



A thermally sensitive permeability model for coal-gas interactions including thermal fracturing and volatilization



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ABSTRACT

Experiments have observed that coal permeability experiences significant change when temperature varies from room temperature up to 100 °C. However, current permeability models have not well described this change so far. This paper proposes a thermally sensitive permeability model to describe the coal-gas interactions under variable temperatures. This model includes matrix permeability and fracture permeability. It describes the impacts of thermal expansion, thermal fracturing, the change of matrix sorption capacity, and the thermal volatilization of fracture surfaces on coal permeability. Particularly, the change of temperature in coal matrix may initiate, nucleate and grow up micro-pores and cracks, forming a crack cloud and changing the porosity of this matrix block. The fractal of cracks and pores is linearly evolved with temperature change. Second, the gas sorption capacity of coal matrix is modified by temperature change through an exponential function. Third, the thermal expansion of matrix is linearly related to temperature change but thermal volatilization occurs on the fracture surfaces and widens gas flow channels. Through the thickness change of volatile membrane, the change of fracture aperture is described by a quadratic function. This model is verified by three series of experimental data from either literature or our newly conducted tests. It is found that the permeability evolution with temperature has four stages which are dominated by one of four primary factors: thermal expansion, thermal volatilization, thermal fracturing and crack coalescence. In each stage, secondary factors may modify the evolution of permeability into sub-classes: linear curve, upward bending curve, or concave bending curve. These verifications confirm that this thermally sensitive permeability model can well describe the permeability evolution of different coals at either thermal expansion stage, or volatilization stage, or their transition.

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1. Introduction

Temperature is a key parameter to the permeability evolution and the coalbed methane extraction in fractured coal seams (Bourdet, 2002; Clarkson and McGovern, 2005; Zhu et al., 2011a). As coal seams are both the source and the storage space of coalbed methane, the coal permeability and gas transport in coal seams vary with moisture, temperature, and stress compaction (Connell, 2009; Pan and Connell, 2012; Perera et al., 2012; Yin et al., 2013). A dual-porosity medium is generally assumed to model the gas

flow in a fractured coal seam (Warren and Root, 1963; Wu et al., 2011a,b; Wang et al., 2012; Chareonsuppanimit et al., 2014). This porous medium is composed of well-defined primary porosity system and secondary porosity system. The primary porosity system is made up of distributive pores in coal matrix blocks. The matrix blocks are bounded by a network of natural fractures called cleats. This fracture network forms the secondary porosity system. Most of coalbed methane is predominantly stored in the micro-pores of the coal matrix in an adsorbed state (Harpalani and Schraufnagel, 1990; Cui and Bustin, 2005) and geological storage conditions are complicated such as high temperature, high geostress, variable moisture content, and low permeability (He et al., 2010; Zhu et al., 2011a,b; Chen et al., 2012; Xia et al., 2014a,b). Coal seams are usually located beneath the table of underground

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water. The underground water is usually stored in fracture network and a dewatering process is commonly implemented before any gas extraction. This water flow usually experiences four stages as shown in Fig. 1 (Aminian and Ameri, 2009; Packham et al., 2011). In the last stage, gas flow accompanies with some moisture. The residual water film on the fracture surface may become thinner with further gas flow. In this stage, the physical process is complicated and the smoothness of fracture surface may change with the evaporation of water film (Nakagawa et al., 2000; Pan, 2012). So far, the impact of temperature-induced change of this water film on the evolution of gas permeability in coal seams has not been investigated.

The evolution of permeability in coal seams is affected by many factors. First of all, stress compaction is the most important mechanism whether single or dual porosity system is concerned. Based on numerous field and laboratory observations, a coal permeability model is generally expressed as a function of effective stress and pore pressure (Somerton et al., 1975; Palmer and Mansoori, 1998; Cui and Bustin, 2005; Zhang et al., 2008; Connell, 2009; Wang et al., 2014). Stress and pore pressure are the first two and most important factors to impact the evolution of gas permeability in coal seams (Palmer and Mansoori, 1996, 1998; Shi and Durucan, 2004; Cui and Bustin, 2005; Zhu et al., 2007; Palmer, 2009; Perera et al., 2013; Qu et al., 2014). The relationship between permeability and gas injection pressure, confining pressure, axial load and gas sorption was developed under various loading conditions. Particularly, the change of porosity during coal gas production is firstly estimated in the P&M model. The change of permeability is correspondingly computed by the cubic law between porosity and permeability. However, all above models do not consider the effect of temperature on coal-gas interactions.

Temperature is a significant and indispensable factor to affect both storage and transport of coal seam gas. The geothermal gradient in subsurface is usually 25 °C/km. This potentially results in high temperature even at a shallow depth (Zhu et al., 2011a; Yin et al., 2013). For example, the temperature at the 3 km deep Altmark natural gas field in Germany is about 120 °C (Rebscher et al., 2006). When coal is extracted by mining and geofluid is recovered or injected, a new geothermal equilibrium should be approached in the subsurface. Such a re-equilibrium due to temperature change may induce strongly thermal interactions between coal and gas. A new enhancement technology for the exploitation of coalbed methane was developed by heat injection (Alireza and

Manouchehr, 2012; Wang et al., 2015). Therefore, it is necessary to investigate the effect of temperature on the evolution of permeability in the range of low temperatures (below 100 °C).

Some coal permeability models have been proposed under complex geological conditions, including the effects of temperature and moisture. For example, Crosdale et al. (2008) observed a power law relationship between the moisture content and the permeability of the low rank coal from Huntly Coalfield in the North Island of New Zealand. Mastalerz et al. (2009) monitored the changes in chemical and physical properties of coal during storage. Their tests were conducted under controlled laboratory conditions at low temperature. After evaluating the moisture loss in coals, they found that the methane adsorption capacity increased by 40% during a period of 13 months. A series of theoretical developments have been done to consider the thermal effects on coal permeability as well as the temperature-induced coal-gas interactions. For example, Zhu et al. (2011a) developed a mathematical model to describe the evolution of coal porosity under the combination of gas pressure, thermally induced solid deformation, thermally induced change of gas adsorption and matrix swelling. Qu et al. (2012) analyzed the complex evolution of coal permeability during CO₂ injection under variable temperatures. They just studied the temperature induced change of gas sorption capacity. Xia et al. (2014b) proposed a fully coupled hydro-thermo-mechanical model for the spontaneous combustion of underground coal seams. Although these coal permeability models have achieved a certain extent of success under variable temperatures, fewer studied the phenomena of thermal fracturing and thermal volatilization in the gas extraction engineering or related experiments.

Thermal fracturing and thermal volatilization have been observed in both field observations and laboratory tests (Nakagawa et al., 2000; Yu et al., 2012). Yu et al. (2012) studied the development of micropores in a lean coal with temperature through a new micro-CT system. Arenillas et al. (2003) found that heating coal might cause drying or vaporization and pyrolysis (moisture loss). After temperature exceeds some critical values, the chemical process of pyrolysis happens and volatile matter is released which, in turn, intensifies microcrack formation and increases the porosity and permeability of coal seams. Some laboratory experiments (Akbarzadeh and Chalaturnyk, 2014; Niu et al., 2014) have found two critical temperatures of 100 °C and 470 °C at which significant changes of coal structures occur during pyrolysis. Nakagawa et al. (2000) observed the change of coal microstructures during temperature change. They found that water was desorbed from coal surface and removed in the temperature range of 25 °C–150 °C. They proposed a conceptual model on water film based on their observations (see Fig. 2). Therefore, thermal fracturing and thermal volatilization are physical phenomena in the elevated temperature environment, but no permeability model has been available so far to comprehensively consider these phenomena.

This study is to develop a thermally-sensitive permeability model for the effects of thermal expansion, thermal fracturing, and temperature-affected gas adsorption/desorption in coal matrix, thermal volatilization in fracture network under a low range of temperature change (from room temperature to 100 °C) in gas extraction engineering and related experiments. With the concept of the coal fracture-matrix system, this model describes the changes of porosity and permeability in both matrix blocks and fracture network with variable temperatures. The model is then verified by fitting three series of experimental data available from either literature or our newly conducted tests. Four primary stages of permeability evolution are identified through these fittings. Particularly, for the primary stages of thermal expansion and volatilization, three sub-classes of mechanisms are further identified at different temperatures. This paper is organized as follows.

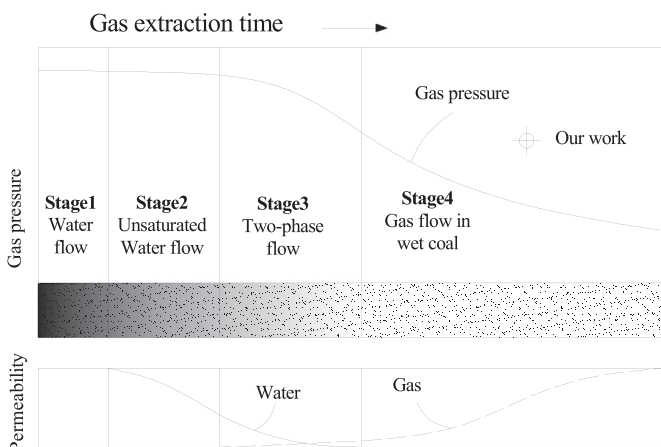


Fig. 1. Four stages water in coal seams.

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