The effects of gas pressure and adsorption in coal permeability under uniaxial strain conditions

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Abstract. Coal permeability evolution related to gas pressure is important to coal mining and coalbed methane exploitation. To apply the exponential model of coal permeability, we simplified the stress of coal reservoirs to the uniaxial strain condition. To investigate the permeability of coal samples changed in gas pressure under strain-controlled conditions, we measured the strain and permeability of coal samples collected from 12-1# coal seam in Hongyang No. 3 Mine in Shenyang, China, during gas pressure reduction under strain-controlled and constant temperature conditions using the Gas seepage measurement system in State Key Laboratory of Coal Resources and Safe Mining of China University of Mining & Technology (Beijing). The permeability experiment was performed under uniaxial strain conditions using adsorptive gas (carbon dioxide) and non-adsorptive gas (helium). The experimental results show that with decrease in gas pressure, the permeability ratio, \( k/k_0 \), of coal samples with helium and carbon dioxide firstly changed slightly with gas pressure from 4.0 to 1.5 MPa and then increased sharply with a gas pressure of <1.5 MPa. Coal samples shrank with the reduction of gas pressure under the uniaxial strain condition. The gas pressure of 1.5 MPa can be considered as the turning point of the volumetric strain change. When gas pressure was <1.5 MPa, the volumetric strain of samples sharply changed because of carbon dioxide gas desorbed from coal when the outlet was open. As the gas pressure decreased, the radial stresses of coal samples with carbon dioxide were less than those of samples with helium. Therefore, coal matrix shrinkage because of gas desorption has an important influence on the radial stress of coal samples under the uniaxial strain condition.

1. Introduction
Coalbed methane (CBM) is a type of unconventional natural gas resource. With the growth of energy demand and the development of new fuel resources, many countries, such as the United States, Australia, and China, have been exploiting CBM [1,2]. In Australia, the annual gas production in 2016 reached \(32 \times 10^9\) m\(^3\), surpassing the United States as the world's largest producer of CBM [3]. China's proven CBM reserves with a burial depth of fewer than 2000 m are \(29.8 \times 10^9\) m\(^3\), and approximately \(12.5 \times 10^9\) m\(^3\) is technically recoverable [4]. In 2019, the CBM production in China reached \(8.88 \times 10^9\) m\(^3\).

Coal permeability is one of the important factors that determine the production of CBM [5]. The structure of the coal is dual-porosity, which includes matrix and cleat. Methane is mainly stored in the form of an adsorbed state in the matrix, and the cleat is the main gas transport channel [6]. In the production process of CBM, the pressure of the reservoir decreases, leading to cleat compression, gas desorption, and coal permeability change [7]. Many studies focused on the influence of coal matrix deformation due to gas
adsorption/desorption on permeability. It is shown that methane desorption from coal causes the shrinkage of the coal matrix; as a result, coal permeability may increase at lower gas pressures [8]. Harpalani and Schraufnagel [9] found that the permeability of coal samples with helium gas decline with the decrease of gas pressure, whereas the permeability with methane had firstly fallen and then rose because of methane desorption from coal. Harpalani and Chen [10] showed that there was a linear relationship between the change in permeability caused by the matrix shrinkage and the volumetric strain. George and Barakat [11] measured the volumetric strain of coal samples with a variety of gases, in which they found that the volume of coal sample with helium expands as the pressure of the gas decreases without stress constraints. The volume shrinkage of coal sample with carbon dioxide at lower gas pressures is greater than the volume shrinkage at higher gas pressures. Robertson [12] found that the permeability first decreased and then increased with the methane pressure increase; matrix shrinkage was dominant at lower gas pressures compared with the effect of effective stress, leading to permeability increase. Mitra et al. [6] found that under uniaxial strain conditions, as the gas pressure decreased, the horizontal stress linearly decreased because of the desorption of the gas; however, the permeability of methane continued to increase. When the uniaxial strain condition of strain control is adopted instead of the condition of stress control, the experimental results are closer to the field observation. Espinoza et al. [13] studied the stress path during the production process away from the wellbore under strain control, in which they found in the experimental data that gas desorption can significantly help to reduce lateral stress until shear failure occurs. The permeability experiments by Feng et al. [14] showed that the effective horizontal stress, which changes with matrix shrinkage, dominated the change in permeability; the permeability rate enlarged rapidly at low pressure.

In this study, to measure coal permeability with decreasing gas pressure, we adopted the strain control experiment method. By adjusting the confining stress on the coal sample, we made sure that the radial strains of coal samples were constant. The axial strains of coal samples changed with gas pressure to simulate the uniaxial strain condition. To discuss the permeability of adsorptive and non-adsorptive gases in coal as the gas pressure decreases, we used the non-adsorptive gas (helium) and the adsorptive gas (carbon dioxide) as the experimental gas. The strains of the coal sample were monitored simultaneously during the experiment. In this study, we discussed the radial stress and effective radial stress under uniaxial strain conditions.

2. Experimental work

2.1 Experimental principle

CBM reservoirs are assumed under uniaxial strains, where changes in stress or pore pressure cause strain only in the vertical direction [15]. The uniaxial strain experimental research in the laboratory did not constrain coal strain in the axial direction but kept the radial strains constant. As the gas pressure decreased, the radial stress was reduced to maintain radial strain [5].

2.2 Sample collection and preparation

In this work, the coal samples were obtained from the 12-1# coal seam (with a depth of 960 m), Hongyang No. 3 Mine, in Shenyang, Liaoning, China. The methane concentration of 12-1# coal seam is 9.5 m³/t, and the coal permeability is 1.73 × 10⁻¹⁶ m².

2.3 Experimental setup and procedure

The permeability experiments were observed by using the Gas seepage under strain-controlled conditions measurement system in State Key Laboratory of Coal Resources and Safe Mining of China University of Mining & Technology (Beijing) (Figure 1). To measure the coal permeability and gas desorption effects under uniaxial strain conditions, we used two kinds of gas, helium and carbon dioxide, as experimental gases. The initially applied radial and axial stresses were 10 MPa. By keeping the temperature constant
during the experiment to eliminate the effect of temperature on permeability, we monitored the strains of coal samples through a strain gauge.

![Figure 1](image)

**Figure 1.** Gas seepage under strain-controlled conditions measurement system: (1) computer, (2) strain gauge, (3) gas collecting device, (4) holder, (5) calorstat, (6) load controller, (7) pressure sensor, (8) calibration tank, (9) gas supply device, and (10) vacuum pump.

The following are the experimental procedures observed.

(i) Coal samples were evacuated with 10 MPa confining stress and axial stress.

(ii) The gas with 4.0 MPa pressure was injected into the sample chamber. The gas pressure in the sample chamber and coal strain were monitored.

(iii) The gas flow was measured at gas pressure of 4.0, 3.5, 3.0, 2.5, 2.0, 1.5, 1.0, 0.5, and 0.3 MPa. Under each gas pressure, the confining stress on the coal sample was adjusted to keep the radial strain constant.

(iv) The outlet was not open until gas pressure and coal strain reached equilibrium, and when the outlet was open, the gas flow was measured.

3. Results and discussion

3.1 Permeability variation under uniaxial strain condition

In this experiment, we tested four samples. The coal sample permeability can be calculated using the following equation:

$$k = \frac{2Qp_0\mu L}{A(p_1^2 - p_2^2)}$$  \hspace{1cm} (1)

where $k$ is the coal sample permeability ($10^{-3}$ μm$^2$), $Q$ is the gas flow rate (mL/s), $p_0$ is the atmospheric pressure with 0.1 MPa, $\mu$ is the dynamic fluid viscosity (Pa · s), $L$ is the length of the coal sample (cm), $A$ is the cross-sectional area of the coal sample (cm$^2$), and $p_1$ and $p_2$ are the gas pressures (MPa) at the inlet and outlet of the coal sample.

Table 1 shows the permeability of coal samples under uniaxial strain conditions changes with gas pressure.

| Specimen | Gas pressure (MPa) | Permeability ($10^{-18}$ m$^2$) |
|----------|--------------------|---------------------------------|
|          |                    | Helium                          | Carbon dioxide |
|          |                    |                                 |                |
To describe the permeability evolution shown in Figure 2, we introduced the permeability ratio, $k/k_0$, where $k$ is the permeability under specific gas pressure, and $k_0$ is the permeability under initial gas pressure (4.0 MPa).

|   | 0.3 | 0.5 | 1.0 | 1.5 | 2.0 | 2.5 | 3.0 | 3.5 | 4.0 |
|---|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 1 | 110.86 | 66.18 | 46.52 | 31.37 | 28.12 | 24.96 | 23.70 | 23.20 | 20.29 |
| 2 | 117.37 | 30.61 | 21.98 | 16.66 | 15.66 | 15.28 | 14.85 | 14.77 | 11.03 |
| 3 | 213.59 | 121.85 | 94.42 | 73.28 | 62.33 | 59.66 | 58.64 | 57.43 | 55.04 |
| 4 | 178.46 | 125.37 | 94.42 | 73.28 | 62.33 | 59.66 | 58.84 | 61.61 | 60.88 |


As shown in Figure 2, when helium was the experimental gas, the coal permeability increased monotonically with the decrease of gas pressure. The rebound pressure of coal permeability did not appear, which occurs in the condition of stress control [12]. When the gas pressure decreased from 4.0 to 1.5 MPa and from 1.5 to 0.3 MPa, the permeability ratio $k/k_0$ increased to 1.22–1.54 and 3.03–10.65, respectively. When carbon dioxide was used as the experimental gas, the permeability change of the coal sample was similar to that of helium. When the gas pressure decreased from 4.0 to 1.5 MPa and from 1.5 to 0.3 MPa, the permeability ratio of samples increased to 3.99–6.36 and 30.33–127.59, respectively. For the four samples, during the process of decreasing gas pressure, the permeability ratio of carbon dioxide was greater than that of helium at the same gas pressure. At the higher gas pressure with 4.0–1.5MPa, the permeability ratio of carbon dioxide was 2.6–4.2 times than that of helium. When the gas pressure was lower than 1.5 MPa, the difference between the permeability ratios of the two gases became greater. The permeability ratio of carbon dioxide was 5.6–25.4 times than that of helium because carbon dioxide has a strong adsorption capacity in the coal matrix. At lower gas pressures, coal matrix shrinkage that is caused by a large amount of the carbon dioxide desorption increased the seepage fracture aperture of the coal samples.

3.2 Volumetric strain variation under uniaxial strain condition

The desorption-induced matrix shrinkage can significantly influence the strain of micropores and macropores in coal, resulting in coal permeability change [16]. During the experiment, we monitored the radial and axial strains of coal samples simultaneously, and we calculated the volumetric strain using the following equation:

**Figure 2.** Coal permeability ratio with various gas pressures.
\[ \varepsilon_v = 2\varepsilon_r + \varepsilon_a \]  \hspace{1cm} (2)

where \( \varepsilon_v \) is the volumetric strain \((10^{-3})\), \( \varepsilon_r \) is the radial strain \((10^{-3})\), and \( \varepsilon_a \) is the axial strain \((10^{-3})\). Because the radial strain in this experiment was constant, the Eq. (2) can be simplified as

\[ \varepsilon_v = \varepsilon_a \]  \hspace{1cm} (3)

Figure 3 shows the volumetric strains of coal samples with gas pressure (coal shrinkage was positive volumetric strain). The shrinkage of coal samples with helium gas results from the effective stress change, but not from gas desorption. During the process of gas pressure reduction, a linear correlation between volumetric strain and helium gas pressure was observed. The volumetric strains of coal samples continuously shrank during the process of decreasing carbon dioxide pressure. The gas pressure of 1.5 MPa could be taken as the threshold. When gas pressure was less than 1.5 MPa, the volume of coal samples shrank dramatically because of carbon dioxide desorption when the outlet was open. At a lower gas pressure of 1.5–0.3 MPa, the desorption rate of carbon dioxide increased, which induced the shrinkage strain of the coal sample increased [10,11].

Both permeability and volumetric strain of coal samples appeared inflection point when the gas pressure was 1.5 MPa. Their rate of change is slight when the gas pressure is greater than 1.5 MPa and dramatically lower than 1.5 MPa. As the gas pressure decreases, the permeability of the coal sample increases, and the volumetric shrinks. Thus, the change in coal permeability and volumetric strain rate is a result of gas pressure. The volumetric strain of the coal sample does not directly influence its permeability, but the desorption strain, the part of coal volumetric strain, which may result in a net permeability increase [17]. The previous laboratory results indicate that there is a direct influence from sorption strain on permeability. By adding a sorption strain term, Connell [18] developed the model for determining the coal permeability and found the acting of the sorption strain term to increase the rebound of permeability during pore pressure drawdown.

![Figure 3](image-url)

Figure 3. The volumetric strains of the coal samples with various gas pressures.
3.3 Radial stress variation under uniaxial strain condition

Previous studies under stress-controlled conditions have found that as the gas pressure decreases, the effective stress increases, and the permeability decreases [19]. Under uniaxial strain conditions, the radial stresses need to be reduced to maintain the radial strain constant [6]. Figure 4 shows the evolution of the radial stresses in this experiment.

For coal samples with helium, the reduction in gas pressure resulted in the decline of the radial stress, indicating that there was a linear relationship between the radial stress and gas pressure. The slopes of the fitted linear function changed from 0.60 to 0.88 and were less than 1.0, which means that the reduction of radial stress was less than the reduction of gas pressure.

![Graphs showing radial stress variation under uniaxial strain condition](image_url)

Figure 4. The radial stress of the coal samples with various gas pressures.

The radial stress of coal samples with carbon dioxide had a quadratic function relationship with gas pressure. As the gas pressure decreased, the slopes of the tangent of the quadratic function curve were greater than 1.0, and the slopes increased continuously. The reduction of radial stress was greater than that of gas pressure, and the rate of radial stress reduction was increased.

Under uniaxial strain condition, the desorption of carbon dioxide led to coal matrix shrinkage as the gas pressure decreased. To balance the strain changes, we reduced the radial stress of coal samples with carbon dioxide than those with helium gas, resulting in a larger slope under the condition of carbon dioxide.
Thus, the effective radial stress equation can be shown as

$$
\sigma_{er} = \sigma_r - \alpha p
$$

where $\sigma_{eh}$ is the effective radial stress (MPa), $\sigma_h$ is the radial stress (MPa), and $\alpha$ is the effective stress coefficient, ranging from 0 to 1. Figure 5 shows the relationship between effective radial stress and gas pressure.

![Graphs showing the relationship between effective radial stress and gas pressure for different coal samples](image)

**Figure 5.** The effective radial stress of the coal samples with various gas pressures.

As the gas pressure decreased, the effective radial stress of coal samples with helium decreased linearly. The slopes of the fitted linear function changed from 0.38 to 0.68, but they are always less than 1.0. In the process of gas pressure reduction, the reduction of effective radial stress was also less than that of gas pressure. However, the curves of the effective radial stress of carbon dioxide could be described with the quadratic function. The rate of reduction of the radial stress of coal samples with carbon dioxide accelerated continuously. The reduction of the effective radial stress of coal samples with carbon dioxide was larger than that of helium. Because carbon dioxide is an adsorbent gas, as the gas pressure decreased, the desorption rate of carbon dioxide accelerated continuously. To maintain the constant of the radial strain of the coal sample due to gas desorption, we need to decrease the radial stress more.

4. Conclusions

On the basis of controlling the radial strain of coal samples, we studied the permeability evolution with gas pressure decreasing. It was found that as the gas pressure decreased, the permeability of coal samples with helium gas (non-absorptive gas) and carbon dioxide gas (absorptive gas) increased continuously.
Coal permeability at high gas pressures (4.0–1.5 MPa) changed less than at low gas pressures (1.5–0.3 MPa). It results from the radial stress reduction for maintaining the radial strain of coal samples. The radial stress on coal samples with helium gas decreased linearly as gas pressure decreased. However, when carbon dioxide was used as the experimental gas, there is a need to reduce the radial stress and effective radial stress.

Compared with the volumetric strain of coal samples with helium gas, the shrinkage of coal samples with carbon dioxide gas was larger. The volumetric strain of coal with helium reduced linearly with gas pressure. The volumetric strain of coal samples with carbon dioxide gas dropped differently in various gas pressure stages. When gas pressure varied from 4.0 to 1.5 MPa, coal shrank slightly. The sharp shrinkage occurred at the gas pressure of less than 1.5 MPa. Carbon dioxide gas desorption from coal is significantly contributed to coal shrinkage. It was verified that the permeability of coal samples with carbon dioxide gas enhances more than that with helium gas during gas pressure decreasing.

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References
[1] Liu J, Chen Z, Elsworth D, Qu H and Chen D 2011. Interactions of multiple processes during CBM extraction: a critical review. International Journal of Coal Geology. 87(3-4) 17–189
[2] Moore T A 2012. Coalbed methane: a review. International Journal of Coal Geology. 101 36–81
[3] Li H Y, Lau H C, Huang S 2018. China's coalbed methane development: A review of the challenges and opportunities in subsurface and surface engineering. Journal of Petroleum Science and Engineering. 166 621–635
[4] Tao S, Chen S D, Pan Z J 2019. Current status, challenges, and policy suggestions for coalbed methane industry development in China: A review. Energy Sci Eng. 7(4) 1059–1074
[5] Chen Y, Liu D, Yao Y, Cai Y and Chen L 2015. Dynamic permeability change during coalbed methane production and its controlling factors. Journal of Natural Gas Science and Engineering. 25 335–346
[6] Mitra A, Harpalani S and Liu S 2012. Laboratory measurement and modeling of coal permeability with continued methane production: part 1 – laboratory results. Fuel. 94(1) 110–116
[7] Connell L D, and Detournay C 2009. Coupled flow and geomechanical processes during enhanced coal seam methane recovery through CO₂ sequestration. International Journal of Coal Geology. 77(1-2) 222–233
[8] Gray I 1987. Reservoir engineering in coal seams: part 1 – The physical process of gas storage and movement in coal seams. SPE Reservoir Engineering. 2 28–34
[9] Harpalani S and Schraufnagel R A 1990. Shrinkage of coal matrix with release of gas and its impact on permeability of coal. Fuel. 69(5) 551–556
[10] Harpalani S and Chen G 1997. Influence of gas production induced volumetric strain on permeability of coal. Geotechnical and Geological Engineering. 15(4) 303–325
[11] George J D S and Barakat M A 2001. The change in effective stress associated with shrinkage from gas desorption in coal. International Journal of Coal Geology. 45(2-3) 105–113
[12] Robertson EP 2005. Measurement and modeling of sorption–induced strain and permeability changes in coal. PhD dissertation. Colorado School of Mines
[13] Espinoza D N, Pereira J M, Vandamme M 2015. Desorption-induced shear failure of coal bed seams during gas depletion. International Journal of Coal Geology. 137 142–151
[14] Feng R M, Harpalani S, Pandey R 2016. Laboratory measurement of stress-dependent coal permeability using pulse-decay technique and flow modeling with gas depletion. Fuel. 177 76–86
[15] Palmer I and Mansoori J 1998. How permeability depends on stress and pore pressure in coalbeds: a new model. *Spe Reservoir Evaluation & Engineering*. 1 539–544

[16] Wang G X, Wei X R, Wang K, Massarotto P and Rudolph V 2010. Sorption–induced swelling/shrinkage and permeability of coal under stressed adsorption/desorption conditions. *International Journal of Coal Geology*. 83(1) 46–54

[17] Liu J, Chen Z, Elsworth D, Miao X, Mao X 2011. Evolution of coal permeability from stress-controlled to displacement-controlled swelling conditions. *Fuel*. 90, 2987–2997.

[18] Connell L D 2016. A new interpretation of the response of coal permeability to changes in pore pressure, stress and matrix shrinkage. *International Journal of Coal Geology*. 162 169–182.

[19] Pan Z and Connell L D 2012. Modelling permeability for coal reservoirs: a review of analytical models and testing data. *International Journal of Coal Geology*. 92 1–44