Evaluation and modeling of gas permeability changes in anthracite coals

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HIGHLIGHTS

- The gas (CO₂) permeability changes in anthracite coals were comprehensively evaluated.
- The permeability change is the result of the effective stress increase, the matrix shrinkage and the gas slippage.
- We calculated the permeability increments caused respectively by the three factors.
- We constructed an empirically coupled model predicting gas permeability change.

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ABSTRACT

The gas permeability of anthracite coal is altered as a result of the effective stress increase, the coal matrix shrinkage and the gas slippage that occur during the gas pressure depletion process. This paper describes an investigation of changes in the adsorbing-gas (CO₂) permeability of three anthracite coal cores (samples A, B and C). The changes in permeability under a constant confining stress condition (4.3 MPa) were found to be distinct for the three cores, and these observations are considered as the superimposed results of the three effects based on the following findings. During the gas pressure depletion: (a) the permeability is negatively proportional to the effective stress, and the slopes of the straight lines are near unity when the mean gas pressures are greater than 0.2–0.4 MPa; (b) the permeability increment induced by the gas slippage levels off to an approximately constant value (core A, 0.5 D; core B, 0.6 D; core C, 0.02 D) when the mean gas pressure is greater than 0.8 MPa and subsequently becomes more significant at pressures less than 0.8 MPa; (c) the matrix shrinkage-induced permeability increment increases linearly for cores A and B but increases logarithmically for core C; and (d) the effect on the permeability of the effective stress predominates for core A, but for core C, the effect of the matrix shrinkage is most significant. Furthermore, an empirical model that predicts the adsorbing-gas permeability change was proposed as a function of the permeability increments caused by the effective stress, the matrix shrinkage and the gas slippage at each gas pressure under a constant confining stress condition, and can be mathematically expressed as:

\[ k_{gt} = k_0 + \Delta k_{sl}(p_i) + \Delta k_{sh}(p_i) + \Delta k_{eff}(p_i) \].

The results demonstrate that good agreement was achieved between the empirical models and the experimental data.

1. Introduction

The change in gas permeability of coal has been definitively verified using field data and laboratory measurements and is widely studied due to its importance in coal-bed methane (CBM) production. During the primary and enhanced CBM recovery processes, the coal permeability declines due to the increase in the effective stress induced by the reservoir pressure drawdown. However, this decline can be offset potentially by the permeability enhancement caused by the coal matrix shrinkage associated with gas desorption.

The effective stress–permeability relationship was frequently considered as an exponential function [1,2]. In comparison, the adsorption/desorption-induced matrix swelling/shrinkage relationship is much more complex and has been investigated in the laboratory by various researchers [3–8]. Accompanied by the matrix-shrinkage/swelling, a volumetric strain occurs in the coals and further impacts the permeability changes [9–14]. A number of researchers have observed that the relationship between the swelling strain and the amount of adsorbed gas is either approximately linear [3,15] or non-linear [16,17]. In most cases, an empirical approach using a Langmuir-like equation was employed to describe the volumetric strain change related to the gas adsorption/desorption [3]. Recently, Pan and Connell [18] derived a theoretical model to describe the volumetric strain based on an energy balance principle.

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Prediction of the change in coal permeability during CBM production has been commonly performed with the aid of analytical or coupled models. To date, several analytical models that link porosity or effective stress to permeability have been developed and have achieved good agreement with field data or experimental results [19–26]. In addition, Gu and Chalaturnyk [27] developed a coupled model by combining a GEM simulator with FLAC software. Liu and Rutqvist [28] also reported a coal permeability model for uniaxial strain and constant confining stress conditions. This model considers the fracture-matrix interaction during coal deformation and is based on a newly proposed internal swelling stress concept.

In this paper, which references the work of Harpalani and Chen [29], the primary efforts were focused on a comprehensive investigation of the effects of the effective stress, the coal matrix shrinkage and the gas slippage on the adsorbing-gas permeability of anthracite coals. Previous researchers usually assumed that the first two effects were the key influences on the permeability change but neglected the effect of the latter. In this paper, the mechanism that controls the gas permeability change in anthracite coals was investigated using analysis of all three effects. Furthermore, the permeability increments caused by the three effects were calculated at each gas pressure under a constant confining stress condition. Based on the calculated results, an empirically coupled model was proposed to predict the gas permeability change.

2. Experimental work

2.1. Sample preparation and experimental setup

Three bulk anthracite coal samples were obtained from three active mines (Tang’an, Yong’an and Gushuyuan) located in the southern Qinshui basin of China. All samples were wrapped in a timely manner with preservative films and were carefully transferred to the laboratory for experimental measurements. These samples were cut perpendicular to the bedding surface into the shape of cylindrical cores. After drying at a temperature of 150 °C, the length and the radius of the cores were precisely measured with a micrometer.

Prior to the start of the permeability test, the core (together with the upper and lower spacers) was encased with insulating tape and subsequently with heat-shrink tubing to prevent gas leakage during the test. Then, the test was performed at a constant ambient temperature of 26 °C. The experimental setup primarily consists of four independent systems for stress control, gas pressure control, gas flow-rate measurement and stress–strain monitoring (Fig. 1):

1. The process that produces stress on the core was governed using a control system linked to a computer. The triaxial cell was connected to a hydraulic pump to provide the confining stress, and the axial stress was set at zero in this study. Thus, the core was subjected to an isotropic stress resulting from the interconnection between the upper and lower cavities separating the triaxial cell.

2. The inlet gas pressure was directly controlled by a pressure gauge, and the outlet pressure was set at atmospheric pressure.

3. The tip of the graduated cylinder was wetted with prepared soapy water. A soap bubble was generated as the gas flowed through the tip and subsequently moved upwards with the increasing gas volume. The time interval during which the soap bubble flowed through a certain volume within the graduated cylinder was measured to obtain the gas flow rate. The measurement was halted when the time intervals for three continuous measurements were approximately equal under the same experimental conditions. The gas flow rate was estimated by the following equation:

\[ Q_o = \frac{V_2 - V_1}{t_2 - t_1} \]

where \( Q_o \) is the gas flow rate (ml/s), \( t_1 \) and \( t_2 \) are the start and end times recorded during the soap bubble flow (s) and \( V_1 \) and \( V_2 \) are the apparent volumes obtained directly from the graduated cylinder at the time of \( t_1 \) and \( t_2 \), respectively (ml).

4. The real-time radial strain in the core was monitored using two radial strain gauges. The measured data were captured by a Data Acquisition System (DAS) and subsequently output from the computer.

2.2. Experimental design

Three widely used assumptions with respect to the coal reservoir changes include the presence of a uniaxial strain [22,26], a constant volume [30] and a constant confining stress [28]. In this paper, we assume that the confining stress acting on the coal is constant during the gas drainage; it follows that the changes in the coal reservoir conditions are limited to only the decrease in the gas pressure and the corresponding increase in the effective stress. The objective of this work is to investigate the mechanism...
that controls the gas permeability change under a constant confining stress condition.

Five effective stress conditions were first designed. Under each effective stress condition, both the confining stress and the gas pressure were increased to maintain a constant positive effective stress on the core. During this process, a series of gas flow-rate measurements were recorded for inert helium (He) gas. Next, the same procedures were repeated for the adsorbing carbon dioxide (CO₂) gas. The gas permeability was subsequently evaluated according to the measured flow rate.

Furthermore, the CO₂ permeability increments caused by the gas slippage and the coal matrix shrinkage at each gas pressure can be obtained by simultaneous analysis of the seepage behaviors of He and CO₂ within the anthracite coals. Because He is a non-adsorbing gas and only appears as a slippage phenomenon during gas pressure depletion while the typical adsorbing gas (CO₂) possesses a strong affinity with coal matrix, both the gas slippage and the coal matrix shrinkage will occur with the decrease in the gas pressure.

2.3. Calculation models

2.3.1. Gas permeability

With respect to the tight porous media observed in anthracite coals, the permeability to gas is commonly calculated with the following equation:

\[ k_g = \frac{2P_o Q_w \mu_k}{A (p_1 - p_2)} \]  

(2)

where \( k_g \) is the coal permeability to gas (μD); \( P_o \) is the standard atmospheric pressure (10⁻⁵ MPa); \( Q_w \) is the gas flow rate at standard atmospheric pressure (ml/s); \( p_1 \) and \( p_2 \) are the inlet and outlet gas pressures, respectively (10⁻⁵ MPa); \( \mu_k \) is the coefficient of kinetic viscosity for the gas at the mean pressure ((\( p_1 + p_2 \))/2) and the experimental temperature (mPas); \( L \) is the core length (cm); and \( A \) is the cross-sectional area of the core (cm²).

2.3.2. Gas slippage and coal matrix shrinkage

The gas slippage phenomenon in porous media was mathematically described [31] as:

\[ k_g = k_o \left( 1 + \frac{b}{P_m^c} \right) \]  

(3)

where \( k_g \) is the gas permeability obtained from Eq. (2); \( P_m \) is the mean gas pressure (MPa), \( k_o \) is a Klinkenberg-corrected value of \( k_g \) at an infinite mean gas pressure (also known as the equivalent liquid permeability) and \( b \) is a slippage factor defined as \( b = \frac{k_{Sli}}{k_{Sli}} \) in which \( c \) is a proportionality factor, \( r \) is the mean radius of the pores in the porous media and \( \lambda \) is the mean free path of the gas molecules.

The slippage factor \( b \) was further given [29,32] as:

\[ b = \frac{16c \mu}{w} \sqrt{\frac{2RT}{\pi M}} \]  

(4)

where \( c \) is a constant, \( \mu \) is the kinetic viscosity of the gas, \( M \) is the molecular weight of the gas, \( w \) is the flow path width, \( R \) is the universal gas constant and \( T \) is the absolute temperature.

Using Eq. (4), the CO₂ slippage factor \( (b_c) \) can be expressed as a function of the He slippage factor \( (b_h) \):

\[ b_c = \frac{b_h}{M_c} \left( \frac{M_{H_2}}{M_H} \right) \]  

(5)

Thus, for a CO₂ adsorbing-gas, the gas slippage-induced permeability increment can be obtained as:

\[ \Delta k_{Sli} = k_g - k_o = k_o \left( 1 + \frac{b_c}{P_m^c} \right) - k_o = k_o \frac{b_c}{P_m^c} \]  

(6)

The matrix shrinkage-induced permeability increment can subsequently be obtained and is written as:

\[ \Delta k_{Shr} = k_g - k_o - \Delta k_{Sli} = k_g - k_o - k_o \frac{b_c}{P_m^c} \]  

(7)

In Eqs. (5)–(7), \( \mu_c \) and \( \mu_H \) are the kinetic viscosity for the CO₂ and He gases, respectively, and \( M_c \) and \( M_H \) are the molecular weights for the CO₂ and He gases, respectively.

3. Results

3.1. Permeability change

As measured under inlet gas pressures of 0.3–4.1 MPa (corresponding to the mean gas pressures of 0.2–2.1 MPa) and confining stresses of 2.4–5.5 MPa, the anthracite coal permeabilities to CO₂ are notably low, with values of 1.30–13.59 μD, 3.24–14.92 μD and 0.07–1.06 μD for cores A, B and C, respectively (Table 1). The changes in the permeability with gas pressure depletion under a 4.3-MPa confining stress condition are distinct for the three cores. The permeability of core A initially decreases but subsequently increases with the decrease in the gas pressure, while the rebound begins at an inlet gas pressure of approximately 1.5 MPa (corresponding to a mean gas pressure of approximately 0.8 MPa). For core B, the permeability is approximately constant at an inlet gas pressure greater than 1.5 MPa and subsequently increases as the gas pressure falls below 1.5 MPa. However, the permeability of core C exhibits a monotonic increase during the decrease in gas pressure. In addition, a marked difference among cores A, B and C is that the gas permeability of the former two is generally ten times larger than that of the last under the same experimental conditions.

3.2. Effects on permeability change

3.2.1. Effective stress

A series of permeability values for varied effective stress and constant gas pressure conditions were selected to evaluate the impact of the effective stress on the gas permeability. Previous experimental measurements indicated that the coal permeability decreases exponentially with increasing effective stress [1,2]. However, in this paper, the agreement is much better if a straight line is fit to the effective stress–permeability data rather than an exponential curve. As shown in Fig. 2, the gas permeability is considered to be a negative linear function of the effective stress. Furthermore, the slopes of the straight lines are near unity when the inlet gas pressures are greater than 0.3–0.7 MPa (corresponding to a mean gas pressures of 0.2–0.4 MPa). This observation indicates that the coal permeability is much more sensitive to the effective stress variation under a lower inlet gas pressure, such as 0.3 MPa.

3.2.2. Gas slippage and coal matrix shrinkage

To illustrate the effects of the matrix shrinkage and the gas slippage on permeability, the behaviors of the permeability changes were investigated under constant effective stress conditions. For each core, the tendencies of the permeability change are similar for all five effective stress conditions during gas pressure depletion. However, the changes among the three coals are markedly distinct due to the differences in the superimposed effects of the matrix shrinkage and the gas slippage on the gas permeability. These two effects are the main factors that lead to the increase in gas permeability during gas pressure depletion. In this paper, the changes
and \( \Delta k_{\text{shr}} \) can be expressed in the following relationship:

\[
\Delta k = k_{\text{shr}} + \Delta k_{\text{slip}}(p) + \Delta k_{\text{eff}}(p)
\]

where \( k_{\text{shr}} \) is the matrix shrinkage-induced permeability increment, \( \Delta k_{\text{slip}}(p) \) is the gas slippage-induced permeability increment, and \( \Delta k_{\text{eff}}(p) \) is due to the effective stress on the coal matrix. The empirical model was constructed based on the following equations:

\[
\Delta k_{\text{shr}} = k_{\text{shr}}(p), \quad \Delta k_{\text{slip}}(p) = \Delta k_{\text{slip}}(p)\sigma, \quad \Delta k_{\text{eff}}(p) = \Delta k_{\text{eff}}(p)\sigma
\]

where \( k_{\text{shr}}(p) \) and \( \Delta k_{\text{slip}}(p) \) are functions of the gas pressure, and \( \Delta k_{\text{eff}}(p) \) depends on the effective stress. The permeability of coal to adsorbing gas increases with the decrease in gas pressure in the form of a power exponent. Under the same effective stress condition, the variations in the permeability change are completely identical and only depend on the gas pressure. In this study, the permeability increment levels off during the pressure depletion to an approximately constant value when the inlet gas pressure is greater than 1.5 MPa and subsequently undergoes a sharp increase. Moreover, the influence of the effective stress on the permeability increment is minor.

The change characteristics of the permeability increment due to coal matrix shrinkage show good agreement with the change trends of the gas permeability under constant effective stress conditions. For core A, during gas pressure depletion, the increment initially decreases and subsequently increases sharply at an inlet gas pressure of approximately 1.5 MPa while for cores B and C, it increases gradually but becomes significant at an inlet gas pressure of approximately 1.5 MPa.
where \( k_0 \) is considered as the initial reference permeability; \( \Delta k_{sl}(p_t) \) and \( \Delta k_{shr}(p_t) \) are the permeability gain terms caused, respectively by the gas slippage and the matrix shrinkage at the inlet gas pressure of \( p_t \); and \( \Delta k_{ef}(p_t) \) is the accumulated permeability loss term associated with the effective stress increase as the inlet gas pressure is reduced from \( p_i \) to \( p_t \).

Based on the permeability increment induced by the gas slippage and the matrix shrinkage at each gas pressure under a constant confining stress condition, it was observed that both increments could be described as a function of the difference in the gas pressure between the inlet and outlet (Fig. 3). The gas slippage-induced permeability increment can be uniformly described as:

\[
\Delta k_{sl}(p_t) = a\left(\frac{p_t}{C_0p_2}\right)^b
\]

where \( p_2 \) is the outlet gas pressure equal to the atmospheric pressure.

The matrix shrinkage-induced permeability increment at an inlet gas pressure of \( p_t \) for cores A and B can be written as:

\[
\Delta k_{shr}(p_t) = c_1\left(\frac{p_t}{C_0p_2}\right) + d_1
\]

For core C, it is written as:

\[
\Delta k_{shr}(p_t) = c_2\ln\left(\frac{p_t}{C_0p_2}\right) + d_2
\]

As mentioned previously, the permeability decreases linearly with the increase in the effective stress. Furthermore, the variations in the gradients of permeability (i.e., the slope of the straight line) are approximately equal at an inlet gas pressure greater than 0.3–0.7 MPa. Thus, the permeability increment induced by the effective stress can be calculated and is given as a function of average slope \( \overline{k} \):

\[
\Delta k_{ef}(p_t) = \overline{k}(\sigma - \sigma_c)
\]

Substituting Eqs. (9), (10a) and (11) into Eq. (8), an equation for coals similar to that of cores A and B was obtained in the form of:

\[
k_{gt} = k_0 + a(p_t - p_2)^b + c_1(p_t - p_2) + \overline{k}(p_t - p_i)/2 + d_1
\]

Similarly, an equation for the coals similar to that of core C was obtained as:

\[
k_{gt} = k_0 + a(p_t - p_2)^b + c_2\ln(p_t - p_2) + \overline{k}(p_t - p_i)/2 + d_2
\]

In Eqs. (9)–(12b), \( a, b, c_1, c_2, d_1 \) and \( d_2 \) are dimensionless coefficients.

By fitting Eqs. (12a) or (12b) to the experimental data, good agreement was achieved between the empirical models and the experimental data, as shown in Fig. 4. The fitting result can be used to predict the change in the adsorbing-gas permeability of anthracite coals. Furthermore, the optimal coefficients produced by fitting the models to experimental data were obtained.

4. Discussion

The changes in the permeability of anthracite coals are comprehensively influenced by the effective stress variation, the coal...
matrix shrinkage and the gas slippage. The first two cause the deformation of the pore-fracture structure of the coals, which in turn affects the coal permeability. The last is related to the kinetics of the gas flow through tightly porous rocks and becomes significant at low pressures.

During the decrease in the inlet gas pressure (4.1–0.5 MPa) under a constant confining stress condition (4.3 MPa), the gas-slipage-induced permeability increment remains nearly constant down to a notably low gas pressure, and the change in the permeability increment caused by the matrix shrinkage increases in a linear or exponential manner. The total changes in the permeability increment caused by the matrix shrinkage are 5.45 and 14.12 times larger than those caused by the gas slippage for cores B and C, respectively, which indicate that the effect of the matrix shrinkage on gas permeability may be much stronger than that of the gas slippage. The increase in the effective stress that results in the contraction of the cleat/fracture of coals is the most significant factor affecting permeability losses during the gas pressure depletion.

The coal matrix shrinkage can be reflected by the coal elastic strain. As the gas is gradually desorbed, the cleat/fracture aperture within the coals is opened due to the shrinkage of the coal matrix and will be compressed when the coal is subjected to a certain confining stress. At the same time, the coal deforms and generates a strain. However, the average slope $k$ reflects the influence of the effective stress on the coal permeability. The higher the absolute value of the average slope, the larger the negative impact of the effective stress on the coal permeability.

The radial strain–average slope data were plotted in Fig. 5. It can be observed that core A displays the maximum absolute value of the average slope and the least radial strain while core C shows the maximum radial strain and the least absolute value of the average slope. This observation suggests that the possible mechanisms for the change in permeability for different cores are: (1) when the inlet gas pressure is greater than 1.5 MPa, the negative impact of the effective stress on the permeability dominates for core A but is nearly offset by the positive effect of the matrix shrinkage for core B. (2) As the inlet gas pressure falls below 1.5 MPa, both the matrix shrinkage and the gas slippage effects play an important role in influencing the permeability for cores A and B. (3) For core C, the positive effect of the matrix shrinkage on the permeability dominates during gas pressure depletion.

5. Conclusions

(1) This study has shown that the gas permeability changes in anthracite coals during gas pressure depletion under a constant confining stress condition (4.3 MPa) are multiple and represent the superimposed results of the effects of the effective stress, the matrix shrinkage and the gas slippage. Change behaviors of the gas permeability are mainly impacted by the effective stress and the matrix shrinkage. As the mean gas pressure falls below 0.8 MPa, the effect of the gas slippage becomes significant.

(2) An empirical model was proposed as a function of the permeability increments caused by the effective stress, the matrix shrinkage and the gas slippage at each gas pressure under a constant confining stress condition and can be used to predict the gas permeability change of anthracite coals.

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References


