Journal of Natural Gas Science and Engineering 50 (2018) 240–249

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

journal homepage: www.elsevier.com/locate/jngse

Inversion of gas permeability coefficient of coal particle based on Darcy's permeation model

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ARTICLE INFO

Keywords:
Permeability
Gas permeability coefficient
Coal particles
Inversion
Darcy's law

ABSTRACT

Permeability is an important indicator for predicting gas drainage yield and preventing mine gas disasters. Gas permeability coefficient derived from the permeability is introduced in this work to develop a model of methane adsorption of coal particle based on Darcy's permeation, which is solved by our self-developed software, and then the methane isothermal adsorption of six granular coal samples are measured by quasi-constant pressure adsorption experiments. A new inversion approach for gas permeability coefficient of coal particle is performed by matching simulation results with experiment data. Meanwhile, the impacts of adsorption pressure and coal rank on gas permeability coefficient are also analyzed quantitatively. The results show that (i) a suitable gas permeability coefficient of coal particle can be determined by adjusting simulated curve to match with experimental data, which verifies the feasibility and effectiveness of the inversions; (ii) the gas permeability coefficient of coal particle decreases exponentially as the adsorption pressure or volatile matter content grows. This research provides an alternative approach to determine the permeability of granular coal samples and we hope it will bring some references to researchers.

"1. Introduction

Methane is one of the products from a series of physicochemical reactions associated with coal formation and coalification (Moore, 2012), which is not only a major hazard in coal mining underground, but also regarded as the second most important greenhouse gas after carbon dioxide (Jiang et al., 2016). However, there is a promising side that methane is a clean and efficient energy when it is extracted out of coal seams (Liu and Harpalani, 2013; Zhou et al., 2015), but the efficient gas drainage is a worldwide problem due to low permeability of coal seam (Karacan et al., 2011). It is generally known that the permeability is an important indicator to evaluate gas seepage capacity and predict coalbed methane yield (Pan and Connell, 2012; Wang et al., 2017), and thus the determination of permeability is a key step for coalbed methane extraction.

Coal is a porous medium with abundant internal pores (Nie et al., 2015). The basic transport pattern of methane in coal has an important influence on the permeability of coal. A number of theories have been developed to assess the state of methane flow in coal, including Darcy's permeation, Fick's diffusion and the diffusion-permeation mixture (Nandi and Walker, 1969; Ruckenstein et al., 1971; Sun, 1994). It is generally believed that gas flowing through cleat system of coal is pressure driven so that can be described by Darcy's law, but the flow in coal matrix should be modeled by Fick's diffusion based on concentration driven (Busch et al., 2004; Liu et al., 2015; Yi et al., 2009). Nevertheless, some studies still suggest that there are some limitations for the Fick's diffusion using in the coal matrix. Ritger and Peppas reported that the transport of pyridine vapour in coal does not comply with Fick's diffusion but is purely relaxation-controlled (Ritger and Peppas, 1987). Kang et al. established an anomalous subdiffusion model for gas transport in coal matrix instead of Fick's diffusion-based model (Kang et al., 2016). Li et al. believed that gas flowing in original multipore media reservoirs is usually regarded as a steady and linear process and can be described by Darcy's law (Li et al., 2016a). In fact, as early as 1968, Airey had put forward that the gas emission from broken coal conformed to Darcy's law (Airey, 1968). Our group has done an in-depth study on the methane desorption from coal particles, including simulation analyses and experiments (Qin et al., 2012, 2013, 2015). The simulation results based on diffusion were not consistent with the whole experimental process, which only overlap with the experimental data in the initial stage, but the results of Darcy's permeation model had a better correspondence with the experimental data.

The methane desorption model based on diffusion holds that methane emissions from coal matrix depend only on the content gradient

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https://doi.org/10.1016/j.jngse.2017.12.017
Received 16 July 2017; Received in revised form 25 September 2017; Accepted 17 December 2017
Available online 20 December 2017
1875-5100/

of methane. This is a debatable issue, because it has failed to distinguish the methane between free-state and adsorbed-state. It is well known that free methane and adsorbed methane in original coal seams reach a dynamic equilibrium. Once external pressure is relieved, the free methane will transport outward in proportional to its density gradient. According to Perry and Green, in most underground cases (0.1 MPa ≤ Pressure ≤ 4 Mpa; 10 °C ≤ Temperature ≤ 40 °C), methane can be treated as ideal gas due to its compressibility factors close to 1 (Perry et al., 1997), and thus the methane density is proportional to its pressure based on the state equation of ideal gas. In this way, the density gradient can be transformed into the pressure gradient so that the methane desorption model can be obtained in formally consistent with Darcy's law. The adsorption and desorption are two different properties of the same behavior of methane transport in coal (Zhou et al., 2017), just like two sides of a coin, but few attentions have been paid to the methane transport in adsorption process, which will be investigated by using Darcy's permeation model in this work.

In China, gas permeability coefficient derived from permeability is widely used to assess the difficulty level of methane flow in coal seams (Zhou, 1990). There have been many practical methods focused on obtaining the gas permeability coefficient of coal seams or cylindrical coal samples, including experimental measures, history simulation using production data, injection/falloff well test and geophysical logging measures (Li et al., 2011). Among them, the common steady-state test is to establish a relationship between pressure differences and gas flow rates through loading different pressures on both ends of a cylindrical coal sample, and then the gas permeability coefficient can be calculated by Darcy's law (Wang et al., 2017), but the scale effects caused by fractures cannot be neglected in this method. However, few studies have involved the permeation behavior of methane in coal particles that are considered as the fundamental units of raw coal. The small particles of coal are less affected by the fractures, but their permeability controlled by pores cannot be tested by the usual steady-state method. Moreover, the impacts of gas pressure and coal rank on the gas permeability coefficient of coal particles are not well understood.

These knowledge gaps are taken as the main objectives in this work for investigation. Concretely, a model of methane adsorption of coal particle based on Darcy's permeation is developed first, and an inversion approach is proposed to evaluate the gas permeability coefficient by matching simulation results with the experiment data of methane isothermal adsorption. Different from the usual steady-state test method, this research provides an unsteady-state test method to determine the permeability of granular coal samples, which is similar to the transient hot-wire method for measuring the thermal conductivity (Healy et al., 1976).

2. Coal samples collection

2.1. Properties of coal samples

Six coal samples were collected from five coal mines in Northern China, in which two samples came from two coal seams (#9, #10) of Shuiyu Coal Mine in Shanxi Province. These coal samples are in different coal ranks from lignite to anthracite, and their basic properties are shown in Table 1.

2.2. Pores test of coal samples

Mercury intrusion tests of six coal samples were conducted by PM33GT-18 (Quantachrom Co., US) (Avnir et al., 1984; Friesen and Mikula, 1987). This instrument can measure the range of pore diameter from 950 μm to 6.4 nm for its working pressure intervals at 0.0082–227.53 MPa. All coal samples were prepared in particle size of 180 μm–250 μm (60–80 meshes). The results are shown in Table 2. It indicates that the vast majority of pores volume in coal particle is occupied by macropores.

Table 1
Basic properties and coal ranks of coal samples.

Coal mine	M_{ad} (%)	A_{ad} (%)	V_{daf} (%)	FC_{ad} (%)	Coal rank
Wangniutan (WNT)	6.620	3.070	41.090	49.220	Lignite
Anze (AZ)	0.681	8.881	24.598	65.841	Medium-volatile bituminous
Shuiyu#10 (SY#10)	0.726	12.840	24.744	61.690	Medium-volatile bituminous
Shuiyu#9 (SY#9)	0.735	14.741	18.658	65.866	Low-volatile bituminous
Baijigou (BJG)	1.124	10.922	12.998	74.956	Low-volatile bituminous
Yangquanwu (YQW)	0.750	14.210	8.850	76.190	Anthracite

Table 2
Results of mercury intrusion.

Coal mine	V_t (cm^3/g)	Percentage of pores volume (%)			
		V_1/V_t	V_2/V_t	V_3/V_t	V_4/V_t
WNT	0.5659	0.97	7.14	8.73	83.16
AZ	0.7374	1.18	1.65	0.37	96.79
SY#10	0.6976	2.17	2.13	0.78	94.94
SY#9	0.7350	2.04	4.31	1.78	91.92
BJG	0.6697	1.03	0.88	0.13	97.96
YQW	0.7971	0.74	0.55	0.74	97.78

V_t—total pore volume; V_1—micropore (< 10 nm); V_2—transitional pore (10–100 nm); V_3—mesopore (100–1000 nm); V_4—macropore (> 1000 nm).

3. Methane adsorption model of coal particles and experiment

3.1. Methane adsorption model

There are two prerequisites that need to be clarified: (i) coal particle is treated as a spherical, homogeneous and isotropic porous medium; (ii) the adsorbed methane obeys the Langmuir Equation, and the free methane is regarded as ideal gas; (iii) the effects of moisture and water evaporation have not been considered in mathematical models. Consequently, the methane content of coal particle can be expressed as

$$X = \frac{abp_m}{1 + bp_m} + Bn_0 p_m \tag{1}$$

Where X is the existing volume of methane per mass coal, m^3/t; a is the saturated adsorption capacity, m^3/t; b is the adsorption constant, MPa^{-1}; p_m is the methane pressure, MPa; B is the coefficient, m^3/(t·MPa); n_0 is the porosity, %.

In this work, the transport of methane in coal particle is governed by Darcy's law as

$$v = -\frac{k}{\mu}\frac{\partial p_m}{\partial r} \tag{2}$$

Where v is the seepage velocity of methane, m/s; k is the permeability of coal, m^2; μ is the dynamic viscosity, MPa·s.

Based on Eq. (2), the specific flow rate of methane per unit area of coal surface (Zhou, 1990) can be expressed as