1 - \frac{E_x}{E_m}\right)\right]\frac{\Delta \sigma_{etx}}{E}\right]^3 + \frac{m^3}{m^3 + n^3}\left[1 + \left[1 + \frac{1 + m + n}{m\phi_{f0}}\left(1 - \frac{E_z}{E_m}\right)\right]\frac{\Delta \sigma_{etz}}{E}\right]^3 \\ \frac{k_z}{k_{z0}} &= \frac{m^3}{m^3 + n^3}\left[1 + \left[1 + \frac{1 + m + n}{m\phi_{f0}}\left(1 - \frac{E_x}{E_m}\right)\right]\frac{\Delta \sigma_{etx}}{E}\right]^3 + \frac{m^3}{m^3 + n^3}\left[1 + \left[1 + \frac{1 + m + n}{m\phi_{f0}}\left(1 - \frac{E_y}{E_m}\right)\right]\frac{\Delta \sigma_{ety}}{E}\right]^3\end{aligned} \tag{9}$$

Verification of coal permeability model based on orthogonal anisotropy

The permeability model of orthotropic anisotropy coal was verified by CT scanning and triaxial compression seepage test. In this paper, the *x*- and *y*-directions belong to parallel bedding, and the *z*-direction is vertical bedding. It can be seen from the CT scanning test results, tab. 1, that the permeability of coal samples in the *x*-direction and *y*-direction is not much different, according to eq. (9), permeability in different directions is related to elastic modulus, effective stress, and initial permeability in corresponding directions, while the *x*-direction and *y*-direction are equivalent to parallel bedding direction, so the differences between them are caused by initial permeability. Therefore, the permeability models in the *x*-direction (parallel bedding) and *z*-direction (vertical bedding) are mainly verified.

The fitting results of the stress-permeability co-evolution curve of coal samples are shown in fig. 3. The degree of fit of parallel bedding direction under different confining pressures is 0.89, 0.85, and 0.98, respectively. The degree of fit of vertical bedding direction are 0.99, 0.78, and 0.89, and the fitting results correspond well with the experimental results. The permeability of the two directions decreases with the increase of axial pressure, showing a negative correlation, which is consistent with the rule shown in eq. (9).

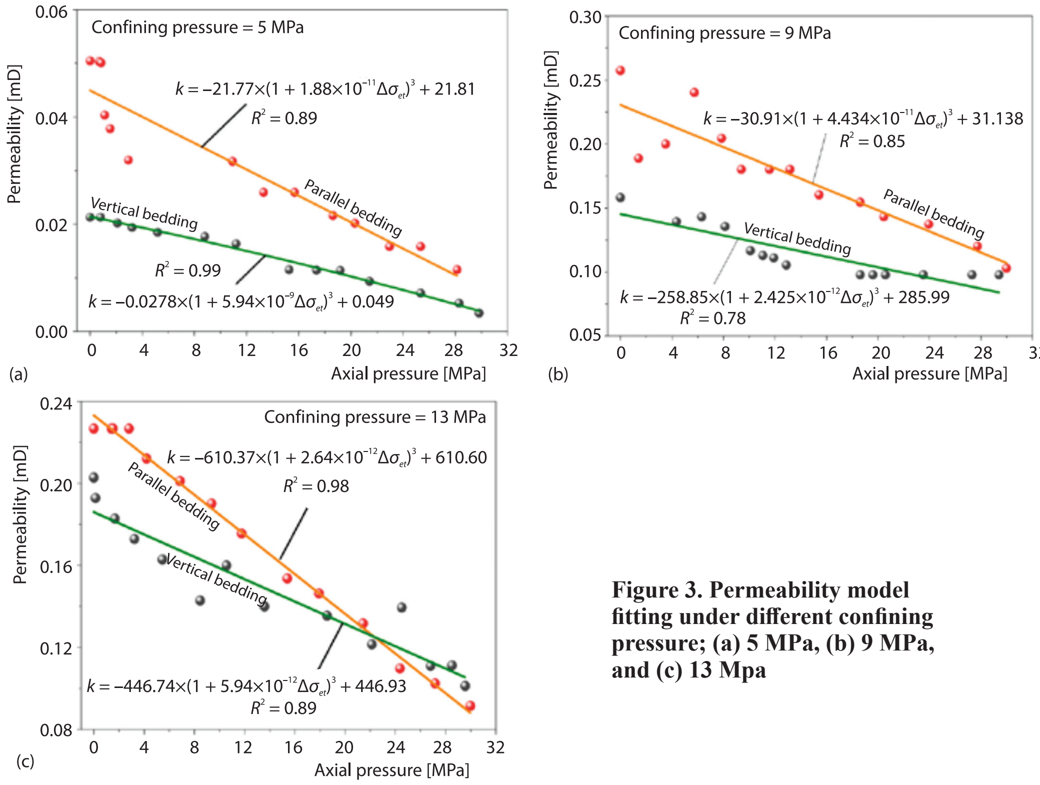


Figure 3. Permeability model fitting under different confining pressure; (a) 5 MPa, (b) 9 MPa, and (c) 13 Mpa

Conclusion

This paper implemented the CT spiral scanning and triaxial gas seepage tests to research the seepage behavior of gas in orthorhombic anisotropy coal. A coal permeability model considering orthotropic structure is then proposed and validated by the experiment data. The research results provide a reference for the efficient development of coalbed methane.

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References

[1] Wang, J., *et al*., Dynamic Changes Laws of The Coal Reservoirs Permeability under the Superimposition of Multi Influential Factors, *Journal of China Coal Society*, *37* (2012), Aug., pp. 1348-1353
[2] Liu Y., *et al*., Mechanical Frontiers in Shale-Gas Development, *Advances in Mechanics*, *49* (2019), July, pp. 1-236
[3] Zhao, Y., *et al*., Experimental Study on Ultrasonic Anisotropic Characteristics of Nitrogen-Containing Caol Bodies, *Journal of Southwest Petrolcum University (Science and Technology Edition*), *40* (2018), Apr., pp. 83-90
[4] Deng, B., *et al.*, Effect of Different Bedding Directions on Coal Deformation and Permeability Characteristics, *Journal Of China Coal Society*, *40* (2015), Apr. pp. 888-894
[5] Jia, L., *et al*., Experimental Study on Anisotropic Permeability of Raw Coal under Low Stress, *Safety in* Coal Mines, *54* (2023), Apr., pp. 12-17
[6] Wang, D., *et al*., Experimental Study on Anisotropic Permeability Rule of Coal Bearing Methane, *Journal of China Coal Society*, *43* (2018), Sept., pp. 1008-1015
[7] Zang, J., *et al*., Anorthotropic Coal Permeability Model, *Journal of China University of Mining and Technology*, *48* (2019), Jan., pp. 36-45
[8] Teng, T., *et al*., Experimental and Numerical Validation of an Effective Stress-Sensitive Permeability Model under Hydromechanical Interactions, *Transp. Porous. Med*., *151* (2024), Jan., pp. 449-467
[9] Liu, J., *et al*., Linking Stress-Dependent Effective Porosity and Hydraulic Conductivity Fields to RMR, *International Journal of Rock Mechanics and Mining Sciences*, *36* (1999), Jul., pp. 581-596
[10] Teng, T., *et al.*, Model of Thermal Fracturing Induced Permeability Enhancement In Coal Matrix Block, *Journal of China Coal Society*, *45* (2020), Nov., pp. 676-683
[11] Gu, F., *et al.*, Permeability and Porosity Models Considering Anisotropy and Discontinuity of Coalbeds and Application in Coupled Simulation, *Journal of Petroleum Science and Engineering*, *74* (2010), Nov., pp. 113-131
[12] Liu, J., *et al.*, Linking Gas-Sorption Induced Changes in Coal Permeability to Directional Strains through a Modulus Reduction Ratio, *International Journal of Coal Geology*, *83* (2010), Apr., pp. 21-30

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