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Impact of gas adsorption-induced coal damage on the evolution of coal permeability

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ABSTRACT

During the injection of CO₂ into coalbed for geologic sequestration, CO₂ is likely both adsorbed and dissolved in coals, and swells them slightly. When coal is swollen due to the adsorption and dissolution, the induced strain is relieved as the coal structure rearranges to a lower free energy state, causing coal damage and resulting in permeability change. This adsorption- and dissolution- induced coal damage is usually ignored in the permeability model, even though this kind of damage has been observed and detected in the past CO₂ injection experiments. In a previous study we generated a sequence of coal permeability profiles from the “V” shape as observed in experiments through a newly dual-permeability model. Based on this work, in this paper, the dual-permeability model is extended to take the coal damage induced by gas adsorption and dissolution into account according to the principle of damage mechanics, and this model is used to examine the permeability evolution during the injections of different gases, including CO₂, CH₄ and N₂, into coal specimen. Numerical simulation indicates that the model predicts well the permeability increase during the high injected gas pressure. In addition, since the highest gas adsorption into coal occurs for CO₂, the coal permeability during CO₂ injection decreases most pronounced, in contrast, the permeability reduction during N₂ injection is the smallest. Also, it is confirmed that the adsorption-induced coal damage is dominated by tensile damage of coal during the injection of CO₂.

1. Introduction

Sequestration of carbon dioxide in unmineable coal seams is an option to combat climate change and an opportunity to enhance coalbed methane production. Prediction of sequestration potential in coal requires characterization of porosity, permeability, sorption capacity and the magnitude of swelling due to carbon dioxide uptake and methane desorption, in order to attempt a prediction of the long-term effects of sequestration. During the injection of CO₂ into coalbed, CO₂ was likely both adsorbed and dissolved in coals, and swells them slightly. When coal is swollen, the induced strain is relieved as the coal structure rearranges to a lower free energy state.¹ This result could be summarized in Fig. 1², although this figure was obtained when a bituminous coal was exposed to toluene vapor, it is general and not specific to toluene.³ That means that the similar phenomenon may happen for any fluid that can be adsorbed and dissolved in a coal, including CO₂.³

As shown in Fig. 1, adsorption on the coal surface is almost instantaneous, then immediately followed by a much slower diffusion of

the gas molecules into the coal. The amount of a gas that dissolves or adsorbs in the coal will increase with rising gas pressure. The last process identified in Fig. 1 is relaxation stage, which is characterized as the rearrangement of the coal structure in a transition from a glassy, strained state to a rubber, plasticized state.² It is believed that the driving force for the rearrangement is the release of stored elastic strain.¹ Coal swelling provides the macromolecule with the opportunity to undergo conformational rearrangements and to adopt a lower free energy more highly associated structure. Mined coals are in strained state, they cannot relax from this state rapidly to reach and maintain an equilibrium state until they are swollen with a solvent (e.g. CO₂).⁴

Simultaneous measurements of acoustic emission (AE) and expansion/contraction of coal samples subjected to three subsequent cycles of sorption-desorption of gas (CO₂ and CH₄) have also substantiated the coal damage due to gas adsorption.⁵ In addition, the effects of CO₂ adsorption on coal strength have been studied by a number of researchers,^{6–12} it is confirmed that the weakening effect of gas sorption due to the introduction of CO₂ to a coal could be characterized by the reduction of elastic modulus and strength.^{9,13} Viete and Rangith also

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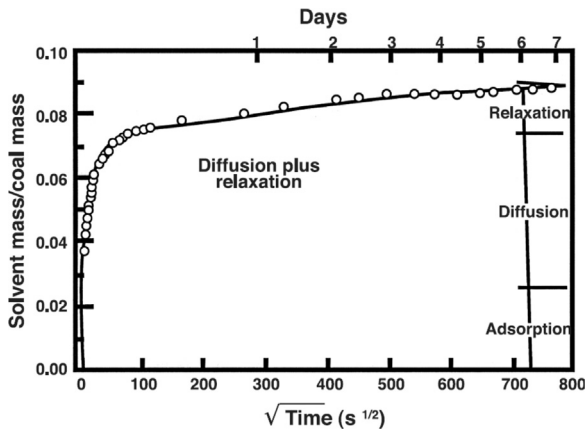


Fig. 1. Rate of toluene uptake by a pyridine extracted bituminous coal (71.0%C, daf)².

explained the mechanism of adsorption of CO₂ induced coal strength reduction according to theory of fracture mechanics and thermodynamics.⁹

The time-dependent swelling and gas adsorption kinetics of the coal under effective stress conditions have been quantified using dual energy X-ray CT imaging.⁴ The 3D X-ray CT characterization of coal strain induced by compression, CO₂ sorption, and desorption at in-situ stress condition confirmed that, alternating positive and negative strain values are observed during compression, emphasizing that both compression/compaction and expansion of coal will occur during CO₂ sequestration.¹⁴ This kind of swelling/compaction in the coal due to the heterogeneous microstructure of coal may be one mechanism of the adsorption-induced coal damage.

Therefore, it is confirmed from previous experimental observations that the coal damage occurs during the gas adsorption, thus altering the mechanical strength and structure of coal. In the past decade, Liu et al.^{15–20} have made persistent efforts to develop coal permeability models in order to explore the mechanism for coal permeability evolution both in space and time, and their permeability models can match coal permeability profiles from the “V” shape as observed in experiments. To achieve the full potential of coal seams to sequester CO₂, this full time-scale permeability response during the coal-gas interaction must be well characterized with predictive models when the gas adsorption-induced coal damage is taken into account. The availability of such knowledge may allow for the adjustment of existing permeability models by incorporating the effects of adsorption-induced coal damage.

2. Governing equations

In this section, we present the governing equations for the deformation of coal, gas flow in the fracture networks, and the matrix-fracture mass transfer, respectively. Most importantly, the gas adsorption/desorption-induced coal swelling/contraction and damage are also taken into account. The strain around fracture walls is defined as the fracture local strain and the coal strain is defined as the global strain.¹⁵ The matrix permeability and fracture permeability models should reflect dynamic effects of local strains and the global strain on matrix and fracture permeability, together with the gas adsorption /desorption-induced coal swelling/contraction and damage.

2.1. Mechanical equilibrium

According to the dual porosity model, the coal is assumed to be consisted of matrix and fractures, and they interact with each other and contribute to the mechanical deformation of coal. According to the theory of poroelasticity, the mechanical equilibrium for the mixture of matrix and fracture networks in coal is described with the Navier-type equation as¹⁸:

$$Gu_{i,kk} + \frac{G}{1-2\nu}u_{k,ki} - \alpha_m p_{m,i} - K(1-\phi_f)\varepsilon_{ms,i} - \alpha_f p_{f,i} - K\phi_f \varepsilon_{fs,i} + f_i = 0 \quad (1)$$

where $G = E/2(1 + \nu)$, $K = E/3(1 - 2\nu)$, $\alpha_m = 1 - K_m/K_s$, $\alpha_f = 1 - K/K_m$, G is the shear modulus of coal (Pa), E is Young's modulus of coal (Pa), ν is Poisson's ratio of coal, K_s is the bulk modulus of grains, K_m is the bulk modulus of coal matrix (Pa), α_m is the Biot coefficient of matrix, α_f is the Biot coefficient of fracture, p_m is the matrix pressure (Pa), ε_{ms} is the gas sorption-induced strain of matrix, p_f is the fracture pressure (Pa), ε_{fs} is the gas adsorption-induced strain of fracture, ϕ_f is the fracture porosity and f_i is the body force of coal (N/m³), u_i is the displacement of coal (m).

Accordingly, the constitutive relations for coalbed deformation, in consideration of the gas adsorption/desorption, can be expressed in terms of the total stress σ_{ij} (positive for tension), the total strain ε_{ij} , the matrix pressure p_m , the gas sorption-induced strain of matrix ε_{ms} , the fracture pressure p_f , the gas sorption-induced strain of fracture ε_{fs} , as follows:

$$\sigma_{ij} = 2G\varepsilon_{ij} + \frac{2G\nu}{1-2\nu}\varepsilon_{kk}\delta_{ij} - \alpha_m p_m \delta_{ij} - \alpha_f p_f \delta_{ij} - K(1-\phi_f)\varepsilon_{ms}\delta_{ij} - K\phi_f \varepsilon_{fs}\delta_{ij} \quad (2)$$

For a system containing a single gas phase the sorption-induced strain of matrix and fracture could be represented by the Langmuir type function,^{21–23} defined as:

$$\varepsilon_{ms} = \frac{\varepsilon_L p_m}{P_L + p_m} \quad (3)$$

$$\varepsilon_{fs} = \frac{\varepsilon_L p_f}{P_L + p_f} \quad (4)$$

where ε_L and P_L are the Langmuir-type fracture and matrix swelling constants, which represent the maximum swelling capacity and the fracture pressure at which the measured volumetric strain is equal to $0.5\varepsilon_L$, respectively.

2.2. Coal damage

As illustrated in Fig. 2, the coal damage in tension or shear occurs when its stress (positive for tension) satisfies the maximum tensile stress criterion or the Mohr-Coulomb criterion, as expressed by²⁴:

$$F_1 \equiv \sigma_1 - f_{t0} = 0 \text{ or } F_2 \equiv -\sigma_3 + \sigma_1 \frac{1 + \sin \phi}{1 - \sin \phi} - f_{c0} = 0 \quad (5)$$

where f_{t0} and f_{c0} are uniaxial tensile and compressive strength (Pa), respectively, σ_1 and σ_3 are major and minor principal stresses (Pa), respectively, ϕ is internal frictional angle (°), and F_1 and F_2 are two damage threshold functions (Pa). According to Eq. (2), the damage is

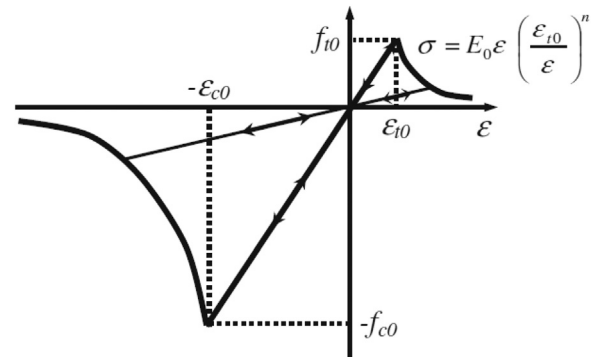


Fig. 2. The elastic damage-based constitutive law of elements under uniaxial stress condition. (f_{t0} and f_{c0} are uniaxial tensile strength and uniaxial compressive strength, respectively).

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