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Anisotropic permeability evolution of coal with effective stress variation and gas sorption: Model development and analysis

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ABSTRACT

Anisotropy is an important intrinsic attribute of the coal permeability, a crucial property for coal–gas activities such as coalbed methane recovery and enhanced coalbed methane production using carbon dioxide injection. In this paper, we propose an analytical model in order to represent the anisotropic permeability evolution of coal due to effective stress change and gas sorption, and this model captures the anisotropic characteristics in both mechanical properties and gas sorption-induced directional strains. We select a representative elementary volume of improved matchstick geometry where the coal matrix blocks are connected by the matrix bridges rather than completely separated by the cleats. According to this geometry, only part of the matrix swelling contributes to the cleat aperture alteration, and an internal swelling ratio is introduced in order to represent the effects of the matrix swelling on the cleat porosity and the permeability. This model is independent of any specific boundary conditions and can be extended to different representations of the prescribed boundary conditions, *i.e.*, uniaxial strain, constant confining stress, constant effective stress and constant pore pressure conditions. The model is validated by matching it against three sets of laboratory permeability data measured with adsorbing gases under constant confining stress, constant effective stress and constant pore pressure conditions. Under constant confining stress conditions, by assuming the internal swelling ratio to be invariant, the model agrees well with the measured permeability data. As for the constant effective stress conditions, where both the pore pressure and the confining stress varies, the constant internal swelling ratio makes the model deviate from the experimental observations. This indicates that the internal swelling ratio varies under the varying confining stress conditions. Under constant pore pressure conditions, the model values are lower than the laboratory ones due to the increasing confining stress-induced matrix shrinkage. In order to identify the anisotropic features of the directional permeabilities under *in situ* conditions, a simplified and idealized modeling under uniaxial strain conditions is conducted by introducing an anisotropic permeability ratio to represent the ratio of one directional permeability to another. The modeling results clearly demonstrate the strong anisotropy in both magnitudes and variation trends of the directional permeabilities.

1. Introduction

As a naturally occurring gas in coal, coalbed methane (CBM) can be a source of coal mine catastrophes such as the coal and gas outburst and the gas explosion (Flores, 1998; Wang and Xue, 2008), but now CBM is treated as a clean-burning and eco-friendly energy resource (Rogers, 1994). Methane (CH_4) is also a strong greenhouse gas which has over twenty times the greenhouse effect of carbon dioxide (CO_2) (Warmuzinski, 2008). In order to reduce the negative impacts of CBM on both coal mines and the environment and utilize CBM efficiently, CBM recovery and the underground drainage have been extensively applied for the recovery of methane gas from coalbeds. In order to enhance the productivity of CBM, CO_2 or its mixture with other gases (such as nitrogen) is normally injected into coalbeds to accelerate CH_4 desorption and thus increase CBM production with the superior adsorption capacity of CO_2 on coal (Koperna et al., 2009; Mavor et al., 2002; Ross et al., 2009; Wong et al., 2007). This injection activity also has the added benefit of the concomitant long-term storage of CO_2 (Chen et al., 2012) and thus reduces the CO_2-induced greenhouse effect.

Both CBM recovery and CO_2 injection into coal will initiate a series of coal–gas interactions (Chen et al., 2012). With CBM recovery, the pore pressure drawdown induces gas desorption which causes matrix shrinkage, while CO_2 injection produces an increase in pore pressure and thus gas adsorption, which causes matrix swelling. In this paper this adsorption or desorption will be referred to as 'sorption', and the corresponding swelling or shrinkage as 'sorption strain' (Connell et al., 2010). Both pore pressure variation and sorption strain exert significant impacts on permeability, an extremely critical property which influences gas flow in coal and thus determines the efficiency of CBM production or CO_2 injection.

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A large number of permeability models have been developed for representing coal permeability evolution. Among these models, some, such as the Seidle and Huitt model (Seidle and Huitt, 1995), the Palmer and Mansoori model (Palmer and Mansoori, 1998), the Pekot and Reeves model (Pekot and Reeves, 2003) and the updated Palmer and Mansoori model (Palmer et al., 2007), are porosity-dependent. While some, instead, such as the Gray model (Gray, 1987), and the Shi and Durucan model (Shi and Durucan, 2004) are stress-dependent. The Cui and Bustin model (Cui and Bustin, 2005), instead, can be either porosity-dependent or stress-dependent depending on different stress–pore–strain relationships.

In order to replicate *in situ* conditions and represent field boundaries, many permeability models (Cui and Bustin, 2005; Gray, 1987; Palmer and Mansoori, 1998; Palmer et al., 2007; Pekot and Reeves, 2002; Shi and Durucan, 2004) apply uniaxial strain conditions where only one component of the principal strain (normally vertical) is not zero and the other boundaries are strictly constrained (Liu et al., 2011a). However, the uniaxial strain-based permeability models generally cannot adequately explain the resulting laboratory measurements, where, under hydraulic conditions, the coal sample can expand in all directions (Pini et al., 2009; Robertson and Christiansen, 2005). In order to interpret the permeability data obtained in laboratory, Robertson and Christiansen (2005), Liu and Rutqvist (2010) and Chen et al. (2012) have developed permeability models, all with the assumption that only part of sorption strain contributes to cleat aperture (porosity) alteration under the constant confining stress conditions, which are normally used for laboratory permeability measurements (Pini et al., 2009; Robertson and Christiansen, 2005).

More importantly, the permeability models presented above all overlooked the anisotropic features of permeability by treating the porosity and sorption strain as isotropic. However, the existence of permeability anisotropy has been confirmed by both field observations (Koenig and Stubbs, 1986) and laboratory measurements (Gash et al., 1992; Massarotto et al., 2003). To date, only a few permeability models have been developed to accommodate this. Laboratory measurements (Anggara et al., 2014; Day et al., 2008; Levine, 1996; Pan and Connell, 2011) have confirmed that the swelling strains in the two directions parallel to the bedding planes were almost identical, while the anisotropic swelling was mainly perpendicular and parallel to the bedding. Based on this concept, Pan and Connell (2011) developed a stress-dependent anisotropic permeability model which included both anisotropic mechanical properties and directional sorption strains. Both Wang et al. (2009) and Gu and Chalaturnyk (2010) developed anisotropic permeability models by treating both directional stress and mechanical properties as anisotropic. Gu and Chalaturnyk (2010) implemented their model into a numerical simulator for coupled simulation in pressure depleting CBM reservoirs, and the two horizontal permeabilities at different production stages were simulated and investigated. Liu et al. (2010) derived a cleat aperture-dependent anisotropic permeability model where the directional permeability was linked to the directional strain through an elastic modulus reduction ratio. Recently, Wang et al. (2013) extended Liu's model (Liu et al., 2010) by introducing the anisotropic sorption strain, and this model was implemented into a fully coupled model for simulating a production well. Based on this simulation, the permeability anisotropy induced by directional compaction and swelling was investigated.

In this paper, an anisotropic permeability model independent of any specific boundary conditions is formulated based on an improved matchstick geometry where the coal matrix blocks are connected by the matrix bridges rather than thoroughly partitioned by the cleats. This model can be modified by applying different boundary conditions. Then the model validity is evaluated by matching model results with the three series of experimental data observed under constant confining stress, constant effective stress and constant pore pressure conditions. Subsequently, the anisotropic characteristics of the directional permeabilities with respect to pore pressure depletion under uniaxial strain conditions are evaluated with a simplified modeling exercise.

2. Coal structure

Coal is a collection of matrix blocks and fractures, where the fractures can be classified into three orthogonal classes: face cleats, butt cleats and bedding plies, in terms of their direction and connectedness, as depicted in Fig. 1. Face cleats are composed of well-developed, extensive, roughly planar fractures which run parallel to each other, and butt cleats are also roughly planar but are neither as well-developed nor as continuous as face cleats (Seidle et al., 1992). Though the bedding plies may be compressed by the lithological pressure, in this paper, they are treated as the flow path in the same fashion as the cleats and have some effect on permeability (Wang et al., 2009).

The classic conceptual matchstick geometry, which has been widely used for describing the coal structure (Gu and Chalaturnyk, 2010; Harpalani and Chen, 1995; Ma et al., 2011; Seidle and Huitt, 1995; Seidle et al., 1992), typically assumes that the matrix blocks are completely separated and isolated by the cleats. According to these models, the matrix swelling caused by gas sorption will not affect permeability under constant confining stress conditions (Liu et al., 2011b), but this is inconsistent with laboratory measurements where the permeability decreased as the pore pressure increased during the injection of adsorbing gases even with constant confining stress (Chen et al., 2012). In order to interpret this unexpected result, an improved matchstick geometry where the matrix blocks are connected by the matrix bridges rather than completely separated by the cleats, as illustrated in Fig. 2, is adopted for representing the coal structure in this paper (Liu and Rutqvist, 2010).

3. The internal matrix swelling

In a coal block with two matrix blocks and one connecting coal bridge under confined (stress or strain) conditions, as depicted in Fig. 3a, when injecting an adsorbing gas into the coal, the coal bridge and the local matrix block around the cleat begin to swell. Because of the larger area of the matrix block, its swelling force is greater than that of the matrix bridge and as a result the coal bridge and the cleat are compressed by the internal swelling of the matrix block, assuming identical elastic properties of the bridge and the matrix block, as shown in Fig. 3b. As the gas diffuses into the matrix block, it swells continuously and the external boundaries expand outward, as illustrated in Fig. 3c. Therefore, the incremental length of the coal block only caused by gas sorption is expressed as

$$\begin{aligned}\Delta l &= l - l_0 = a + 2b - (a_0 + 2b_0) = a_0 - 2b_0\Delta\varepsilon_{sl} \\ &+ 2b_0(1 + \Delta\varepsilon^m_{scon}) - (a_0 + 2b_0) = 2b_0(\Delta\varepsilon^m_{scon} - \Delta\varepsilon_{sl})\end{aligned} \quad (1)$$

where Δl denotes the incremental coal block length resulting from gas sorption only, l denotes the length of the coal block after gas sorption,

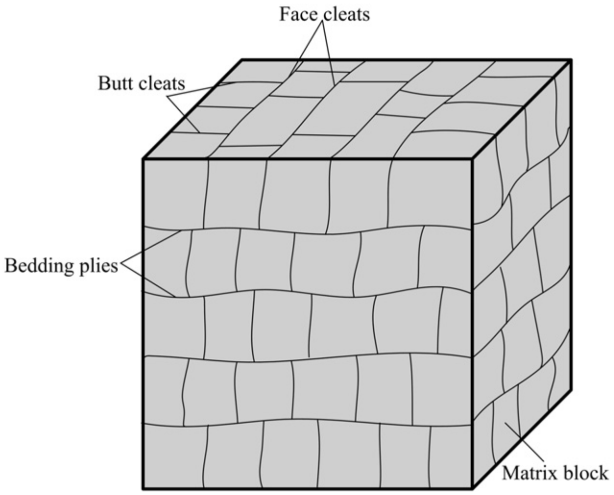

Fig. 1. Physical representation of coal structure.