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Full Length Article

Gas sorption-induced coal swelling kinetics and its effects on coal permeability evolution: Model development and analysis

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HIGHLIGHTS

- A semi-analytical kinetic swelling model is proposed.
- A swelling kinetics-improved coal permeability model is developed.
- Swelling kinetics can mitigate the gas sorption-induced permeability change.
- Swelling kinetics can benefit ECBM production but harm primary CBM recovery.

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ABSTRACT

Gas sorption-induced coal swelling plays an important role in coal permeability evolution. Experimental measurements have observed the kinetic feature of this swelling and this feature is normally referred to as 'swelling kinetics'. However, existing coal swelling models only consider the pressure-dependence of coal swelling, none coal swelling models have been developed to describe the swelling kinetic behavior. This paper proposes a semi-analytical swelling kinetic model based on the quasi-steady state diffusion model. The proposed model agrees reasonably with the literature swelling kinetic data. A swelling kinetics-improved coal permeability model is then developed by substituting the proposed swelling kinetic model into our previously developed coal permeability model. The swelling kinetics-improved permeability model also agrees well with the literature permeability data. Based on the swelling kinetics-improved permeability model, the effects of the swelling kinetics on coal permeability evolution are evaluated. The results show that the permeability variation also exhibits the kinetic feature due to the effects of the swelling kinetics. The swelling kinetics can mitigate the gas sorption-induced permeability change, both permeability increase induced by gas desorption and permeability decrease induced by gas adsorption, under uniaxial strain conditions. These effects may be favorable for CO_2 injection-enhanced coalbed methane (ECBM) production but be detrimental to primary coalbed methane (CBM) recovery. Because of the significance of the swelling kinetics for coal permeability evolution, CBM production, and ECBM production, more efforts are needed to investigate the swelling kinetics of coal in the future.

1. Introduction

Both coalbed methane (CBM) recovery and CO_2 injection-enhanced coalbed methane (ECBM) production have stimulated investigations on the sorption behavior of coal to gases such as methane (CH_4), carbon dioxide (CO_2), and nitrogen (N_2) [1]. One noticeable feature of gas sorption in coal is the time-dependence of the sorption volume [2–12]. This feature is normally referred to as 'sorption kinetics'. Many laboratory experiments have been conducted to investigate the gas sorption kinetics in pulverized coal samples [3–11,13]. The results show that the sorption uptake increases with time until reaching sorption equilibrium. Sorption kinetics is normally treated as a diffusion process, thus the mathematical models describing diffusion behavior are often used to interpret the sorption kinetic data. These models include the quasi-steady state diffusion model [14], the unipore diffusion model [15], the Ruckenstein bidisperse diffusion model [16], the double exponential model [10], and the Fickian diffusion–relaxation model [4,17]. Recently, Staib et al. [18] introduced a stretched exponential model coupling a characteristic rate parameter with a stretching parameter to interpret the sorption kinetic data.

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Another important feature of gas sorption in coal is the resultant coal deformation [19,20]. As gas pressure increases, gas adsorbs in coal and makes coal swell. For decreasing gas pressure, however, gas desorbs from coal and induces coal shrinkage [21]. Experimental observations have shown that the gas sorption-induced coal swelling also exhibits the kinetic feature: the coal swelling increases with time until reaching swelling equilibrium [2,22–24]. This feature is normally referred to as 'swelling kinetics' [2]. However, existing coal swelling models only consider the pressure-dependence of coal swelling [19,20,25], none coal swelling models have been proposed to describe the swelling kinetic behavior.

The gas sorption-induced coal swelling affects coal permeability evolution significantly and many coal permeability models have incorporated this effect [21,26–32]. Since existing coal swelling models do not take into account the swelling kinetic behavior, these permeability models do not incorporate the kinetic feature of coal swelling as well. However, experimental measurements have observed the time-dependence of coal permeability when exposing cores to an adsorbing gas. Siriwardane et al. [33] investigated the effects of CO_2 exposure time on coal permeability variation under constant confining stress and constant pore pressure conditions by using the pressure transient method. According to existing coal permeability models, permeability should keep constant under constant confining stress and constant pore pressure conditions. However, Siriwardane et al. [33]'s data show that the permeability changed notably with the CO_2 exposure time and the permeability variation exhibits an evident kinetic feature. Siriwardane et al. [33] have also measured coal permeability variation with respect to the exposure time of argon, which is an inert gas and does not swell coal matrix. The argon permeability, however, nearly kept constant with the exposure time. This indicates that the kinetic permeability feature during CO_2 exposure is induced by the swelling kinetics rather than the pore pressure change within the core.

This paper will propose a semi-analytical swelling kinetic model based on the quasi-steady state diffusion model. The proposed model will be then substituted into our previously proposed coal permeability model [32]. Based on this improved permeability model, the effects of the swelling kinetics on coal permeability evolution will be evaluated. The possible effects of the swelling kinetics on both primary CBM recovery and CO_2 injection-ECBM production will be evaluated as well.

2. Semi-analytical model representing the gas sorption-induced coal swelling kinetics

2.1. Model development

For a given coal matrix initially saturated with an adsorbing gas, a pressure change external of the coal matrix can produce concentration gradients in the coal matrix and the adsorbing gas will diffuse into or out from the coal matrix. This process can be represented approximately by the quasi-steady state diffusion model [14,34]

$$\frac{dV^{NEQ}_{sor}(t)}{dt} = \frac{V^{p}_{sor}(t) - V^{NEQ}_{sor}(t)}{\tau} \tag{1}$$

where τ is the diffusion time and also referred to as 'sorption time' in some other works [35,36]. $V^{NEQ}_{sor}(t)$ is the non-equilibrium sorption volume within the coal matrix at time t. The superscript 'NEQ' indicates that the gas pressure within the coal matrix does not equilibrate to the gas pressure external of the coal matrix. $V^{p}_{sor}(t)$ is the sorption volume within the coal matrix when the gas pressure within the coal matrix equilibrates to the gas pressure external of the coal matrix. Note that $V^{p}_{sor}(t)$ is also time-dependent if the gas pressure external of the coal matrix changes with time.

Laboratory experiments have observed that the gas sorption-induced coal swelling can be approximated by a linear function of the sorption volume [28,37]

$$\varepsilon_{sorV} = C_{swel} V_{sor} \tag{2}$$

where ε_{sorV} is the gas sorption-induced volumetric coal swelling. C_{swel} is the ratio of the swelling to the sorption volume.

If C_{swel} is assumed constant and independent of time, substituting Eq. (2) into Eq. (1) leads to

$$\frac{d\varepsilon^{NEQ}_{sorV}(t)}{dt} = \frac{\varepsilon^{p}_{sorV}(t) - \varepsilon^{NEQ}_{sorV}(t)}{\tau} \tag{3}$$

where $\varepsilon^{NEQ}_{sorV}(t)$ is the gas sorption-induced non-equilibrium volumetric swelling of coal at time t. $\varepsilon^{p}_{sorV}(t)$ is the gas sorption-induced volumetric coal swelling when the gas pressure within the coal matrix equilibrates to the gas pressure external of the coal matrix. $\varepsilon^{p}_{sorV}(t)$ is gas pressure-dependent and can be represented by the Langmuir equation [25]

$$\varepsilon^{p}_{sorV}(t) = \frac{\varepsilon_L p(t)}{p_L + p(t)} \tag{4}$$

where ε_L and p_L are Langmuir swelling constants. $p(t)$ is the gas pressure external of the coal matrix at time t. Note that $\varepsilon^{p}_{sorV}(t)$ is also time-dependent if $p(t)$ changes with time.

Within a small time step Δt, integrating Eq. (3) leads to

$$\int_{\varepsilon^{NEQ}_{sorV}(t-\Delta t)}^{\varepsilon^{NEQ}_{sorV}(t)} \frac{1}{\varepsilon^{p}_{sorV}\left(t-\frac{1}{2}\Delta t\right) - \varepsilon^{NEQ}_{sorV}} d\varepsilon^{NEQ}_{sorV} = \frac{1}{\tau}\int_{t-\Delta t}^{t} dt \tag{5}$$

Rearranging Eq. (5) leads to

$$\frac{\varepsilon^{p}_{sorV}\left(t-\frac{1}{2}\Delta t\right) - \varepsilon^{NEQ}_{sorV}(t)}{\varepsilon^{p}_{sorV}\left(t-\frac{1}{2}\Delta t\right) - \varepsilon^{NEQ}_{sorV}(t-\Delta t)} = e^{-\frac{\Delta t}{\tau}} \tag{6}$$

$\varepsilon^{p}_{sorV}\left(t-\frac{1}{2}\Delta t\right)$ can be assumed to be the arithmetical average of $\varepsilon^{p}_{sor}(t)$ and $\varepsilon^{p}_{sor}(t-\Delta t)$

$$\varepsilon^{p}_{sorV}\left(t-\frac{1}{2}\Delta t\right) = \frac{\varepsilon^{p}_{sorV}(t) + \varepsilon^{p}_{sorV}(t-\Delta t)}{2} \tag{7}$$

Substituting Eq. (7) into Eq. (6) leads to

$$\varepsilon^{NEQ}_{sorV}(t) = \varepsilon^{NEQ}_{sorV}(t-\Delta t)e^{-\frac{\Delta t}{\tau}} + \frac{\varepsilon^{p}_{sorV}(t) + \varepsilon^{p}_{sorV}(t-\Delta t)}{2}\left(1 - e^{-\frac{\Delta t}{\tau}}\right) \tag{8}$$

Eq. (8) is the swelling kinetic model representing the kinetic feature of the gas sorption-induced coal swelling. Since the quasi-steady state diffusion model is an approximation of the diffusion process and is slightly empirical, the proposed swelling kinetic model can be categorized as a semi-analytical model. For Eq. (8), the initial conditions are defined as that the coal is uniformly saturated with a gas pressure of p_0. Thus both $\varepsilon^{NEQ}_{sorV}(0)$ and $\varepsilon^{p}_{sorV}(0)$ are equal to the initial coal swelling, that is, $\varepsilon^{NEQ}_{sorV}(0) = \varepsilon^{p}_{sorV}(0) = \varepsilon^{p_0}_{sorV} = \varepsilon_L p_0/(p_L + p_0)$.

2.2. Model validation

2.2.1. Data source

Although many researchers have measured the gas sorption kinetic data of coal, only a few efforts have been made to measure the swelling kinetic data of coal. Staib et al. [2] have measured a series of swelling kinetic data by using five Australian coal bulks: Coal-C, Coal-D, Coal-E, Coal-F, and Coal-G. The sorbate gases included CO_2, CH_4, ethane, and xenon. The gas pressure increased