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Numerical investigation on the coupled gas-solid behavior of coal using an improved anisotropic permeability model

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ABSTRACT

Coalbed methane (CBM) extraction uses coal seam depressurization to extract methane adsorbed into the coal matrix. The process involves complex interactions between solid and gas, and between mechanical and chemical effects. Permeability of coal is one of the most important parameters to evaluate the production of CBM reservoirs. Several models have been proposed to establish the relationship between permeability and poromechanical response, gas desorption, and coal shrinkage. However, there have been only a few attempts in describing the anisotropic permeability of coal, which is an important characteristic of gas flow in coal. This paper focuses on the anisotropic properties of coals and its effects on the coupled gas-solid behavior. We develop an improved anisotropic permeability based on linear elastic poromechanical theory and then implement this model into a finite element package to study the effects of the anisotropic permeability on the gas transport in coal. Cases with three boundary conditions including uniaxial strain, constant volume, and constant confining stress are analyzed in details. Numerical simulation results show that the proposed model can well represent the anisotropic permeability of coal. Permeability is closely related to the mechanical properties of coal. We find that modulus reduction ratio is a key parameter to control the anisotropic characteristics. Different modulus reduction ratios alter directional permeability significantly. Anisotropic permeability changes with time and pressure during gas desorption and gas flow. Further, the magnitude of directional permeability variations depends on both the modulus and the boundary conditions. Permeability evolution is controlled by the change in effective stress and matrix shrinkage due to desorption. The effects of anisotropic permeability on the coupled gas-solid behavior of coal during gas desorption and flow processes are demonstrated in this work.

1. Introduction

As a clean-burning and eco-friendly energy resource, coalbed methane has been exploited from subsurface coal formations for a few decades. The commercialization of CBM has made great success in North America, Australia, China, and other countries. Significant advancement in enhancing exploitation techniques has been achieved and new technologies make it possible to provide a reliable and important source of natural gas for many countries. CBM extraction induced complex interactions between stress and sorptive gases exert strong influences on the transport and sorptive properties of coal (Liu et al., 2011a,b) and it is a complicated coupled gas-solid process in which gas sorption and flow, coal deformation and permeability interacts with each other. In order to evaluate this process, a better understanding in mechanical behavior and transport properties of coal, and in the coupled interactions between these two aspects is required. Among many, permeability is one of the most important parameters to describe transport properties.

Numerous experimental and numerical investigations have been performed on the permeability of coal (Chen et al., 2013; Connell et al., 2010, 2016; Espinoza et al., 2014; Harpalani and

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Schraufnagel, 1990, 1997; Izadi et al., 2011; Liu and Elsworth, 1997, 2010; Liu et al., 2014; Palmer, 2009; Palmer and Mansoori, 1996; Pan and Connell, 2012; Seidle and Huitt, 1995; Seidle et al., 1992; Shi and Durucan, 2005; Wang et al., 2011; Zhang et al., 2012a,b, 2014; Zhu et al., 2007). The absolute permeability of coal reservoirs changes significantly during gas production, often initially decreasing but then increasing as the reservoir pressure and gas content is drawn down (Pan and Connell, 2012). In order to simplify the numerical study, most permeability models proposed so far are isotropic (Connell et al., 2010; Liu and Rutqvist, 2010; Palmer, 2009; Pan and Connell, 2012; Seidle et al., 1992; Shi and Durucan, 2005; Wang et al., 2012; Zhang et al., 2015a,b; 2016). Most of these models consider the coal as an isotropic fractured medium and establish the relationship between permeability and porosity following the cubic law (Cui and Bustin, 2005; Palmer and Mansoori, 1996). In fact, coal is a sedimentary rock with cleats and thus is anisotropic in nature. Koenig and Stubbs (1986) found that the permeability in the parallel direction of bedding plane was 17 times higher than that obtained in the perpendicular direction to the bedding plane. Gash et al. (1992) hypothesized that the bedding and cleat structure were changed differently during mechanical loading history and resulted in the anisotropic permeability. Under constant confined stress condition, permeabilities of coal in the directions of bedding planes, face cleat planes, and butt cleat plane are very different. Day et al. (2008) found similar results during permeability tests using three different sorptive gases (CO_2, N_2, CH_4). To date, there have been only a few anisotropic permeability models published in the literature (An et al., 2015; Chen et al., 2012; Liu et al., 2016; Pan and Connell, 2011; Wang et al., 2014) and the effect of anisotropic permeability on the coupled gas-solid behavior of coal and gas production remains unclear. Following the linear isotropic elastic theory, Liu et al. (2010) used the concept of modulus reduction ratio and studied the anisotropic permeability of coal under uniaxial strain condition and constant volume condition. Their model focuses on the effect of the different boundary conditions on the anisotropic permeability and coal is considered as an isotropic medium. Pan and Connell (2011) proposed an anisotropic swelling model to describe the gas adsorption-induced anisotropic coal swelling from a consideration of anisotropic mechanical properties of coals. Wang et al. (2014) proposed an analytical anisotropic permeability model combining the effective stress change and gas sorption-induced directional strains. An et al. (2015) and Liu et al. (2016) presented the effect of anisotropic permeability on the production of CBM reservoirs. There have been limited studies aiming to study the anisotropic parameters and their effects on the anisotropic permeability and gas-solid behavior of coal. In this work, we propose an improved anisotropic permeability model in which coal is assumed as a transversely isotropic medium and the coupled effect of effective stress and sorption is taken into account as well and then we explore the gas transport behavior during CBM extraction using this developed model and investigate the parameters influencing the anisotropic permeability and the coupled gas-solid behavior of coals. We will derive the anisotropic permeability model in the next section and focus on the coupled gas-solid behavior in the third section. Three cases including uniaxial strain condition, constant volume condition and constant confining stress condition will be analyzed using the COMSOL PDE solver. The simulation conditions and the numerical results are presented in the fourth and fifth section, respectively.

2. Anisotropic permeability model

2.1. Structural model of coal

Coal is usually considered as a dual porosity dual permeability dual stiffness medium composed of cleat system and matrix system (Wang et al., 2012). As such, coal has two types of permeability (matrix permeability k_m and cleat permeability k_f) and two types of porosity (matrix porosity and cleat porosity). Cleat system is considered as the main channel of gas migration and matrix porosity system is considered as the main space for gas storage. Robertson (2005) noted that the value of cleat permeability was about eight orders of magnitude larger than that of the matrix permeability. Therefore, matrix permeability is sometimes neglected for production engineering analysis. In this paper, we focus on the effects of cleat aperture on the anisotropic permeability and ignore the influence of matrix permeability on the gas flow. A schematic of coal structure in this model is simplified as shown in Fig. 1, in which b_1, b_2, b_3 represent cleat aperture in the x, y, z directions, s is the cleat spacing.

2.2. Anisotropic permeability model of coal

For fractured material, the cubic law is often used to describe the relationship between permeability and porosity as written in Equation (1). As presented above, permeability evolution is mainly controlled by the change in cleat aperture. Porosity change is also directly related to the cleat aperture change which in turns depends on the stress level and the swelling or shrinkage of the matrix. Seidle and Huitt (1995) considered coal as an isotropic material and established a coal permeability model based on the Matchstick geometric model. Palmer and Mansoori (1996) proposed a permeability model considering effective stress and adsorption effects under uniaxial strain condition and constant vertical stress condition. Palmer's model has been widely utilized and is described as

$$\frac{k}{k_0} = \left(\frac{\varphi}{\varphi_0}\right)^3 \tag{1}$$

$$\frac{\varphi}{\varphi_0} = 1 + \frac{C_m}{\varphi_0}(p - p_0) + \frac{\varepsilon_l}{\varphi_0}\left(\frac{K}{M} - 1\right)\left(\frac{p}{p_L + p} - \frac{p_0}{p_L + p_0}\right) \tag{2}$$

$$C_m = \frac{1}{M} - \gamma\left(\frac{K}{M} + f - 1\right) \tag{3}$$

where k and φ are permeability and porosity of coal, respectively; k_0 and φ_0 are the initial permeability and porosity at the reference state; p is the gas pressure in the cheat andp_0 is the initial gas pressure at $t = 0$; ε_l andp_L are the Langmuir strain and Langmuir

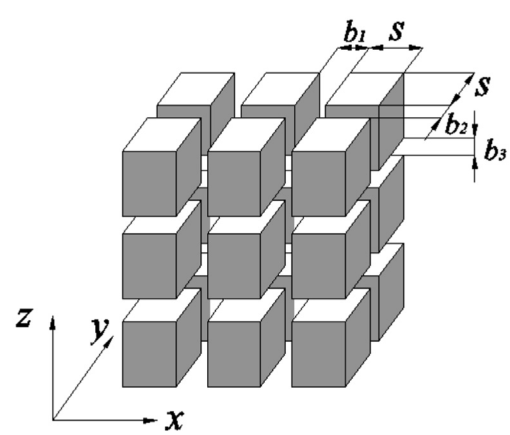

Fig. 1. Schematic of the structural of coal.