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Effect of adsorption-induced matrix deformation on coalbed methane transport analyzed using fractal theory

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ABSTRACT

It is well-known that adsorption-induced deformation of coal matrices influences the prediction of the estimated coalbed methane (CBM) yield. Additionally, changes in porosity contribute to changes in matrix permeability. In this paper, changes in porosity and absolute permeability are studied on the basis of fractal theory, and the reliability of equations are verified by experimental data from coal samples from the San Juan Basin. Furthermore, two permeability-affecting stages (i.e., rapid and slow deformation stages) are identified, and the result also illustrates that its applicability varies with different gas pressures that arise from the decay of the Klinkenberg effect when the gas pressure is increasing. However, its applicability is limited when the gas pressure remains high because of the same decay effect; therefore, using a reasonable value for the Klinkenberg constant plays a crucial role in formulating a sound permeability-change model for high pressure environments. Fractal theory can clearly explain permeability change patterns due to the adsorption-induced matrix deformation, which can be applied to understand the mechanism underlying methane seepage during CBM production.

1. Introduction

The process of coalification has an impact on the formation of gas, especially methane. Coalification is the process of the formation of coal by the compression of organic matter (Chen et al., 2014). Gas in coalbeds has typically been considered to be an obstacle to coal mining; however, recently, it has become a green energy source (Cervik, 1967). The exploitation of CBM gas can address the pressing energy crisis and efficiently reduce the effects of greenhouse gases. Therefore, mastering the methane seepage rule in coal seams can strongly contribute to the better utilization of resources, thereby only having a minimal impact on the environment (Chen et al., 1999; Saghafi et al., 2007; Zhang et al., 2008).

As a porous medium, coal acts as a tunnel for methane transition because of the presence of numerous pores and fractures on its structure (Meyers, 2012; Zhang et al., 2014; Zhang and Nemcik, 2013; Zhang et al., 2015). Therefore, studying structural changes in the coal pore structure aids in better understanding of the "methane seepage" process. Fractal theory is widely applied to model self-similar complex systems, so a great deal of research has indicated various fractal characteristics of pores in coal samples (Hu and Stroeven, 2005; Jiang et al., 2010; Posadas et al., 2001; Rieu and Sposito, 1991). Some scholars have also formulated theoretical models describing methane permeability in porous media to uncover how the pore structure can affect the methane adsorption–desorption rule (Adler, 1996; Li et al., 2010).

According to Darcy's Law, gas and liquid flows show different characteristics, which can be attributed to the intermolecular interaction and the respective nature of gases and solids (Craft et al., 1959; Muskat, 1938; Noman and Kalam, 1990). Some studies have demonstrated that the apparent permeability of low-pressure gas is much higher compared with its liquid counterpart, and this phenomenon is termed as the "Klinkenberg effect." (Jones and Owens, 1980; Klinkenberg, 1941).

Different from other types of gas adsorption processes, the methane adsorption of coalbeds fits the nonlinear Langmuir isotherm (Clarkson and Bustin, 1999a, b). This difference is largely due to adsorption-induced volumetric strain of the coal matrix, and the narrowing space in coal matrix is directly responsible for the reduction in the estimated adsorption capacity (Cui and Bustin,

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2005; Harpalani and Schraufnagel, 1990; Robertson and Christiansen, 2005). Because of its easy absorption characteristics, the methane flow in a coal matrix varies from that of non-adsorption gases, such as the modified FE model proposed by Zhang et al. (2005), that better describe the methane permeability in the matrix by evaluating the methane seepage characteristics in the deformed matrix. Wang et al. (2014) reconstructed the permeability model by monitoring the change of gas slippage in the shrinking matrix. Previous studies showed that changes in the pore structure exerted by methane adsorption can have a great effect on methane seepage. Adler (1996) studied the permeability function of porous media with fractal theory. Yu and Cheng (2002) constructed a fractal model that described the permeability of saturated porous media. Although adsorption-induced matrix deformation causes changes in the fractal dimensions, very few studies have considered this factor while investigating methane seepage during the adsorption and desorption processes Thus, this study aims to provide a better understanding of the methane seepage rule by applying fractal theory. The results of this study can be used to improve CBM yield.

2. Theoretical basis of the research method

2.1. Physical structure of coal fractures

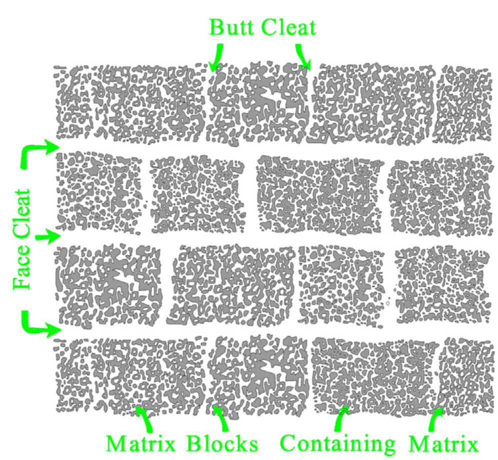
A coal matrix is a typical dual-porosity system that contains both macropores and micropores. The macropore system contains mutually perpendicular cleats, including a face cleat and butt cleat (Alexeev et al., 1999; Rice, 1993). Fig. 1 illustrates the face cleat that constantly passes through the entire matrix, whereas the discontinuous butt cleat connects the face cleats with each other. Some researchers constructed capillary tubes and matchstick models to describe the distribution of cleats in a coal matrix to further explore the in-matrix methane flow (Gates and Lietz, 1950; Seidle et al., 1992). Comparing these two models, Harpalani and McPherson (1986) reported that the matchstick model better describes the distribution of cleats because of the precision of the model to describe methane seepage. Therefore, the experiments in this study are mainly conducted according to the matchstick model.

2.2. Fractal model of matrix porosity

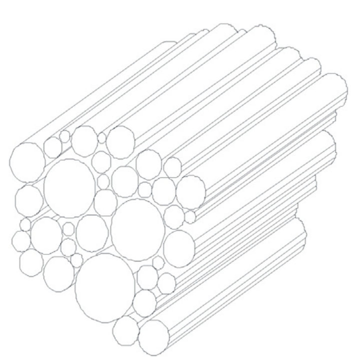
The self-similarity of pores in porous media leads to the complex pore structure that was simplified according to fractal theory; the distribution of pores was analyzed based on the matchstick model. Some authors quantitatively defined the fractal relationship between the number and size of units in a self-similar system (Hongwei, 1997; Mandelbrot and Wheeler, 1983) as

$$N\left(1\big/b^i\right) = k\left(1\big/b^i\right)^{-D}(i = 1, 2, \ldots, \infty) \tag{1}$$

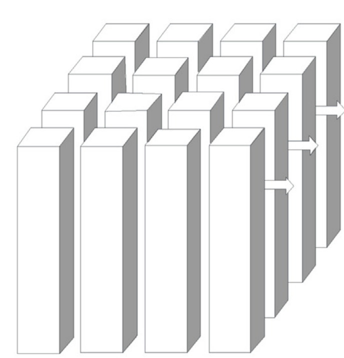
where $N(1/b^i)$ is the number of $(1/b^i)$-long units; k is the number of initial element with unit length; i represents iterations; b is the scaling factor ($b > 1$); and D is fractal dimension. Based on the matchstick model of a coal matrix, the Menger sponge model was



(a) Fracture system of coal (Harpalani and Chen, 1997)



(b) Capillary tubes model (Gates and Lietz,1950)



(c) Matchstick model (Seidle et al., 1992)

Fig. 1. Dual-porosity coal system.