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Journal of Sustainable Mining

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Numerical modeling of gas flow in coal pores for methane drainage

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ARTICLE INFO

Article history:

Received 5 June 2016

Accepted 11 October 2016

Available online xxx

Keywords:

Coal mining

Methane drainage

Gas flow

Numerical simulation

ABSTRACT

The sudden explosion of methane during underground coal mining is a major dilemma. To mitigate its occurrence and reduce the extent of methane diffusion, gas drainage operations are carried out before mining. This paper investigates methane gas flow in a coal block in order to calculate the pressure of gas and its molecule velocity for methane gas drainage operation. A coal piece surrounded by cleats was used for geometrical modeling and numerical simulation. Movements of fluid and gas molecules in a porous medium were successfully simulated. The numerical solution is based on COMSOL Multiphysics software. The validity of the numerical simulation was assessed using an analytical model with satisfactory results.

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1. Introduction

Coal bed methane is one of the major causes of underground coal mine explosions. Despite the negative financial and environmental impacts of coal bed gas, it is still considered as a fuel source (MacDonald, 1990). Coal gasification is a sequence of thermochemical transformations taking place at high temperature between the organic part of coal matter and gasifying agents, such as oxygen, steam, air and carbon dioxide (Cempa-Balewicz, Laczny, Smolinski, & Iwaszenko, 2013). Methane is present within the natural pores of coal and micro pores of coal matrix, some of this methane is absorbed by coal molecules and bonded to them (Holditch, 1989). Coal seam gas content increases with depth and mining intensity in underground coal mines, and is a primary factor in mining safety and efficiency. Coal is a complex porous medium that consists of primary pores and fissures that result from tectonic movement, therefore, it has a large amount of free space and multiple pore surfaces. Coal seam gas exists in an adsorbed and free state. Only free gas can flow to a working face or be extracted (Wang, Wu, & Zhang, 2015). The amount of free state methane depends on many factors. These include:

- The structure and permeability of the overburden strata,
- Methane desorption rate from the unexploited gassy coal seams, which are distressed as a consequence of earlier mining,

- The spatial location of these unexploited coal seams in relation to the water level in a flooded mine (Krause & Pokryszka, 2013).

If underground coal seams are pressurized, coal molecules will be trapped within the seams. If there is a pressure drop (due to mining, construction of a front or gas drainage drilling), coal molecules will start to move towards the low pressure area. As coal has high potential for absorbing methane, coal seams will accumulate a considerable amount of gas. For example, 450 gm of coal has an absorbing surface of 46,500 m² (Sereshki, Aziz, & Porter, 2003). Although coal is of a porous nature with low permeability, its pore structure is far more complex than ordinary layers of other rocks (Soeder, 1991). Natural fractures and coal permeability create a route for gas and water to flow into coal seams from the cleats. Cleats in a coal seam are natural systematic fractures similar to those of sedimentary rocks (Kendall & Briggs, 1993). Cleat systems are among the features of gas reservoirs that influence the economic viability of gas drainage from coal seams. This affects the success or failure of such projects, and is influential in the progress of gas drainage operations (Dhir, Dern, & Mavor, 1991). Cleats are considered an indicator of permeability in coal that follows Darcy's law for water and gas. There are two sets of cleats, face and butt cleats which are orthogonal to each other (Gray, 1987). Face cleats usually have planar and smooth fractures and form the main part of the fracture system. The permeability of coal bed methane is 3–10 times greater in the direction of the face cleat, when compared to other directions (McCulloch, Duel, & Jeran). In coal seams, there is a two-phase flow of gas into the well bore. In the first phase, the

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E-mail address: Adel_Taheri@Shahroodut.ac.ir (A. Taheri).<http://dx.doi.org/10.1016/j.jsm.2016.10.001>2300-3960/© 2016 Central Mining Institute in Katowice. Production and hosting by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

absorbed methane diffuses through the micro pores of the coal matrix and reaches the natural fracture (cleats). In the second phase, the gas flow passes through the face and butt cleats and reaches the well bore, depending on the pressure differentials as described by Darcy law (Harpalani & Schraufnagel, 1990). The flow of methane is a function of effective coal permeability. According to mathematical and computerized models of methane drainage, the distance between micro pores and cleats plays an important role in methane gas flow in coal seams (Harpalani, Zhao, & Farmer, 1992). In an undisturbed coal seam, however, methane molecules remain in the micro pores of the coal matrix (Solano, Mastalerza, & Schimmelmann, 2007).

In this study, a two dimensional coal matrix model surrounded by rectangular blocks, is developed for gas drainage through two face and butt cleats. It is assumed that there are only six pores in each coal matrix block. The methane that diffuses through the micro pores and cleats will eventually reach the main fractures. These joints allow diffused methane to enter the wellbore. The COMSOL Multiphysics software was incorporated to simulate this phenomenon, which is the subject of the paper.

2. Materials and methods

A simulation of the process of gas flow from micro pores inside coal towards cleats was developed. In this simulation, the method of mass and energy transfer was applied. Firstly, general equations for mass transfer in a porous space were defined. Subsequently, the method of Probability Density Function (PDF) was adopted for the process of methane gas diffusion in coal (Society of Composite energy, 2014). This method is based on solving the equation for the movement of a mixture in a closed medium where the combination of mass and energy remains constant (Janoszek, Laczny, Stanczyk, Smolinski, & Wiatowski, 2013). Other assumptions applied in model development include:

1. Methane gas flow inside the cleats is laminar and follows Darcy's law,
2. Temperature remains constant in the coal environment during the gas extraction process,
3. Cleats are straight and without any twists,
4. There are no coal particles in these cleats,
5. No matrix shrinkage occurs due to methane drainage,
6. Permeability is postulated to follow Klinkenberg's law,

The continuity function for the gas phase of a fluid is extended as (Table 1 defines parameters used in these equations):

$$-\left(\frac{1}{r}\right)\left(\frac{\partial}{\partial r}\right)\left[\frac{rP_a}{Z_{pa}}\vec{v}\right] + \frac{RT}{M}\frac{q_m}{V_{ba}} + \frac{RT}{M}\frac{q_{ai}}{V_{ba}} = \phi_a\frac{\partial}{\partial t}\left[\frac{P_a}{Z_{pa}}\right] \quad (1)$$

According to Darcy's law, the equation for the flow in a fracture

is defined as:

$$\vec{v} = -\left[\frac{k}{\mu}\right]\left(\frac{\partial P_a}{\partial r}\right) \quad (2)$$

By substituting Equation (2) in Equation (1):

$$\left(\frac{1}{r}\right)\left(\frac{\partial}{\partial r}\right)\left[\frac{krP_a}{Z_{pa}\mu}\left(\frac{\partial P_a}{\partial r}\right)\right] + \frac{TP_{SC}}{T_{SC}}\frac{q_{SC}}{V_{ba}} + \frac{RT}{M}\frac{q_{ai}}{V_{ba}} = \phi_a\frac{\partial}{\partial t}\left[\frac{P_a}{Z_{pa}}\right] \quad (3)$$

According to Fick's law of diffusion, the flow in pores is obtained using:

$$\left(\frac{1}{r}\right)\left(\frac{\partial}{\partial r}\right)\left[rD\left(\frac{\partial C}{\partial r}\right)\right] = \left(\frac{\partial C}{\partial t}\right) \quad (4)$$

Values of gas absorption and drainage are determined from Langmuir's equation:

$$V_E = \frac{V_{\infty}P}{P + P_L} \quad (5)$$

The total concentration of the gas in a coal matrix per unit of volume is obtained using the following relationship:

$$C = \left(\frac{PM\phi_i}{ZRT}\right) + \left[\frac{V_{\infty}P}{P + P_L}\right] \quad (6)$$

By introducing the value of C from Equation (4), the following governing equation for numerical simulation is obtained (Janoszek et al., 2013):

$$\left(\frac{1}{r}\right)\left(\frac{\partial}{\partial r}\right)\left[rD\left(\frac{\partial}{\partial r}\left\{\left(\frac{PM\phi_i}{Z_pRT}\right) + \left[\frac{V_{\infty}P}{P + P_L}\right]\right\}\right)\right] = \frac{\partial}{\partial t}\left[\left(\frac{PM\phi_i}{Z_pRT}\right) + \left[\frac{V_{\infty}P}{P + P_L}\right]\right] \quad (7)$$

3. Results and discussion

As with every numerical simulation, the model characteristics including interface thickness, mesh size and diffusion coefficient were determined (Akhlaghi Amir, & Hamouda, 2013). For this purpose, the pores in which the gas diffuses were plotted in the coal block. It was assumed that there were six gas pores in each 100 × 200 mm coal block. The geometry and other relevant required data were introduced to the software as shown in Fig. 1.

Pores containing methane gas and the rectangular coal blocks have the characteristics as shown in Fig. 2. Also, the material parameters used in the numerical simulation are listed in Table 2.

The Finite Element method with interfacial adaptive mesh refinement was employed to solve the governing equation (Akhlaghi Amir, & Hamouda, 2014). Since the software is based on

Table 1
Relevant parameters used for model development.

Symbol	Description	Symbol	Description
C	Gas concentration in coal matrix (kg/m ³)	t	Time (s)
D	Diffusion coefficient (cm ² /Sec)	T	Temperature (K)
K	Permeability md	V _E	Equilibrium isotherm (kg/m ³)
M	Molecular weight (kg/kmol ³)	V _∞	Langmuir volume constant (kg/m ³)
P	Pressure psi (kPa)	Z	Gas compressibility factor
P _L	Langmuir pressure constant (psi, kPa)	M	Viscosity cp
Q	Volumetric flow rate(std m ³ /s)	P	Density(kg/m ³)
q _m	Mass flow rate (kg/s)	ϕ	Porosity
R	Universal gas constant		

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