Fuel 215 (2018) 844–852

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

Coal permeability: Gas slippage linked to permeability rebound

Yufu Niu, Peyman Mostaghimi, Igor Shikhov, Zhixi Chen, Ryan T. Armstrong*

School of Petroleum Engineering, The University of New South Wales, NSW 2052, Australia

ARTICLE INFO

Keywords:
Coal permeability
Gas slippage
Permeability rebound
Slip length
Knudsen number

ABSTRACT

The main factors/mechanisms that influence coal permeability are effective stress, swelling, shrinkage, deformation and gas slippage. After an extended period of gas production, coal can have a rebound phenomenon where permeability increases with increasing effective stress. This rebound can have a significant impact on gas recovery during the late stages of a reservoir life cycle. This paper aims to characterise coal permeability by combining laboratory measurements with a simple gas slippage model that explains the rebound phenomenon. Gas and Klinkenberg corrected permeabilities of coal are measured at (1) constant confining pressure and (2) constant effective stress. We estimate the length scales relevant to gas flow using mercury intrusion, a permeability slip model, and the kinetic theory of gases, which allows us to estimate the Knudsen number for gas flow. Results show a linear relationship between slip length and the mean free path of gas for all of the tested mean pore pressures. This result suggests that a first order slip boundary condition is sufficient to explain the momentum exchange at the gas/solid boundary during flow under normal reservoir conditions. A correlation between Knudsen number and increased permeability is developed, which further demonstrates that slippage cannot be neglected in coals when Knudsen number is greater than 0.1. Overall, we present a simple model that explains permeability rebound in coal by considering only gas slippage. We do not discredit the mechanism of coal shrinkage, which could also influence coal permeability. We confirm that gas slippage should be considered in coal permeability models.

1. Introduction

Coal bed methane is a significant unconventional resource for natural gas. During methane production and/or CO_2 storage in coal beds, a primary parameter to evaluate production and/or injection rate is permeability. Unlike sandstone and carbonate reservoirs, coal permeability is highly dependent on reservoir parameters [52,17,50,40,35]. Coal is deformable and thus, increasing effective stress can drastically reduce permeability. In addition, coal is known to shrink as gas is desorbed, which could influence its pore volume and permeability. Lastly, the characteristic length scales associated with the internal structure of coal are often comparable to the mean free path of methane gas and thus, gas slippage is a relevant flow mechanism. However, current coal permeability models often consider only the mechanical effects and often overlook the influence of gas slippage.

Coal is composed of matrix and cleats, which are denoted as face and butt cleats. These cleats are normal to the bedding plane and perpendicular to each other [7,42,26,37]. Coal permeability is influenced by a series of cleat characteristics including size, spacing, connectivity, filled mineral and orientation patterns [26,40,22,22]. Coal permeability has been evaluated widely based on various effective stresses and matrix shrinkage studies [52,14,19,19,41,5,21,34,29,56]. These studies have concluded that coal permeability in higher permeability (100 mD) samples can decrease a full order of magnitude when increasing effective stress whereas lower permeability (1 mD) coal samples can decrease over two orders of magnitude. They have also concluded that coal permeability increases with decreasing pore pressure due to a mechanism commonly referred to as shrinkage. While gas slippage may also play a role it has been suggested that the effect of gas slippage is relatively small compared with the shrinkage effect at intermediate pore pressures around 10–25 MPa [9]. However, how shrinkage actually influences cleat aperture sizes and cleat network topology has yet to be shown experimentally. To verify the contribution of the slippage effect on coal permeability, the length scales associated with gas slippage and those relevant to the coal structural morphology must be considered. In addition, laboratory studies have found that coal permeability with adsorbed gas such as methane is lower than permeability with inert gases such as helium because of the swelling effect that occurs when methane gas is adsorbed to the coal matrix. Overall, the coupling between coal mechanics, swelling, and slippage has yet to be fully explained in coal permeability models.

One of the first coal permeability models was proposed by Gray

* Corresponding author.
E-mail address: Ryan.Armstrong@unsw.edu.au (R.T. Armstrong).

https://doi.org/10.1016/j.fuel.2017.11.082
Received 7 September 2017; Received in revised form 21 November 2017; Accepted 22 November 2017
0016-2361/

[17], which considered various effective stresses and matrix shrinkage with desorption. The relationship between shrinkage strain and sorption pressure was built by considering an elastic relation between stress and strain. Sawyer et al. [47] demonstrated a 3D coal bed model, which was built by considering the correlation between matrix compressibility and adsorbed gas amount. They illustrated that the shrinkage effect of coal can offset the effective stress from cleat shrinkage related to pore volume compaction. However, a systematic coal permeability model was not developed until the matchstick geometry model, which was first built by Reiss [44]. Based on the matchstick geometry, Seidle et al. [49] derived a permeability equation with matrix shrinkage, hydrostatic stress and laboratory results using uniaxial stress condition. This model was further developed by Shi and Durucan [51] to address the impact of matrix shrinkage and swelling with the assumption that permeability varies exponentially with horizontal effective stress. Palmer and Mansoori [39] built a popular permeability model to correlate permeability with stress and pore pressure by assuming uniaxial strain and constant vertical stress. In addition, many other researchers developed permeability models for coal by considering stress-induced matrix shrinkage [28,39,43,8,50,45,8,31,30,57]. But only a few developed models consider gas slippage [18,18,16,56].

This paper examines coal permeability based on the coupling of gas slippage and matrix deformation. We exclude the effect of matrix shrinkage by using helium gas, which does not undergo sorption to coal. Two conditions are considered in this paper: (1) constant confining pressure and (2) constant effective stress. We conclusively show that permeability rebound can occur in the absence of coal shrinkage. The results demonstrate that coal permeability models should account for both gas slippage and shrinkage. A simple permeability model using the Maxwell slippage boundary condition [33] is developed to explain permeability rebound observed with helium gas. We provide a detailed analysis of the length scales involved, boundary conditions required to model the physics, and provide conceptual insights into coal permeability rebound. Our model and experimental data demonstrate that permeability rebound due to gas slippage is most prevalent in coals with permeabilities less than 1 mD and at pore pressures approaching the expiration of a coal seam.

2. Materials and methods

The experimental setup is displayed in Fig. 1. The coal samples are 6 cm in diameter and of various lengths from 3.70 cm to 9.65 cm, which are placed in a triaxial core holder and hydrostatic confining pressure is applied. Two high-precision transducers of maximum 1000 psig and 100 psig with precision of 0.08% are used to measure the inlet and outlet pressure. Flow rate is measured three to five times by a Ruska gasometer and measured values are averaged to calculate permeability. A backpressure regulator is installed at the outlet to keep the pressure drop over the sample limited to 40 psig for all experiments. Controlling the pressure drop is critical for gas experiments with coal since coal is highly deformable and gases can exhibit large pressure drops. A large pressure drop would make it difficult to interpret the results since effective stress would change along the cores length and thus, average values for the experiment would not be representative.

The volumetric flow rate for gas varies along the core due to compressibility. Following Darcy's law and applying the ideal gas law, the gas permeability is measured as

$$K_{g=}\frac{2QP_a\mu L}{0.001127A\,(P_1^2-P_2^2)} \tag{1}$$

where P_a is atmosphere pressure, Q is flow rate measured at P_a, μ is viscosity, L is sample length, A is area, P_1 is inlet pressure and P_2 is outlet pressure [48]. To determine the samples Klinkenberg corrected permeability, we follow the work of Klinkenberg [25] where it was proposed that gas permeability (K_g) is a linear function of the reciprocal mean pore pressure ($\overline{\mathrm{p}}$), defined as

$$\frac{\mathrm{K_g}}{\mathrm{K}} = 1 + \frac{\mathrm{b}}{\overline{p}} \tag{2}$$

$$\overline{p} = \frac{P_1 + P_2}{2} \tag{3}$$

where K is absolute (Klinkenberg corrected) permeability and b is the Klinkenberg coefficient. Here, $\overline{\mathrm{p}}$ is related to the characteristic length scale as

$$\frac{b}{\overline{p}} = 4c\frac{\lambda}{r} \tag{4}$$

where λ is the mean free path for gas, r is the characteristic system size and c is a proportionality factor. The parameters b and c must be determined empirically for a given gas and rock combination. The mean free path of a gas can be determined from the kinetic theory of gases, defined as

$$\lambda = \frac{k_B T}{\sqrt{2}\pi \mathrm{d}^2 p} \tag{5}$$

where k_B is the Boltzmann constant, T is absolute temperature, d is cross-sectional diameter of the gas molecule and p is pressure [4].

From Eq. (2), when gas permeability is plotted verse $1/\overline{p}$, the apparent gas permeability extrapolated to infinite pressure provides a constant permeability without the effects of slippage. This concept is utilised to determine the Klinkenberg corrected permeability of our samples by plotting gas permeability versus $1/\overline{p}$ for constant effective stress with variable mean pore pressure. The resulting extrapolated permeability value is the Klinkenberg corrected permeability of the coal samples at a given effective stress.

Three coal samples are considered, which we refer to as low (0.05–0.25 mD), intermediate (1.5–2.2 mD) and high permeability (6–8.5 mD). One sandstone sample is also used as a control, which is relatively non-deformable and has permeability in range of 0.5–1.5 mD that is in the same order of magnitude as the coal samples. The coal samples are from Gloucester Basin, New South Wales, Australia and the tight sandstone sample is from Camden South, New South Wales, Australia. Images of the inlet and outlet faces of all samples are displayed in Fig. 2. Coal is a brittle material and it is nearly impossible to get a core sample without some degree of damage. There are damaged regions along the perimeter of the samples, where we apply blue tack to fill the gaps between the rubber sleave and sample. This is required to prevent gas flow along the cores perimeter, i.e. between the sleeve and core.

Two experimental conditions are used: (1) constant confining pressure and (2) constant effective stress. Condition (1) is applied to mimic the production process. The inlet pressure decreases from 140 psig to 10 psig (Effective stress increases from 80 psig to 195 psig) and the outlet pressure, which is controlled by a backpressure regulator decreases from 100 psig to 0 psig. Following the work of Terzaghi [53], the effective stress is defined as:

$$\sigma_e = \sigma_a - \alpha\overline{p} \tag{6}$$

where σ_e is effective stress, σ_a is confining pressure, α is Biot number and $\overline{p}$ is mean pore pressure [53]. While $\alpha = 1$ is not necessarily the case for coal, the assumption is valid since we only compare trends between similar samples and thus we only need constant/similar values of α for the comparison. For Condition (2), we maintain constant effective stress by increasing/decreasing both pore pressure and confining pressure at the same time. The range of pressures used for Condition (2) is the same as that used for Condition (1). This allows us to remove the influence of matrix deformation and thus, study gas slippage independently. According to the changing mean pore pressure at constant effective stress; we are able to apply the Klinkenberg correction to determine the theoretical Klinkenberg corrected permeability for each effective stress.