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Coal cleat permeability for gas movement under triaxial, non-zero lateral strain condition: A theoretical and experimental study

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HIGHLIGHTS

- Theoretical model for coal cleat permeability under non-zero lateral strain condition.
- Relationship among permeability, injecting, confining pressures, load and adsorption.
- Accurately predicts the combined effects of effective stress and coal matrix swelling.
- Contains parameters for fractured properties; fracture Poisson's ratio and Young's modulus.
- Verification of model using experimentally-determined black coal permeability data.

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ABSTRACT

As the permeability of coal seams is mainly determined by the network of natural fractures known as the cleat system, estimation of cleat permeability is of utmost importance for the carbon dioxide sequestration process in deep coal seams. The main objective of this study is to develop a new mathematical model for predicting cleat permeability under non-zero lateral strain conditions such as the conditions encountered in laboratory triaxial experiments. By applying the theory of elasticity to the constitutive behaviour of fractured rocks, a theoretical relationship between permeability and gas injecting pressure, confining pressure, axial load and gas adsorption in triaxial tests is developed. The new model was then verified using experimentally-determined permeability data of two coal samples. Results indicate that the new model can fairly accurately predict the combined effects of effective stress and coal matrix swelling on cleat permeability for both CO_2 and N_2 injections at various injection pressures. The model also provides quite accurate prediction of the effect of confining pressure on cleat permeability for both CO_2 and N_2 injections. The model includes parameters for fractured rock properties, namely Poisson's ratio and Young's modulus. The model can be applied to predict cleat permeability, regardless of cleat size. When the accuracy of the new model is compared with the existing Gilman and Beckie [5] model, with increasing injecting pressure both models show similar increments of N_2 permeability and different reductions for CO_2 permeability. This is due to the zero lateral strain assumption of the existing model, which is not applicable to the swelling process under triaxial test condition. The new model is more accurate for the prediction of CO_2 cleat permeability under triaxial test condition.

1. Introduction

The process of carbon dioxide (CO_2) sequestration in deep unminable coal seams has been identified as an economical approach to the reduction of greenhouse gas emissions into the atmosphere, as it has a beneficial by-product, methane (CH_4), obtained through enhanced coal bed methane recovery. The main storage mechanism of CO_2 in the coal mass is adsorption [1]. However, CO_2 adsorption into the coal matrix causes the coal to swell, leading potentially to permeability reduction. Permeability reduction and loss of injectivity are the main difficulties encountered in field applications to date and require further studies [2,3]. According to Balan and Gumrah [4], cleat permeability is the most important parameter which determines the CO_2 sequestration potential of coal seams. It represents the contribution of effective stress and matrix shrinkage and swelling. Coal mass has two types of cleats, face cleats and butt cleats, and they are normally orthogonal to each other. Of these two types, face cleats are the governing fractures for gas movement as they are more continuous and extensive, and normally make up the connected fracture network for

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fluid flow. Permeability along the face cleat direction is usually much higher than along the butt cleat direction. It is not uncommon that the permeability can be more than ten times higher [5].

Theoretical and empirical models play a very important role in the prediction of coal permeability as they obviate laboratory experimentation and speed the identification of coal mass properties in deep coal seams. Many research papers can be found related to the effect of stress on coal permeability. One of the earliest studies was by Somerton [6]. According to their study, stress history greatly affects permeability measurements and neither the loading sequence nor the maximum principal stress application directions have much effect on permeability. They presented the relationship among permeability and effective principal stress as follows:

$$k = k_o\left[\exp\left\{-(3\times 10^3\sigma_m k_o^{-0.1})\right\} + \left(2\times 10^{-4}\sigma_m^{1/3}k_o^{1/3}\right)\right] \quad (1)$$

where k is the permeability under stress σ_m (md), k_o is the permeability under zero stress (md) and σ_m is mean stress (psi). Durucan and Edwards [7] investigated the radial stress effect on coal permeability for fractured coal and found a common expression for permeability in any type of coal as follows:

$$k = (1.12 - 0.03\sigma_3)k_i \times \exp\{-(1.12 - 0.03\sigma_3)C_c\sigma_3\} \quad (2)$$

where σ_3 is the radial stress (MPa), k is the permeability (md), C and k_i are constants. Here, C_c is defined as the compressibility factor and depends on the volatile matter content of the coal. Durucan and Edwards [7] defined the k_i as the relative incidence of existing fissures and fractures of coal. In this research they maintained the relationship of $\sigma_1 = 3\sigma_3$ and therefore, the determined permeability values have been also affected by the major principal stress (σ_1). Gray [8] suggested the use of Darcy's law for gas permeability calculation in coal:

$$k = \frac{2qp_{out}L\mu}{A(p_{in}^2 - p_{out}^2)} \quad (3)$$

where k is the permeability (m^2), q is the flow rate (m^3/s), p_{out} is the outlet pressure (Pa), p_{in} is the inlet pressure (Pa), L is the length of core (m), μ is the viscosity of the fluid (Pa s), and A is the cross-sectional area of the core sample (m^2). Seidle [9] proposed a new relationship among the permeability and the effective stress as follows:

$$k_{f2} = k_{f1}\left[\exp\{-3C_f(\sigma_{h1} - \sigma_{h2})\}\right] \quad (4)$$

where k_f is the cleat permeability (md), C_f is cleat volume compressibility (kPa^{-1}), and σ_h is hydrostatic stress (kPa). Then, in 1995, Seidle and Huitt [10] investigated the gas desorption effect on coal matrix shrinkage and presented the following equation:

$$\phi - \phi_o = 1 + \left(1 + \frac{2}{\phi_o}\right)\varepsilon_1\left(\frac{bp_o}{1+bp_o} - \frac{bp}{1+bp}\right) \quad (5)$$

where permeability is assumed to follow the cubic law for fracture flow (in the following equation):

$$\frac{k}{k_o} = \left(\frac{\phi}{\phi_o}\right)^3 \quad (6)$$

where ϕ is the coal bed porosity after sorption or desorption of gases, ϕ_o is the initial coal bed porosity, and ε_1 and b are the Langmuir type matrix shrinkage constants. This model considers only the matrix shrinkage effect and not the effective stress effect. Sawyer et al. [11] proposed a new model for coal permeability as a function of both of these effects (ARI model).

$$\phi - \phi_o = [1 + C_p(p - p_o)] - C_m(1-\phi_o)\frac{\Delta p_i}{\Delta c_i}(c - c_o) \quad (7)$$

where C_p is the pore volume compressibility and C_m is the matrix shrinkage compressibility. According to McKee et al. [12], $C_m = \phi C_p$. $\Delta p_i/\Delta c_i$ is the pressure change for Δc_i concentration variation and c_o is the initial gas concentration. In this equation, the first term describes the pressure effect and the second term describes the matrix shrinkage effect. The permeability can be found using Eq. (6). In 1998, Palmer and Mansoori [13] proposed a theoretical formula for coal permeability as a function of both matrix shrinkage and effective stress:

$$\frac{\phi}{\phi_o} = 1 + \frac{C_m}{\phi_o}(p - p_o) + \frac{\varepsilon_1}{\phi_o}\left(\frac{K}{M} - 1\right)\left(\frac{bp}{1+bp} - \frac{bp_o}{1+bp_o}\right) \quad (8)$$

where

$$C_m = \frac{1}{M} - \left[\frac{K}{M} + f - 1\right]\beta \quad (9)$$

where $d\phi$ is change in porosity, dp is change in pore pressure (md), ε_1 is the Langmuir volume, b is the Langmuir constant, f is a fraction (0–1), β_g is the grain compressibility, and K and M are the bulk and the constrained axial modulus, respectively. They are given as follows:

$$M = \frac{E(1-\vartheta)}{(1+\vartheta)(1-2\vartheta)} \quad (10)$$

$$K = \frac{E}{3(1-2\vartheta)} \quad (11)$$

where ϕ_o, p_o and C_m are the initial porosity and pressure (MPa) and matrix shrinkage compressibility (MPa^{-1}), respectively. If the pore volume compressibility factor C_m is constant,

$$\frac{k}{k_o} = \exp[3C_p(p - p_o)] \quad (12)$$

However, Eq. (12) can be used only under conditions of constant applied pressure (only flow effect), and if there is a pressure gradient, it is necessary to consider the stress effect also. Therefore, the original equation should be used (Eq. (8)). In 2002, Pekot and Reeves [14] proposed Eq. (13) to calculate coal permeability. The equation contains a new term to account for the differential shrinkage effect of coal mass due to CO_2 adsorption because, compared to some other gases such as CH_4, CO_2 causes a greater degree of swelling, resulting in greater reduction in associated permeability.

$$\phi = \phi_o[1 + C_p(p - p_o)] - C_m(1-\phi_o)\frac{\Delta p_i}{\Delta c_i}[(c - c_o) + C_K(c_o - c)] \quad (13)$$

where C_K *is* the differential swelling coefficient. In 2000, Gilman and Beckie [5] developed theoretical models for coal matrix and cleat permeabilities for methane gas movement in a coal mass. Methane gas flow in fractures or cleats was modelled using Darcy's law and in the matrix by assuming that Knudsen diffusion applies (coupled with the ideal gas behaviour). They proposed the following equation for cleat permeability of coal based on two basic assumptions: that coal mass behaves as an elastic medium and lateral strain is zero:

$$k_f = k_{fo}\exp\left(\frac{3\vartheta}{1-\vartheta}\frac{\Delta p}{E_f}\right)\exp\left(-\frac{3\alpha E}{1-\vartheta}\frac{\Delta S}{E_f}\right) \quad (14)$$

where k_f is the cleat permeability and k_{fo} is the initial cleat permeability, ϑ is the matrix Poisson's ratio, p is the pore pressure, E is the matrix Young's modulus, E_f is the effective Young's modulus of the sample with fractures, ΔS is the change of adsorbed gas mass and α is the volumetric swelling coefficient. Wang et al. [15] proposed a modified version of Eq. (14) to describe the variation of CO_2 permeability in coal cleats due to adsorption: