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How moisture loss affects coal porosity and permeability during gas recovery in wet reservoirs?

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A B S T R A C T

Moisture in coal seams changes gas adsorption capacity, induces coal deformation, and affects coal porosity. However, fewer studies have investigated the dynamic process of moisture loss. In this study, a fully coupled multi-physical model for coal deformation, gas flow and moisture loss was implemented. It validated the coal-gas-moisture interactions of the decay of gas adsorption capacity and the coal shrinkage. Subsequently, the proposed model was applied to a simulation of coal seam gas recovery from wet reservoir and solved using the finite method in COMSOL Multiphysics 3.5. Analyses of the component factors and the sensitive parameters of moisture loss on coal porosity and permeability were comprehensively studied at last. The results reveal that moisture loss enhances coal porosity and permeability. The decay of gas adsorption capacity decreases coal permeability while the coal shrinkage promotes it. The decrease of the adsorption decay coefficient and the increase of the initial density of saturated water vapor and water evaporation constant can enhance the permeability of wet coal seams.

1. Introduction

Coalbed methane/coal seam gas (CBM/CSG) is an important natural energy source that has been changing our manner from mitigating its dangers as mining hazards into developing its potential as an unconventional gas resource [1–3]. Coal seams are naturally fractured material that usually considered as dual-porosity media with the micro-porous matrix and the fracture network [4,5]. Generally, water is associated with CBM/CSG production as adsorbed moisture in the coal matrix and free water in the fracture network [6]. Dewatering process that including saturated water flow and two phase flow occurs preferentially during water-saturated coal seams gas recovery, gas flow with no liquid water then follows. In wet reservoirs, the minor content of water in both coal matrix and the fracture network can only be brought out in vapor phase during gas production [7,8]. In in-situ dry CBM/CSG reservoirs, the hydro-fracturing technique moistens the coal seams [9,10]. Therefore, it is necessary and important to carry out the work in studying the effects of moisture loss on gas production in wet coal seams.

Moisture is known to play a critical role in the gas adsorption capacity of coal since both moisture and methane compete for the adsorption sites [11,12]. The methane adsorption capacity could increase by 40% after a storage time of 13 months in a humid environment [13]. Coal has critical moisture content, additional moisture beyond this content will not affect the adsorption capacity any more [14]. The effect of moisture on gas sorption is rank-dependent, the coals in high ranks are less affected compared with the coals in low ranks [15,16]. Based on these series of observations, researchers have proposed different theories to describe the results. In 1958, Ettinger introduced a linear relationship between the moisture content and the gas adsorption capacity, and it was further confirmed by Joubert et al. and Levy et al. [17,18]. Crosdale established a power law relationship between the moisture content and the methane capacity for the low-rank coal from Huntly Coalfield in the North Island of New Zealand [11]. He also found that the adsorption capacity was linearly increased with the increasing of coal ranks. Besides of these, an exponential decay equation was proposed to describe the effects of moisture on gas sorption in both high and low rank coals [7].

Moisture adsorption/desorption induces coal swelling or shrinkage, which also has significant implications on coal permeability and CBM/CSG production [19]. First of all, the moisture induced coal swelling is rank-depended [12,20]. Although different

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kinds of coals have different abilities to swell, no difference was found in the anisotropic swelling in a certain kind of coal in dry and wet conditions [14,21]. The moisture sorption induced volumetric swelling was found to be strongly correlated to the moisture content which was linearly related to the pore space [22]. According to Evans, the mass and porosity for coal contracted due to the loss of moisture [23]. In 2012, Chen et al. described the moisture adsorption induced swelling using a Langmuir type equation with two constants [24]. Pan developed a model to describe the coal swelling with respect to the moisture content based on the assumption that only the first layer of adsorbed molecules of the multilayer adsorption could change the surface energy [25]. The model was applied to describe the experiment on Australian coal and finally well validated by the experimental data.

Although a certain degree of success has been achieved in observing the effects of moisture on coal gas interactions, fewer studies take the fully coupled coal-gas-moisture interactions in analyzing the evolution of coal permeability and gas transport in wet coal seams. Even that Chen made a try to evaluate the moisture effects on gas storage and transport in coal seams, he treated the moisture content as a certain constant with limitations [24]. However, his work pointed out the importance of measuring the dynamic loss of moisture. In this study, the moisture content was described by a moisture loss field fully coupled with the coal deformation field and the gas flow field. We defined the chain of reactions as coupled multi-physics, discussed the coal-gas-moisture interactions including gas adsorption decay and the moisture loss induced coal shrinkage. A cubic law not only translated the porosity into permeability but also related the coal deformation with gas transport. Finally, modeling and comprehensive simulations were proposed to show the effects of dynamic moisture loss on the evolutions of coal porosity and permeability. This paper is organized as follows: Section 2 proposed a fully coupled multi-physical model based on three governing equations. Section 3 compared the component effects of moisture loss on coal porosity and permeability based on three simulation scenarios. Section 4 was parametric study of moisture loss factors on gas production. The understanding and conclusions were drawn in Section 5.

2. Governing equations

In the following, a mathematic representation for the coupled solid coal deformation, gas flow and moisture loss is developed based on the mechanical equilibrium equation and the mass conservation equation. The following assumptions are made before the modeling:

(1) Coal is a homogeneous, isotropic and elastic continuum medium, its elasticity modulus and Poisson's ratio are constants.
(2) Gas contained within the pores is ideal with constant viscosity, and gas flow obeys the Darcy's law.
(3) Only adsorbed moisture in the pores is considered, it is evenly distributed in the coal.
(4) Moisture loss in wet coal seams is in form of vapor flow.

2.1. Coal swelling due to gas and moisture sorption

The gas adsorption volume V_s is fitted by a Langmuir-type equation with an exponential decay coefficient that reflects the effects of the moisture. It is expressed as [24]:

$$V_s = V_{sdry} \cdot \exp(-\lambda\theta) = \frac{V_L p}{P_L + p} \exp(-\lambda\theta) \tag{1}$$

where θ is the volumetric content of moisture; V_{sdry} is the gas adsorption volume of dry coal, m^3/kg; V_L is the Langmuir volume constant, m^3/kg, representing the gas adsorption volume at infinite pore pressure; P_L is the Langmuir pressure constant, MPa, representing the pore pressure at which the measured volume is equal to $V_L/2$; λ is the adsorption decay coefficient determined by matching the experimental data. Fig. 1 shows the effect of moisture content on gas adsorption capacity.

Replacing the Langmuir volume constant V_L by the Langmuir volumetric strain constant $\varepsilon_s = a_{sg}V_L$, the gas adsorption, with effects of moisture, induced volumetric strain yields

$$\varepsilon_s = \frac{\varepsilon_L p}{P_L + p} \exp(-\lambda\theta) = \alpha_{sg} \frac{V_L p}{P_L + p} \exp(-\lambda\theta) \tag{2}$$

where α_{sg} is the coefficient for sorption-induced volumetric strain, kg/m^3.

Thus, the partial derivative of ε_s with respect to time t is expressed as:

$$\frac{\partial \varepsilon_s}{\partial t} = \varepsilon_L \cdot \exp(-\lambda\theta)\left[\frac{P_L}{(P_L + p)^2}\frac{\partial p}{\partial t} - \frac{\lambda p}{P_L + p}\frac{\partial \theta}{\partial t}\right] \tag{3}$$

Similarly, a Langmuir type equation for the moisture adsorption induced swelling strain can be expressed as [7,25]

$$\varepsilon_\theta = \frac{\varepsilon_{\theta L}\theta}{\theta_L + \theta} \tag{4}$$

where ε_θ is the moisture sorption induced volumetric strain, $\varepsilon_{\theta L}$ is the moisture induced maximum volumetric strain, θ_L is the Langmuir strain constant for moisture sorption. The partial derivative of ε_θ with respect to time is expressed as:

$$\frac{\partial \varepsilon_\theta}{\partial t} = \frac{\varepsilon_{\theta L}\theta_L}{(\theta_L + \theta)^2}\frac{\partial \theta}{\partial t} \tag{5}$$

2.2. Coal deformation equation

Coal deformation is defined through the Navier type equation for linear poroelastic media, accommodating pore pressure, gas and moisture sorption induced effects as additional body forces. The relationship between the linear strain and the displacement is defined as

$$\varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}) \tag{6}$$

and the equilibrium equation is defined as

$$\sigma_{ij,j} + f_i = 0 \tag{7}$$

where ε_{ij} and σ_{ij} are the components of the strain tensor and the total stress tensor (positive for tension), respectively. u_i and f_i donate the components of displacement and body force in the i direction.

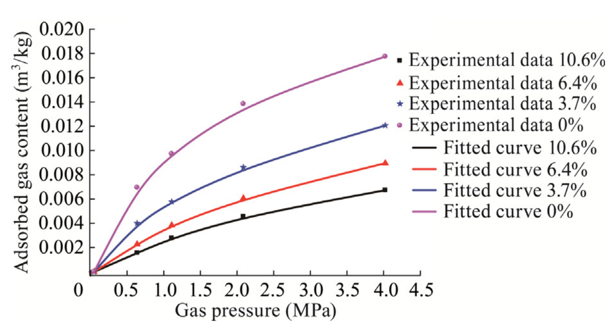

Fig. 1. Langmuir adsorption isotherms of coal under different moisture contents (after [7]).