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Numerical assessment of the effect of equilibration time on coal permeability evolution characteristics

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HIGHLIGHTS

- A novel permeability model derived based on the dual poroelastic theory is proposed.
- Permeability evolution in a coal sample variation with time is investigated.
- Effect of equilibration time on coal permeability evolution is evaluated.

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ABSTRACT

Although equilibration time has great significance in experiments of sorption-induced strain and coal permeability, most permeability models in which only one gas pressure has been taken into account cannot be used to calculate the permeability evolution during the adsorption phase, even though they have been successful in reservoir simulations. Here, a new mathematical model for coupled gas migration and coal deformation is developed to investigate the dynamics of CH_4 adsorption in a coal sample when conducting a coal permeability experiment, and a novel permeability model based on the dual poroelastic theory is formulized to investigate the relationships between equilibration time and coal permeability evolution characteristics during the adsorption phase. A finite element model is applied to investigate the evolution characteristics of two gas pressures and permeability in a coal sample under laboratory conditions. Results illustrate that there is a large difference between the two gas pressures during the adsorption phase; before adsorption equilibrium is achieved, permeability, which is greater than that obtained when adsorption equilibrium is achieved, first increases and then decreases with increasing equilibration time.

1. Introduction

Coalbed methane (CBM) is an abundant, low-cost fuel that has significant long-term potential for discovery and development [1]. Worldwide CBM reserves have been estimated at 84–262 trillion m^3, and the majority are located in Russia (17–113 trillion m^3), Canada (6–76 trillion m^3), China (30–35 trillion m^3), Australia (8–14 trillion m^3), and THE USA (11 trillion m^3) [2,3]. Productivity evaluation and prediction are important steps in the development of CBM reservoirs. There are many factors affecting CBM production, among which the permeability of coal is recognized as the most important parameter [4].

The permeability of coal is more complicated than that of conventional gas reservoirs. Coal permeability is highly sensitive to effective stress and sorption-based volume changes [5,6], and the evolution of coal permeability is controlled by the competing influences of effective stress and sorption-based volume changes [7]. Thus, accurate sorption-induced strain data are needed for building a coal permeability model. Obtaining accurate experimental sorption-induced strain data is closely related to equilibration time, and many researchers have studied this issue. Battistutta et al. [8] conducted a series of swelling and sorption experiments using four different gases and found that the equilibration time depends on gas, temperature of the system and sizes of coal sample used in the experiments, and the time to achieve equilibrium for the four gases is increasing in the following order: He, N_2, CH_4 and CO_2.

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Harpalani and Schraufnagel [9] noted that desorption was an extremely slow process and it took a long time for the reading on the strain indicator to stabilize. Seidle and Huitt [10] measured the sorption-induced strain of coal samples and found that it took nearly three months for the coal matrix strain to stabilize during the adsorption phase at each pressure step. Zutshi and Harpalani [11] also found that equilibration times of over 75 days were needed during the gas adsorption phase. As shown in Fig. 1a and b, van Bergen et al. [12] measured the sorption-induced linear strain of coal samples which were exposed to CO_2 and CH_4; the gas pressures were constant during the measurements, but the linear strain did not stabilize after 35 h for CH_4 and 25 h for CO_2. Robertson [13] measured and modeled sorption-induced strain and permeability changes in coal and used extended Langmuir theory to model strain to avoid the long time needed for experiments. As shown in Fig. 1c and d, S_t, the equilibrated strain (extrapolated to infinite time), was obtained by fitting experimental data measured within the first 24 h of equilibration. As shown in Fig. 1e and f, Pan et al. [5] and Majewska et al. [14] also measured the sorption-induced strain of coal samples exposed to CO_2 or CH_4 and measured the relationship between the sorption-induced strain and equilibration time. From the above-mentioned experimental studies, it can be seen that sorption-induced strain requires a long time to stabilize.

Therefore, equilibration time must also have significance in coal permeability experiments. Siriwardane et al. [15] found that the permeability of coal samples decreased significantly with equilibration time when CO_2 was used as the fluid medium, and the equilibration time can range from 1.5 days to a week or typically approximately two days under laboratory conditions. However, the importance of equilibration time has not drawn considerable attention in coal permeability experiments, mainly because there is no suitable mathematical model to obtain equilibration time, which is usually estimated based on experience. Qu et al. [16] introduced a concept of matrix swelling transition from local to global under stress conditions, and pointed out that the local equilibrium condition has not been achieved under common laboratory conditions. Coal samples are typically dual-porosity systems that consist of coal matrix surrounded by intersecting fractures. In such a system, two pressures are present at every point: one in the fractures, p_f, and the other in the coal matrix, p_m. In a coal permeability experiment, sorption-induced strain will stabilize during the adsorption phase only when the two pressures are both equal to the target pressure. The difference between p_f and p_m results in the long time for the stabilization of the sorption-induced strain. However, only one gas pressure has been used in most coal permeability models. These models cannot be used to calculate the permeability evolution during the adsorption phase, even though they have been successful in reservoir simulations.

The primary objectives of this study are to formulize a fully-coupled gas migration and solid deformation model and to use the model to investigate the relationships between equilibration time and coal permeability evolution characteristics during the adsorption phase of coal permeability experiments. The principal goal of the study is to formulize a coal permeability model based on the dual-poroelastic theory which can be used to calculate the permeability evolution during the adsorption phase.

2. Physical model and governing equations

2.1. Physical model

The common conceptual model applied to coal is that it is a dual-porosity reservoir that consist of coal matrix surrounded by intersecting fractures [17]. This leads to two distinct gas pressures at one point: one in the fractures, p_f, MPa; and the other in coal matrix, p_m, MPa [18]. The gas pressure p_m is defined as the "virtual" pressure that would be in equilibrium with the current concentration of adsorbate in the matrix blocks [19]. The permeability of a coal specimen is a function of its fracture system, and the coal specimen can be treated as a dual-porosity, single-permeability scheme [20,21].

The uniaxial deformation of depleting reservoir was first proposed by Geertsma [22] who hypothesized that, with continued production, an oil reservoir having a high lateral dimension compared to vertical dimension deforms mainly in vertical direction. Many permeability models are developed based on the assumptions that the coal seam is under uniaxial strain condition which is similar to the in-situ condition. Mitra et al. [23] is the first reported experimental study where flow measurement were made while coal was held under uniaxial strain condition. The coal sample setup under uniaxial strain condition for a typical coal permeability experiment is illustrated in Fig. 2. Methane is charged from both the top and the bottom of the coal sample during the adsorption phase. Two phases of methane gas migration in a coal sample are involved in the study: the first phase is the Darcy flow of free methane gas through the fractures in the coal sample, and the second phase involves the Fickian diffusion of free gas from the fractures into the adsorbed phase within the coal matrix blocks [24]. During the adsorption phase, two distinct phenomena are associated with two gradually increasing gas pressure [4,25]. The first phenomenon is a decrease in the effective horizontal stress under uniaxial strain conditions; the second is methane adsorption into the coal matrix, resulting in coal matrix swelling and thus a rise in the horizontal stress.

2.2. Governing equations

2.2.1. Coal deformation

The presence of methane in coal modifies the mechanical response of coal. As two distinct gas pressures are present in a coal specimen which is a dual-porosity media, the effective stress law for dual-porosity media rather than that for single-porosity media is more suitable for obtaining the effective stress [26]:

$$\sigma_{ij}^{e} = \sigma_{ij} - (\beta_f p_f + \beta_m p_m)\delta_{ij} \tag{1}$$

where σ_{ij}^{e} is the effective stress. σ_{ij} is the total stress (positive in compression). δ_{ij} is the Kronecker delta tensor. β_f and β_m are effective stress coefficients for the fractures and the matrix, respectively, and can be expressed as [26]

$$\beta_f = 1 - \frac{K}{K_m} \tag{2}$$

$$\beta_m = \frac{K}{K_m} - \frac{K}{K_s} \tag{3}$$

where K is the bulk modulus of the coal, MPa, where $K = E/3(1-2\upsilon)$. K_m is the bulk modulus of the coal grains, MPa, where $K_m = E_m/3(1-2\upsilon)$. K_s is the bulk modulus of the coal skeleton, MPa. K_s usually cannot be directly measured, however, it can be calculated using the equation [27] $K_s = K_m\{1 - 3\phi_m(1-\upsilon)/[2(1-2\upsilon)]\}$. E is the Young's modulus of the coal, MPa. E_m is the Young's modulus of the coal grains, MPa. υ is the Possion's ratio of the coal.

The strain–displacement relationship is defined as:

$$\varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}) \tag{4}$$

where ε_{ij} denotes the component of the total strain tensor. u_i denotes the displacement component in the i-direction. The equilibrium equation is defined as