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Gas Permeability Change with Deformation and Cracking of a Sandstone under Triaxial Compression

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Abstract:

In this paper, a THMC (Thermal-Hydrological-Mechanical-Chemical) multi-field coupling triaxial cell was used to systematically study the evolution of gas permeability and the deformation characteristics of sandstone. The effects of confining pressure, axial pressure, and air pressure on gas permeability characteristics were fully considered in the test. The gas permeability of sandstone decreases with increasing confining pressure. When the confining pressure is low, the variation of gas permeability is greater than the variation of gas permeability at high confining pressure. The gas injection pressure has a significant effect on the gas permeability evolution of sandstone. As the gas injection pressure increases, the gas permeability of sandstone tends to decrease. At the same confining pressure, the gas permeability of the sample during the unloading path is less than the gas permeability of the sample in the loading path. When axial pressure is applied, it has a significant influence on the permeability evolution of sandstone. When the axial pressure is less than 30 MPa, the gas permeability of the sandstone increases as the axial pressure increases. At axial pressures greater than 30 MPa, the permeability decreases as the axial pressure increases. Finally, the micro-pore/fracture structure of the sample after the gas permeability test was observed using 3D X-ray CT imaging.

Keywords: sandstone; permeability; pore/fracture structure; deformation; gas pressure

1 Introduction

Natural gas is considered to be a cleaner and more efficient energy source than oil and coal. Unconventional resources, such as tight sandstone gas, are at the bottom of the global natural gas resource pyramid. However, its potential resources are considerably greater than the conventional natural gas reserves (Khlaifat et al., 2011). At present, although the exploitation of tight sandstone gas is still in its early stages, its reserves are relatively large, with recoverable reserves of approximately 1/3 of the total amount of natural gas. Sandstone gas is a typical unconventional natural gas resource stored in low-permeability or ultra-low-permeability tight sandstone reservoirs. Sandstone gas is difficult to mine by conventional techniques. Therefore, it is usually necessary to produce natural gas of economic value through large-scale fracturing or special gas recovery process technology (Figure 1). Reservoir porosity and permeability are two important parameters for reservoir evaluation (Wang et al., 2017a; Xiao et al., 2017; Yang and Huang, 2020). In particular, the stress sensitivity of gas permeability strongly impacts the mining effect of low permeability tight oil and gas fields.

In recent years, extensive research has been conducted on the gas permeability characteristics of sandstone (Amann-Hildenbrand et al., 2016; Duan et al., 2014; Fu et al., 2015; Ghanbarian

et al., 2016; Wang et al., 2017b; Wang and Cheng., 2020; Wu et al., 2020; Zhang et al., 2019). Results indicate that crack closure primarily causes the reduction in the effective permeability of the gas due to the increase in the confining pressure under the condition of constant water content. In addition, studies have also found that some samples even have a large dispersion of initial effective permeability. However, there is a confining pressure-saturation threshold, and when this threshold is exceeded, the effective gas permeability of the samples decreases abruptly (Duan et al., 2014; Fu et al., 2015; Wang et al., 2017b). However, these studies have neglected the evolution of gas permeability after sample fracture. In mining, the gas permeability of sandstone after fracturing is a highly important parameter that cannot be ignored. In addition, the microscopic pore structure after fracturing is of great significance for evaluating the mesoscopic mechanism of gas migration. At present, there is little research on this aspect.

Figure 1. Schematic diagram of sandstone gas mining (modified from www.studiosayers.com).

In this paper, we focused on the evolution of gas permeability during cyclic loading and unloading and considered the effect of air pressure on gas permeability characteristics. Furthermore, we also studied the evolution law of gas permeation of sandstone during fracturing and reconstructed the fractured specimen by CT scanning to observe the internal pore fracture structure.

2 Materials and methods

2.1 Materials and experimental scheme

The samples were obtained from a field in Anhui Province, China. The samples were prepared as cylinders 50 mm in diameter and 20 mm in length. Two samples were first placed into a

triaxial cell to perform gas permeability tests. At the end of the test, one of the specimens was sent for three-dimensional CT scanning to observe the internal cracks.

Confining pressure was applied from 1 MPa until 20 MPa. 0.5 MPa was chosen as an initial gas injection pressure to avoid affect the pore structure. Different air pressures were applied at different confining pressure stages. The purpose was to study the barometric sensitivity of permeability. In the first phase, the confining pressure is loaded and unloaded in a stepwise manner. To consider the complexity of the stress on the sand in the field, we performed two cycles of loading and unloading. In the second stage, the confining pressure was restored to 20 MPa, and axial pressure was applied. The axial pressure was applied from 5 MPa with stepwise loading (loading gradient of 5 MPa) until the sample was fractured. The gas pressure was maintained at 0.5 MPa throughout the loading process. The flow chart of the experimental scheme is shown in Figure 2.

Figure 2. Experimental scheme.

2.2 Gas permeability calculation method

The permeability calculation was performed using the steady-state method, which works well for samples with a permeability higher than 10^{-19} m^2 and has been used widely in many studies (Liu et al., 2020; Liu et al., 2015). Another reason is that we need to carry out Klinkenberg (or slip) experiments, and the steady-state method is easier to implement. This study also applied this method combined with our gas permeability test device (Figure 3). The servo system controls the confining pressure/axial pressure. To ensure safety, Argon was chosen and injected from the gas source into a set volume cylinder (0.4 ml). The gas was later injected into a triaxial pressure chamber at a given pressure P_1 , and the gas pressure drop ΔP was recorded over time Δt . The average pressure (P_{mean}) in the cylinder during Δt is

$P_{mean} = P_1 - \Delta P/2$. Darcy's law states that the formula for determining the effective gas permeability (k_{eff}) is as follows:

$$k_{eff} = \frac{\mu_g V_0}{A} \frac{2h\Delta P}{(P_{mean}^2 - P_0^2)\Delta t} \quad (1)$$

where μ_g is the fluid's dynamic viscosity ($2.2 \times 10^{-5} \text{ Pa} \cdot \text{s}$), V_0 is buffer reservoir's volume, h is the sample height, and A is the sample's upper/bottom surface area.

Figure 3. Gas permeability measurement devices.

2.3 Klinkenberg (or slip) effect

The Klinkenberg (or slip) effect refers to the phenomenon where the gas exhibits a finite velocity on the solid wall, and the velocity of the liquid is zero when the gas moves through the porous medium. This phenomenon exhibited by the gas is known as the slip or the Klinkenberg effect (Klinkenberg, 1941; Wang et al., 2018):

$$k_{eff} = k_{int} \left(1 + \frac{4cl}{r} \right) = k_{int} \left(1 + \frac{b}{p} \right) \quad (2)$$

Where:

K_{int} is the intrinsic permeability; l is the average free path of the gas molecule; r is the pore radius; c is the scale factor; b is the Klinkenberg coefficient or the slip factor, and P is the pore pressure. The slip factor is defined as

$$b = \frac{c\kappa T}{\sqrt{2\pi}r^3} \quad (3)$$

where κ is the Boltzmann constant, and T is the absolute temperature.

2.4 Micro-CT observation test

The three-dimensional scan was tested in the Advanced Analysis & Computation Center, China University of Mining and Technology. The test instrument is Carl Zeiss Xradia 510 Versa High Solution 3D X-ray Microanalyser, with a 3D spatial resolution: 55 μ m-0.5 μ m. To observe the macroscopic crack of the rock sample, the observation was performed after the triaxial compression test.

3 Results and discussion

3.1 Effect of loading/unloading on gas permeability

Figures. 4(a) ~ (b) shows the evolution of gas permeability of two samples (C1 and C2) under different confining pressures. To avoid the interference of air pressure on the permeability results, we only plotted the gas permeability results with a pressure of 0.5 MPa. Throughout the experiment, gas permeability was reduced by order of magnitude (from $1.48 \times 10^{-15} \text{ m}^2$ to $1.39 \times 10^{-16} \text{ m}^2$) for sample C1 and by 3.3 times (from $5.01 \times 10^{-16} \text{ m}^2$ to $1.50 \times 10^{-16} \text{ m}^2$) for sample C2. The gas permeability decreases with increasing confining pressure. When the confining pressure is less than 5 MPa, gas permeability decreases rapidly: 7.59 times for sample C1 and 2.27 times for C2(0 $\rightarrow$ 5MPa). When the confining pressure is greater than 5 MPa, the rate of decrease of gas permeability gradually reduces 1.40 times for sample C-1 and 1.66 times for C2(5 $\rightarrow$ 20MPa). When considering the explanation for this phenomenon, there are some large pores inside the sample at the initial stage. As the confining pressure increases, this part of the pores closes rapidly, and the permeability decreases sharply. As the confining pressure continues to increase, the remaining pores are less sensitive to the confining pressure. Therefore, the change in confining pressure has a small effect on the permeability.

For the unloading stage: 20 $\rightarrow$ 5 MPa, the gas permeability difference between the unloading stage and loading stage under the same confining pressure is small (e.g., sample C1: $1.50 \times 10^{-16} \text{ m}^2$ (unloading -10MPa) vs $1.62 \times 10^{-16} \text{ m}^2$ (loading-10MPa)). When the confining pressure is decreased from 5 MPa to 1 MPa, the hysteresis effect of the permeability is obvious. The permeability corresponding to the unloading stage under the same confining pressure is much

smaller than the permeability corresponding to the loading stage (e.g., sample C1: 5.51×10^{-16} m² (unloading-1MPa) vs 14.81×10^{-16} m² (loading-1MPa)).

For the second cycle of loading and unloading, the test results in the loading phase are mostly the same as the results in the unloading phase of the first cycle. Gas permeability changes very little throughout the unloading stage (compared to results from other stages under the same confining pressure). When the confining pressure returned to the initial value (1 MPa), the gas permeability was slightly less than the loading phase (sample C1: 5.51×10^{-16} m² vs. 4.07×10^{-16} m²). Compared with the first cycle loading phase results, the gas permeability decreased from 14.81×10^{-16} m² to 4.07×10^{-16} m². This indicates that some pores cannot be opened after being closed, although the confining pressure returns to the initial state. A similar trend was found for sample C2.

Figure 4. Effect of confining pressure on gas permeability of (a) sample C-1 and (b) C-2;

Figure 5. Effect of confining pressure on deformation of sandstone ($P_g=0.5$ MPa) (a) sample C-1 and (b) sample C-2.

Figures. 5(a) ~ (b) shows the deformation characteristics of the sample during the gas permeability test. In general, the deformation law follows the evolution law of gas permeability. Similarly, when the confining pressure is less than 5 MPa, the deformation of the sample is

large. Above 5 MPa, the deformation of the sample is less sensitive to the confining pressure. In the second loading and unloading cycle, the deformation of the sample is mainly in the elastic range, and some deformation is unrecoverable compared with the first cycle.

3.2 Effect of gas pressure on gas permeability

Figures 6(a) ~ (b) show the effect of gas pressure on gas permeability during the first and second loading-unloading cycles. First, the gas permeability decreases with increasing gas pressure at the same confining pressure. This phenomenon can be attributed to the Klinkenberg effect. Gas permeability is relatively sensitive to gas pressure at lower gas pressures (less than 1 MPa). There is no significant difference in the gas pressure sensitivity of gas permeability under different confining pressures. In the second cycle of loading and unloading, the effect of gas pressure on permeability is largely similar to that of the first cycle. Furthermore, the gas permeability at low pressure is more sensitive to the gas pressure. When the gas pressure exceeds 2 MPa, the change in gas pressure has little effect on the gas permeability.

Figure 6. Effect of gas pressure on the gas permeability during (a) the 1st loading-unloading phase; (b) the 2nd loading-unloading phase.

Figure 7(a) gives an example of how to calculate the slip factor. For example, when $P_c=5$ MPa, the fitting equation is $y=1.1+0.23x$, and the intrinsic permeability is $1.1 \times 10^{-16} m^2$ (k_{int}). The slip factor can be obtained from $0.23/1.1=0.21$ (MPa). As a result, we can obtain the relationship between k_{int} and b . Figure 7(b) illustrates the evolution trend of the slip factor and its relationship with inherent permeability (take sample C1 as an example). In general, the effect of slippage is more evident. There is a positive correlation between the two parameters (i.e., l and b), whereas the pore radius is negatively correlated. From the mercury intrusion test-measured pore size distribution (Figure 7(c)), it can be known that the median pore radius is about $0.129 \mu m$, and the pores are mainly distributed between $0.01-1 \mu m$. The smaller the pore size, the greater the slippage factor when the pore pressure remains constant.

The slip factor decreases as the intrinsic permeability increases, even though the data distribution is rather discrete. The pore size of the rock mass is correlated to this phenomenon. At constant temperature, the pore structure of the sandstone is compressed as the confining pressure increases. Extrusion of the pores results in a decrease in the pore size, leading to a

decrease in the intrinsic permeability. The reduction in the pore size increases the frequency of collision between the gas molecules and the solid wall. As a result, the gas will slip flow, prompting the slip factor to rise. Previous research has also identified a similar phenomenon in gas permeability studies (Duan and Yang, 2014; Moghadam and Chalaturnyk, 2014; Tanikawa and Shimamoto, 2009; Yang et al., 2017).

Figure 7. (a) An example of the slip factor calculation; (b) the relation between slip factor and intrinsic permeability; (c) the pore size distribution based on mercury intrusion test (Ni et al., 2021)

3.3 Effect of loading pressure on gas permeability

Figure 8(a) shows the effect of axial pressure on gas permeability (take sample C1 as an example, confining pressure is constant). When the axial pressure is 5 MPa, the axial pressure has a negligible effect on the gas permeability. As axial pressure increases, the gas permeability increases mainly because the increase in the axial pressure causes the pores in the inner portion of the sample to open, increasing gas permeability. When the axial pressure is 30 MPa, the gas permeability reaches a maximum. When the axial pressure exceeds 30 MPa, as axial pressure rises, gas permeability decreases. In the experiments, when the axial pressure reached 30 MPa, the sample was fractured. At this time, the confining pressure has a compacting effect on the sample, resulting in a decrease in permeability. When the axial pressure is increased continuously, part of the crack gradually closes due to the axial pressure, resulting in a decrease in permeability.

Figure 8(b) shows the deformation characteristics of the specimen during the application of the axial pressure. Similar to the law of permeability change, the sample deforms slightly when the confining pressure is less than 5 MPa. When the axial pressure is greater than 5 MPa, the deformation of the sample gradually increases as the axial pressure increases. However, when the axial pressure is greater than 20 MPa, the deformation of the sample decreases as the axial pressure increases. This phenomenon is difficult to explain, and we will verify it in subsequent trials.

Figure 8. Effect of axial pressure on (a) gas permeability; (b) deformation.

3.4 Micro-pore/fracture structure

3.4.1 3D pore-fracture structure reconstruction

After the gas permeability test, sample C1 was scanned using a 3D X-ray Microanalyser. The image resolution was $53.14 \mu m$, which was scanned a layer at a time from top to bottom. After the scanning was completed, a total of 500 slices were selected. Before reconstruction, image enhancement and threshold segmentation are required. The whole process is shown in Figure 9. These slices were three-dimensionally reconstructed by a compiled algorithm to obtain a three-dimensional reconstruction model of the sample.

Figure 9 Flow chart of 3D reconstruction of the digital core.

As shown in Figure 10, there is a macroscopic crack in the height direction at an angle of $45^\circ \pm \frac{\varphi}{2}$ (φ is internal friction angle). CT scanning can identify rock fracture surfaces when only macro cracks can be visible on the surface. This is primarily due to rock shear failure. With the gradual increase in axial pressure in the static condition confining pressure, the friction between the particles in the rock mass also gradually increases. When it reaches a certain value, the rock mass particles will dislocate, and shear failure occurs. In addition to the shear fracture surface, there are some small cracks.

Figure 10 3D reconstruction model (3D X-ray) of sandstone after the end of the gas permeability test. Figure 11 shows the evolution of the crack generation and permeability. Phase I: in the initial stage, the stress on the pore structure of the sample is weak due to the small axial pressure. Therefore, the permeability remains largely unchanged. Phase II: as the axial pressure increases, the micro-crack appears in the sample, and the gas permeability increases gradually. When a crack (shear failure) is generated at an angle of $45^\circ \pm \frac{\varphi}{2}$ degree in the height direction, the gas permeability is maximized. Phase III: as the axial pressure increases, the axial pressure will compress the crack, decreasing permeability. Therefore, the evolution of permeability during the complete process varies as follows: stable $\rightarrow$ slowly increasing $\rightarrow$ reaching peak $\rightarrow$ gradually decreasing.

Figure 11. Schematic diagram of the crack development and permeability evolution under triaxial conditions.

3.4.2 Quantitative characterization of pore (crack) structure

To quantitatively characterize the pore structure of the sample, we separated the pore structure from the matrix. In the characterisation process, we found that the threshold algorithm has a greater impact on the characterization results. According to the suggestions of Liu et al.(2020), we make a comparative analysis of different algorithms. Figure 12 shows the calculation results based on the two thresholds. It can be found that when the threshold is 49, the porosity is only 1.85%. When the threshold is 51, it is relatively close to the calculated result of the physical experiment. The porosity was calculated as 7.28% by subsequent processing of the CT image. This result is less than the value (10%) measured by the nitrogen adsorption test due to the CT's resolution not allowing some of the smaller pores to be seen. For some nanopores, higher resolution images are needed to characterize them. Usually, the image scanning accuracy is related to the sample size, and a higher resolution digital image can be obtained from a small sample. For nanopores, FIB/SEM (Focus Ion Beam Scanning Electron Microscopes) is a better choice, and the effect is better. This part of the research aims to observe macroscopic cracks, so no higher resolution image scanning is performed.

Because the isolated pore fracture does not contribute to the seepage characteristics, we extract the connected pores from all pores and calculate the pore connectivity:

$$L_C = \frac{V_C}{V_T} \quad (4)$$

Where L_C is the pore connectivity, V_C is the total volume of the connected pores, and V_T is the total pore volume. The calculated pore connectivity of the sample is 64.41%. According to Figure.12, most connected pores are concentrated in half of the sample, while the isolated pores mainly exist in the upper left part. Therefore, the main migration path of gas during gas flow should be via macroscopic fractures and connected pores.

Matrix	Total pore structure	Connected structure

	Porosity=1.85%, Threshold=49	Porosity=0.59% Connectivity=31.80%

	Porosity=7.28%, Threshold=51	Porosity=4.6%, Connectivity=64.41%

Figure 12. Pore network and interconnected pore network of sandstone

4 Conclusions

This study systematically examined the gas permeability of two sandstone samples under various conditions, including confining pressure, axial pressure, and gas pressure. First, the influence of cyclic loading and unloading on the evolution of gas permeation was tested. The evolution of the gas permeability occurred primarily in the first cycle of loading and unloading. Especially at the initial loading stage (confining pressure less than 5 MPa), the gas permeability decreased by 7.59 and 2.27 times for samples C1 and C2, respectively. From 5 MPa to 20 MPa, the gas permeability decreased only a little. This means that most of the pores in the initial stage that allow the gas to flow have been closed, and subsequent pressurization has less effect on the deformation of the pore structure. After two loading and unloading cycles, the gas permeability recovered to $4.07 \times 10^{-16} \text{ m}^2$ (C1) and $2.51 \times 10^{-16} \text{ m}^2$ (C2), which is fairly different from the initial value. This finding indicates that some of the pores have been plastically deformed and cannot be recovered.

When axial pressure is applied, the gas permeability gradually increases due to the expansion of the crack. When macroscopic cracks are generated, the permeability reaches a maximum. The axial pressure increased further, and the permeability reduced due to the compaction of the axial pressure on the macro crack. Based on microscopic CT images, the cracks are mainly oriented at a 45 °C -degree angle along the height direction. Further quantitative analysis

revealed that the porosity was approximately 7.28%, which was relatively tight and indirectly verified the phenomenon of low macroscopic gas permeability. In addition, different algorithms have a greater impact on digital image characterization, and further research is needed.

In addition, we also considered the Klinkenberg (gas slippage) effect and found that when the gas pressure exceeds 2 MPa, the change in gas pressure has little effect on the permeability. There is no significant difference in the gas slippage effect under different confining pressures, and the slippage effect in the loading stage is clearer than that in the unloading stage. Studies have also found that the slip factor tends to increase as the intrinsic permeability decreases. This phenomenon can be primarily attributed to the pore structure being subjected to pressure and causing the pore size to decrease. As a result of this increased collision frequency between the gas molecules and the inner wall of the pores, the gas exhibits a slip phenomenon and increasing the slip factor.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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