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A theoretical model for gas adsorption-induced coal swelling

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Abstract

Swelling and shrinkage (volumetric change) of coal during adsorption and desorption of gas is a well-known phenomenon. For coalbed methane recovery and carbon sequestration in deep, unminable coal beds, adsorption-induced coal volumetric change may cause significant reservoir permeability change. In this work, a theoretical model is derived to describe adsorption-induced coal swelling at adsorption and strain equilibrium. This model applies an energy balance approach, which assumes that the surface energy change caused by adsorption is equal to the elastic energy change of the coal solid. The elastic modulus of the coal, gas adsorption isotherm, and other measurable parameters, including coal density and porosity, are required in this model. Results from the model agree well with experimental observations of swelling. It is shown that the model is able to describe the differences in swelling behaviour with respect to gas species and at very high gas pressures, where the coal swelling ratio reaches a maximum then decreases. Furthermore, this model can be used to describe mixed-gas adsorption induced-coal swelling, and can thus be applied to CO_2-enhanced coalbed methane recovery.

Keywords: Coal swelling; CO_2 sequestration; Gas adsorption; Carbon dioxide; Methane

1. Introduction

Coal swelling due to gas adsorption is a well-known phenomenon. Experiments using either strain gauges (Levine, 1996) or optical methods (Robertson and Christiansen, 2005) have shown that coal swells with adsorption of carbon dioxide (CO_2), methane (CH_4) and other gases. The observed swelling represents the difference between two opposing effects; volumetric expansion of the coal matrix due to the adsorption of gas and the matrix compression as a result of pore pressure. Observations show that swelling initially follows the form of the adsorption isotherm. But at high pressures, as the rate of change in adsorbed gas content becomes small, matrix compression dominates and can decrease the volumetric strain.

Adsorption-induced coal swelling is of great importance to coalbed methane (CBM) recovery and CO_2 sequestration in coal reservoirs. Coal permeability is primarily determined by the cleat aperture, and in coal the aperture size is a function of effective stress; i.e., increased effective stress through decreased pore pressure leads to the cleats closing. Swelling and shrinkage of coal under a confining stress may also change the cleat aperture; some of the volume change has to be accommodated by the coal porosity, of which the cleat porosity makes up a significant component. Although volumetric strain as a result of gas adsorption and desorption is small with respect to the total volume (e.g., up to 4%), cleat porosity also tends to be small (e.g., 2%). Thus, the coal permeability is a function of

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both the effective stress and the coal swelling or shrinkage. In practice, significant permeability change has been observed during CBM production and CO_2 injection (Pekot and Reeves, 2002).

Levine (1996) summarized a series of measurements of adsorption-induced coal swelling. These showed that the linear swelling ratio (or linear strain) of coal in CO_2 was less than 0.6% at pressures up to 2.1 MPa. CH_4 adsorption-induced coal swelling was smaller than CO_2 at the same pressure. With these measurements, the coal linear strain was less than 0.3% with pressures up to 2.1 MPa Levine (1996) also measured the swelling ratio on a sample of bituminous coal from Illinois. Levine's measurements showed a linear swelling ratio in CO_2 at 3.1 MPa of 0.41% and 0.18% in CH_4 at 5.2 MPa. Levine (1996) found that the swelling behaviour followed the same form as the adsorption isotherm, in this case explained using a Langmuir-like equation.

Chikatamarla et al. (2004) measured H_2S, CO_2, CH_4, and N_2 induced swelling on four coal samples with pressures up to 5.0 MPa. Their measurements showed that the volumetric strain at 0.6 MPa is from 1.4% to 9.3% for H_2S, from 0.26% to 0.66% for CO_2, 0.09% to 0.30% for CH_4, and from 0.004% to 0.026% for N_2. Their measurements also showed that the volumetric strain and pressure can be described using a Langmuir-like equation and the volumetric strain is approximately linearly proportional to the amount of gas adsorbed.

Robertson and Christiansen (2005) found a linear strain of less than 1.0% for coal in CO_2 at pressures up to 5.3 MPa and 0.2% for coal in CH_4 at pressures up to 6.9 MPa. They also measured adsorption-induced coal swelling in CO_2, CH_4 and nitrogen (N_2) on a bituminous and a sub-bituminous coal samples. Their results showed that linear strain caused by CO_2 adsorption on the sub-bituminous coal was 2.1% and it was more than twice as much as the bituminous coal at 5.5 MPa; CH_4-induced coal swelling for the two coal types was similar at about 0.5% at 6.9 MPa; N_2-induced swelling was about 0.2% at 6.9 MPa.

In the work of St. George and Barakat (2001), volumetric strains were measured for adsorption at 4.0 MPa for CO_2, CH_4, N_2 and Helium on a coal sample from New Zealand. The volumetric strain was 2.1% for CO_2, 0.4% for CH_4, and 0.2% for N_2. Moffat and Weale (1955) measured coal swelling in CH_4 with pressures up to 70.0 MPa. Although the magnitude of swelling was different for different coal types, the swelling isotherms showed similar trends with a maximum at around 15.0 MPa.

Levine (1996) used a Langmuir form of equation to describe the swelling and achieved good agreement with the experimental measurements. Palmer and Mansoori (1998) applied this model to describe the change in cleat porosity for coal. Pekot and Reeves (2002) used an equation in which the swelling ratio is proportional to the quantity of gas adsorbed. Pekot and Reeves (2002) also introduced an extra parameter to represent the differential swelling behaviour resulting from different gas species, using Levine's experimental results. However, these purely empirical models can describe the swelling behaviour at low and moderate pressures, and require observations of swelling. An additional complication is relating the laboratory swelling data to the situation in the field where coal is under stress. In practice, the parameters describing swelling/shrinkage as it affects the reservoir permeability can only be determined through history matching. However, discerning the effects of this process requires long periods of gas production or CO_2 injection, making prediction of reservoir processes difficult.

In this paper the authors propose a model, based on an energy balance approach, to describe adsorption-induced volumetric changes as a first step in describing the effects of shrinkage/swelling on permeability. The developed model assumes that the surface energy change caused by adsorption is equal to the change in elastic energy of the coal solid. The model is tested by application to published experimental measurements of gas adsorption-induced coal swelling.

2. Model development

A porous body dilates when its surface energy changes, either by adsorption of a gas or by immersion in a liquid (Scherer, 1986). If the specific surface energy (γ) of a body changes by adsorption of a vapour or immersion in a liquid, there is a consequent dilatation of the body; if γ increases, the body shrinks to reduce its surface area, and vice versa (Scherer, 1986). Scherer (1986) and Bentz et al. (1998) applied this approach to model the dilation of porous glass with water vapour adsorption. However, in their work, adsorption of water vapour was at low pressure, whereas gas adsorption-induced swelling on coal is at relatively high gas pressure. In this new work, the surface energy is derived for high-pressure gas adsorption in porous media; then a pore structure model is applied to relate this surface energy to the solid elastic energy to describe the coal swelling.

2.1. Surface potential energy

To derive the surface potential energy, the theory developed by Myers (2002) for the thermodynamics of