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Evolution of coal permeability: Contribution of heterogeneous swelling processes

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ABSTRACT

This study hypothesizes that coal swelling is a heterogeneous process depending on the distribution of coal voids such as fractures, and that coal matrixes swell due to CO_2 sorption while fractures are compressed in response. This explains why coal permeability reduces even when the effective stress on coal samples is kept constant. A dual porosity–dual permeability model, which separately accommodates gas flow and transport in the coal matrix (swelling component) and fracture systems (non-swelling component) and rigorously accommodates the role of mechanical deformations for a dual porosity continuum, was developed and applied to prove this hypothesis.

We use observations of a CO_2 flow-through experiment on coal constrained by X-ray CT to define the heterogeneous distribution of fracture porosity within the coal sample as a basis of mapping material properties for modeling. Matches between experimentally-measured and model-predicted ensemble permeabilities are excellent. More importantly, the model results illustrate the crucial role of heterogeneous swelling in generating swelling-induced reductions in permeability even when the fractured sample is mechanically unconstrained. These results prove that coal swelling is a heterogeneous process depending on the distribution of coal voids: matrix (swelling component) swells while fractures (non-swelling component) are compacted in response.

1. Introduction

Geological sequestration of CO_2 has been considered as one of the most promising options. Deep coal seam is one of geological media to potentially sequester huge amounts of CO_2 (Gale and Freund, 2001). The coal serves as a receptor for the injected CO_2 which is sequestered in the naturally fractured medium. The micro-pores and pores in the coal matrix provide the main storage space for gas and the micro-fractures through macro-fractures comprise rapid pathways for gas seepage and delivery to the micro-pores. In addition, sorption-induced strain of the coal matrix can change the porosity, the permeability and the storage capacity of coal seam via feedbacks to in situ stresses via displacement constraints. Correspondingly, the evolution of in situ stress conditions have an important influence on reservoir response and capacity for CO_2 storage, inferring that both flow and mechanical interactions should be incorporated if realistic simulations of behavior are desired. This study addresses this complex and challenging problem.

The dominance of fluid flow in fractures is exhibited in fractured crystalline rocks, such as granite, where matrix blocks contribute negligible fluid mass to the highly conductive fractures. However, gas flow in unconsolidated materials such as coal is essentially interstitial where flow routes may be rather tortuous. The fractured coal seam comprises both permeable fractures and matrix blocks. Gas flow in such a medium may be intermediate between fracture flow and interstitial flow. Dual porosity representations (Barrenblatt et al., 1960; Warren and Root, 1963) include the response of these two principal components only — release from storage in the porous matrix and transport in the fracture network. Conversely, dual permeability or multiple permeability models represent the porosity and permeability of all constituent components (Bai et al., 1993) including the role of sorption (Bai et al., 1997) and of multiple fluids (Douglas et al., 1991). Traditional flow models accommodate the transport response as overlapping continua but neglect mechanical effects. In situations where mechanical effects are important, this behavior must be included in the response. Conceptualizations include analytical models for dual porosity media with averaged elastic components (Aifantis, 1977), their numerical implementation and models including the component constitutive response for dual (Elsworth and Bai, 1992) and multi-porous (Bai et al., 1993) media. Such models have been applied to represent the response of permeability evolution (Liu and Elsworth, 1999; Ouyang and Elsworth, 1993) in deforming aquifers and reservoirs (Bai et al., 1995), to accommodate gas flow (Zhao et al.,

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2004) and to evaluate the response to external forcing by human-induced effects (Liu and Elsworth, 1999) and by earth tides (Pili et al., 2004).

All of these previous models were developed primarily for the flow of slightly compressible liquids without desorption and not applicable to the flow of compressible fluids such as CO_2 where gas adsorption is the dominant mechanism. The potential impacts of differential swelling on the performance and implementation of CO_2 geological sequestration projects have been investigated through experimental, field-scale, and numerical studies. Experiments on powdered high volatile bituminous Pennsylvanian coals have shown that adsorption rate decreases with increasing grain size for all experimental conditions (Busch et al., 2004). Similarly, coal type and rank (Prusty, 2007; Robertson and Christiansen, 2005) influences the preferential sorption behavior and the evolution of permeability with these changes linked to macromolecular structure (Mazumder and Wolf, 2007). The impacts of gas components on the efficiency of enhanced methane recovery have also been investigated, indicating that the presence of the nitrogen originating from flue gas in the injected gas stream is capable of improving the injectivity significantly (Durucan and Shi, 2008). The adsorption kinetics of CO_2 and CH_4 at different pressures and temperatures have been explored (Charrièrea et al., 2010). Similarly, the sorption and swelling capacities of CO_2 under supercritical conditions have been examined on a variety of dry and wet coals with different pressures and temperatures (Day et al., 2008; Siemons and Busch, 2007). Distributed measurements of the sorption of CO_2 have shown temporal influences of diffusion into dual porosity media (Karacan, 2007) and the role of ambient stress in modulating swelling-induced strain (Pone et al., 2008).

Based on experimental observations, a variety of models have been formulated to quantify the evolution of permeability during coal swelling/shrinkage. The first attempts to quantify the role of stresses on the evolution of coal-reservoir permeability assumed invariant vertical stresses and linked changes in horizontal stress with the gas pressure and the sorption strain (Gray, 1987). Permeability was computed as a function of reservoir pressure with coal-matrix shrinkage assumed directly proportional to changes in the equivalent sorption pressure. Since then, a number of theoretical and empirical permeability models have been proposed. The Seidle–Huitt Model describes the evolution of permeability assuming that all changes in permeability are caused by the sorption-induced strain alone, neglecting the elastic strain (Seidle and Huitt, 1995). Another three of the most widely used permeability models are the Palmer and Mansoori model (P&M Model), the Shi and Durucan (S&D) model, and the Advanced Resources International (ARI) model (Palmer and Mansoori, 1998; Pekot and Reeves, 2003; Shi and Durucan, 2005). The P&M model is strain-based, which means that porosity change is modulated by the change in the volume strain, and the change in permeability is calculated from this change in porosity. It is derived from linear elasticity for strain changes in porous rock assuming no change in overburden stress, that changes in porosity are small and also that the permeating fluid is highly compressible. A cubic relationship between permeability and porosity is used to evaluate changes in permeability. The S&D model is based on an idealized bundled-matchstick geometry to represent a coalbed, and uses a stress-based formulation to correlate changes in the effective horizontal stress caused by the volumetric deformation together with the cleat or pore compressibilities. This stress-based model means that changes in porosity and permeability do not come directly from changes in volume strain but via the swelling-induced augmentation of horizontal stresses. Additionally, the Biot coefficient is set to unity — requiring that the change in net stress is equal to the difference between net overburden pressure and the change in pore pressure. The ARI model describes the evolution of coal permeability using a semi-empirical correlation to account for the changes of coal porosity due to pore compressibility and matrix swelling/shrinkage (Pekot and Reeves, 2003). The ARI model is essentially equivalent to the P&M model in saturated coal and where the strain versus stress fits the Langmuir isotherm (Palmer, 2009). More recently, an alternative approach has been proposed to develop an improved permeability model for CO_2-ECBM recovery and CO_2 geo-sequestration in coal seams. This approach integrates textural and mechanical properties to describe the anisotropy of gas permeability in coal reservoirs under conditions of confined stress (Wang et al., 2009). However, although permeability models incorporating sorption-induced effects have been widely studied, those studies are under the assumption of either a constant overburden load, or derived from the compressibility concept of porosity, which may provide incorrect outcomes or overestimates of permeability change (Pekot and Reeves, 2003; Robertson and Christiansen, 2007). These critical and limiting assumptions have been relaxed in new models rigorously incorporating in-situ stress conditions (Zhang et al., 2008). More importantly, coal is highly anisotropic: both in mechanical properties and permeability. The micro-fractures and cleats in coal are quite different in each direction. Directional permeability cannot be described using a scalar porosity variable, especially for the fracture permeability (Wang et al., 2009).

CO_2 injection into coal seams triggers complex coal–gas interactions because of the phenomena of gas adsorption and coal swelling. The relative roles of stress level, gas pressure, and fracture distribution are intimately connected to the processes of gas adsorption, diffusion, transport, and coal swelling. Although this phenomenon has been studied widely, majority of prior studies are under the assumptions of no change in overburden stress or effective stress-absent and the heterogeneous effects are rarely considered.

As observed in previous studies (Karacan, 2003, 2007; Karacan and Mitchell, 2003), the CO_2 sorption-associated swelling and volumetric strains in consolidated coal under constant effective stress are heterogeneous processes depending on the lithotypes present. In the time scale of the experiment, vitrite showed the highest degree of swelling due to dissolution of CO_2, while the clay (kaolinite) and inertite region was compressed in response. The volumetric strains associated with swelling and compression were between $\pm 15\%$ depending on the location. These observations may have implied that the swelling component of matrix swells while the non-swelling component of matrix is compacted in response. This provides the basis to assume that coal swelling is a heterogeneous process depending on the distribution of coal voids such as fractures, and that coal matrixes show the highest degree of swelling due to dissolution of CO_2 while fractures are compressed in response. In this study, we extended our previous work (Liu et al., 2010a,b; Wu et al., 2009; Wu et al., 2010a,b) to represent heterogeneous swelling processes through the inclusion of spatially-distributed fracture porosity into complex interactive phenomena (mechanical coupling with gas transport).

2. Governing equations

The set of field equations for coupled coal deformation and gas flow are defined in the following. These field equations are coupled through new porosity and permeability models to represent the response of coal matrix and fractures. These derivations are based on the assumptions that:

(a) Coal is a dual poroelastic continuum.
(b) Strains are much smaller than the length scale.
(c) Gas contained within the pores is ideal, and its viscosity is constant under isothermal conditions.
(d) Conditions are isothermal.
(e) Compositions of the gas are not competitive, i.e., one gas component is considered at time.

In the following derivations, the fractured coal is conceptualized as in Fig. 1. It comprises coal matrix and fractures. The edge dimension of the matrix blocks and the fracture aperture are represented