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Roles of coal heterogeneity on evolution of coal permeability under unconstrained boundary conditions

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ABSTRACT

Coal permeability models based on constrained conditions such as constant volume theory can successfully match unconstrained experimental data and field observations. However, these models have a boundary mismatch because the boundary of permeability models is constrained while experiment boundary is free displacement or unconstrained. What the mechanism is to require such a boundary mismatch has not been well understood. In this study, a full coupled approach was developed to explicitly simulate the interactions of coal matrixes and fractures. In this model, a matrix-fracture model is numerically investigated after incorporating heterogeneous distributions of Young's modulus, Langmuir strain constant in the vicinity of the fracture. The impact of these local heterogeneities of coal mechanical and swelling properties on the permeability evolution is explored. The transient permeability evolution during gas swelling process is investigated and the difference between the final equilibrium permeability and transient permeability is compared. With the heterogeneity assumption, a net reduction of coal permeability is achieved from the initial no-swelling state to the final equilibrium state. This net reduction of coal permeability increases with the fracture (injection) pressure and is in good agreement with laboratorial data under the unconstrained swelling conditions. Coal local heterogeneity in vicinity of fracture can therefore be the mechanism of the above mismatch.

1. Introduction

The permeability of coal is a key attribute in determining coalbed methane production and CO_2 storage in coal seam reservoirs. Coal permeability is often determined by regular sets of fractures called cleats, with the aperture of the cleats being a key property in the magnitude of the permeability (Connell et al., 2010). The relative roles of stress level, gas pressure and composition, fracture geometry of coal and water content are intimately connected to the processes of gas sorption, transport and coal swelling/shrinkage (Liu et al., 2011a).

Significant experimental efforts have been made to investigate coal permeability and its evolution. Laboratory measured permeabilities of coal to adsorbing gasses, such as CH_4 and CO_2, are known to be lower than permeabilities to non-absorbing or lightly adsorbing gasses such as argon and nitrogen (Durucan and Edwards, 1986; Siriwardane et al., 2009; Somerton et al., 1975). Under constant total stress, permeability to adsorbing gas decreases with increasing pore pressure due to coal swelling (Chen et al., 2011; Mazumder and Wolf, 2008; Pan et al., 2010a; Robertson, 2005; Wang et al., 2010, 2011), and increases with decreasing pore pressure due to matrix shrinkage (Cui and Bustin, 2005; Harpalani and Schraufnagel, 1990; Harpalani and Chen, 1997; Seidle and Huitt, 1995). It is also impacted by the presence of water and the magnitude of water saturation (Han et al., 2010; Pan et al., 2010b). One thing in common for the above studies is that they were conducted under unconstrained boundary conditions.

A number of proposed coal permeability models have been developed to match experimental data (Cui and Bustin, 2005; Izadi et al., 2011; Liu and Rutqvist, 2010; Palmer and Mansoori, 1998; Pekot and Reeves, 2002; Seidle and Huitt, 1995; Shi and Durucan, 2004; Wang et al., 2011; Zhang et al., 2008). Two assumptions are applied to these models – uniaxial strain and constant overburden or confining stress (Connell et al., 2010; Liu et al., 2011a). These models have been mostly successful in matching experimental data that were conducted under stress-controlled (unconstrained)

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boundary conditions. However, permeability models derived under stress-controlled condition assumption are incapable of matching experimental data, particularly for the models developed with the matchstick or cubic coal geometry. This is because matrix swelling does not affect coal permeability due to the complete separation between matrix blocks caused by through-going fracture. In this case, for a given fracture pore pressure, the swelling results in an increase of fracture spacing, rather than a change in fracture aperture (Liu and Rutqvist, 2010). However, this has not been consistent with laboratory observations that show significant coal permeability variation due to matrix swelling under constant confining stress conditions (Chen et al., 2011; Lin et al., 2008; Pan et al., 2010a). This behaviour remains enigmatic as the permeability of the porous coal is determined by the effective stress only.

A few studies were carried out on either improving current permeability models or explaining why permeability models developed under uniaixal strain condition are capable of matching experimental data. Connell et al. (2010) partitioned the sorption strain into bulk, pore and matrix strains in contrast to existing approaches, and derived several different forms of the permeability models for the distinct geometric and mechanical arrangements that can be encountered with laboratory testing. Liu and Rutqvist (2010) believed that in reality coal matrix blocks are not completely separated from each other by fractures but connected by the coal-matrix bridges, and developed a new coal-permeability model for constant confining-stress conditions, which explicitly considers fracture–matrix interaction during coal-deformation processes based on the internal swelling stress concept. An alternative reasoning has been investigated by J. Liu et al. (2010a), considering the internal actions between coal fractures and matrix. Recently, Izadi et al. (2011) proposed a mechanistic representation of coal as a collection of unconnected cracks in an elastic swelling medium, where voids within a linear solid are surrounded by a damage zone. In the damage zone the Langmuir swelling coefficient decreases outwards from the wall and the modulus increases outwards from the wall. In the analysis, fluid pressures are applied uniformly throughout the body, so it is incapable of observing the transient permeability evolution due to coal–gas interactions during gas transport. J. Liu et al. (2011b) addressed the same phenomena from different point of view, stating that coal permeability is controlled by the switching process between local swelling and macro-swelling, and the extent of switching of coal swelling determines coal permeability is higher or lower than initial value.

However, these studies still have three limitations that need to be improved: (1) they were generally carried out on the assumption of homogeneity, where coal properties were assumed to be same throughout the whole domain; (2) permeability value is assumed to be only related to pore pressure and effective stress, so with the same pore pressure the permeability value is same; and (3) permeability is independent of time. These assumptions have been conflict with many experimental observations. For instance, Maggs (1946) investigated the feature of coal swelling, and shown that in the presence of an adsorbed film, coal swells and a weakening of the structure would result on adsorption. This phenomenon was also observed by Hsieh and Duda (1987). The effect of high-pressure CO_2 on the macromolecular structure of coal has been studied by Mirzaeian and Hall (2006), and showed that the glass transition temperature of coal decreases with CO_2 pressure significantly, indicating that high-pressure CO_2 diffuses through the coal matrix causes significant plasticization effects, and changes the macromolecular structure of coal. Similar observation was obtained by many other researchers (Larsen, 2004; Goodman et al., 2005; John, 2004; C.J. Liu et al., 2010; White et al., 2005). The thermodynamics and mechanism for this phenomenon was examined by Mirzaeian and Hall (2008). The plasticization effects of coal adsorption have been verified by the weakening of coal mechanical strength from experimental measurements (Ates and Barron, 1988; Ranjith et al., 2010; Viete and Ranjith, 2006, 2007; Wang et al., 2011). Recently, Siriwardane et al. (2009) found that permeability of adsorbing gas in coal is a function of gas exposure time.

The non-homogeneous feature of coal swelling has also been observed by other approaches (Day et al., 2008; Karacan and Okandan, 2001; Karacan, 2003, 2007) as apparent from quantitative X-ray CT imaging and from optical methods. Gibbins et al. (1999) examined the heterogeneity of coal samples by means of density separation and optical and scanning electron microscopy, and found that a high degree of heterogeneity exists between average compositions for the different density cuts within each sample, between different particles within the same density cuts and within the particles themselves. Similar work was conducted by Gathitu et al. (2009). Manovic et al. (2009) presents the microscopic observations of coals of different ranks and mineral matter contents, showing an increasing of heterogeneity with mineral matter content. Anisotropic swelling induced by chemical heterogeneity of coal was also seen (Douglas, 1984; French et al., 1993; Pone et al., 2010).

As summarized above, the real behaviours of the sorption-induced swelling/shrinkage of coal are far different from the homogeneous assumption that is generally made for theoretical permeability analysis. The effects of coal chemical heterogeneity and swelling are mutual. The heterogeneity of coal brings the non-homogeneous distribution of coal swelling strain, and meanwhile coal swelling causes the heterogeneous distribution coal physical property (e.g. Young's modulus). In this study, it is considered that the heterogeneities of coal physical properties and swelling strain are responsible for the enigmatic behaviour of coal permeability reduction with adsorbing gas injection under unconstrained conditions. To prove this, a fully coupling numerical model is conducted to simulate the dynamic interactions between coal matrix swelling and fracture aperture alteration, and translate these interactions to transient permeability evolution. In this numerical model, swelling coefficient and Young's modulus are assumed to vary spatially, and numerical predictions are then compared with observed magnitudes of permeability change in coal. This work is trying to explain why permeability changes with absorbing gas injection even under stress controlled conditions.

2. Theoretical evaluation of coal permeability models

2.1. General coal permeability model

It is clear that there is a relationship between porosity, permeability and the grain-size distribution in porous media. Chilingar (1964) defined this relationship as

$$k = \frac{d_e^2 \phi^3}{72(1-\phi)^2} \tag{1}$$

where k is the permeability, ϕ is porosity and d_e is the effective diameter of grains. Based on this equation, we obtain

$$\frac{k}{k_0} = \left(\frac{\phi}{\phi_0}\right)^3 \left(\frac{1-\phi_0}{1-\phi}\right)^2 \tag{2}$$

When the porosity is much smaller than 1 (normally less than 10%), the second term of the right-hand side asymptotes to unity. This yields the cubic relationship between permeability and porosity for coal matrix