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Study on gas seepage from coal seams in the distance between boreholes for gas extraction

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ABSTRACT

In order to research the influence of coal gas seepage law between boreholes for gas extraction, the gas seepage model was established based on the mass conservation equation, Darcy's law, Langmuir adsorption analytic equation, Klinkenberg equation of coal gas, effective stress equation, as well as porosity and permeability dynamic equation. Three-dimensional numerical simulation of coal gas seepage in the surrounding borehole of gas extraction was conducted by the COMSOL Multiphysics software. The law of gas pressure distributions, gas seepage velocity distributions and permeability change were given between two drilled boreholes and around the two boreholes. In order to determine the reasonable spacing of the drilling holes, by simulating the result of the gas pressure drop in different spacing, the arrangement position of the observation hole of the gas pressure is 1/2 along the distance of the drilling test along the center line of the two extraction drilling line. If the gas pressure can be reduced by more than 50% in the pre pumping period, it is indicated that the interval between two holes is a reasonable distance, which will not cause the blank area of extraction, and will not form the superposition area of invalid extraction, which can guarantee the effectiveness of coal mine gas extraction.

1. Introduction

Due to limits of natural conditions and permeability for coal seams, China has low efficiency in gas extraction. Therefore it is urgent to conduct in-depth study on gas seepage law of coal seams.

By designing a gas flow device, Gilman and Beckie (2000) explored the influence of coal dust particles and porosity on the seepage law of gas. Tanikawa and Shimamoto (2009) compared the seepage characteristics of gas in sedimentary rock and liquid water. The results indicated there was a more obvious Kerr effect being found under the conditions including small pore pressure and low-permeability media. Valliappan and Zhang (1996) developed the finite element model of gas migration by combining non-linear gas flow and linear solid deformation equation to analyze the coupled problem of gas pressure, mass transfer and medium deformation when methane gas moved in coal seams. The microscopic coupling constitutive model of coal was established through analyzing the computational process of combined discrete and finite element method by Owen et al. (2004). Karacan et al. (2007) constructed the 3D reservoir model of long-wall face by making use of GEM software, and simulated the effect of different borehole configuration and spacing of in-seam horizontal methane drainage on long-wall face gas drainage. Zagorščak and Thomas (2017) investigated the results of an experimental investigation on gas flow and Klinkenberg effect in coal, the sample was subjected to a range of effective stress conditions in order to investigate a general trend of coal permeability reduction with an increase in effective stress. Jasinge et al. (2011) studied how the change in effective stress and coal swelling may influence the gas permeability in brown coal using natural coal and reconstituted coal specimens. Robertson (2005) improved the accuracy of the permeability model by Langmuir adsorption analytic equation. Harpalani and Schraufnagel (1990) studied the shrinkage and gas release of coal matrix and its influence on coal permeability. Lin and Zhou (1987) investigated the relationship between pore pressure and gas permeability, and the relationship between pore pressure and the deformation of the coals containing gas under a constant confining pressure. Sun (1989) derived an equation for solving the parameters of reasonable borehole arrangement according to two parameters—effective radius and borehole spacing on the basis of coal gas dynamics. Some researchers investigated the effects of confining, axial pressure and pore pressures on gas seepage under a triaxial loading and fitted the empirical correlation of confining, axial and pore pressures with gas permeability coefficient based on Darcy's law (Li et al., 2010;

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Yin et al., 2008, 2009). Peng et al. (2012), by using the self-developed triaxial servo-controlled seepage equipment for thermo-fluid–solid coupling of coal containing gas, experiments to study the influence mechanism of gas seepage on coal and gas outburst disasters. Wang et al. (2013) experimentally investigated the effects of factors including gas desorption, stress level and loading rate on the mechanical behaviors of coals containing gas.

However, most of literature do not sufficiently focus on gas seepage law of boreholes for gas extraction. Borehole spacing is also an important factor affecting the gas drainage efficiency. The existing method to determine the spacing of drilling holes is a simple method of using a single hole to inspect the extraction radius of 2 times or $\sqrt{2}$ times (Yang et al., 2018). By studying 2 times of the extraction radius as the distance of the drill holes, a large area of blank area will be produced. When $\sqrt{2}$ times of the extraction radius is used as the spacing of the drilling holes, the invalid superposition area of the drilling holes will be formed, which causes the waste of the suction pressure, the manpower cost and the sealing material.

In this paper, the velocity field of gas seepage, the law of pressure distribution and the law of permeability change between the drilling holes are studied, and the reasonable spacing of the drilling holes is determined and the reasonable arrangement position of the observation hole of gas pressure is put forward.

2. The establishment of a mathematical model for the gas seepage from boreholes in gas extraction

Gas that is present in the form of adsorption state in coal seam accounts for more than 80% of total gas content. Free gas in coal seams mainly sources from in desorption and diffusion process. The structure and gas occurrence of coal seams can directly affect the migration of gas in coal seams. Generally, gas exists in coal seams at a pressure-bearing state. However, mining activities including mining, excavation and drilling tend to damage the equilibrium state of gas pressure which is initially present in coal seams, and gas is likely to be transported from high-pressure to low-pressure zones under the effects of pressure gradient.

The governing equations affecting the gas seepage in the coal body mainly include the mass conservation equation, Darcy's law, Langmuir adsorption analytic equation, coal seam gas Klinkenberg equation, effective stress equation, porosity and permeability dynamic equation.

2.1. 1. Mass conservation equation

The seepage migration of gas in coal follows mass conservation law and is written as:

$$\frac{\partial M}{\partial t} + \nabla(\rho_g u_g) = Q_p \tag{1}$$

Where M denotes gas content, kg·m^{-3}; t is time, s; ρ_g represents the gas density of coal, kg·m^{-3}; u_g is gas seepage velocity of Darcy's law, m·s^{-1}; Q_p denotes source-sink flow, kg·m^{-3}·s^{-1}.

2.2. 2. Darcy's law

The migration seepage laws of gas containing in pores, cracks and cleat of coal seams have been extensively studied worldwide. Darcy's law was the linear seepage law proposed by Darcy, which is a typical gas seepage law. According to the Darcy's law, gas migration within coal seams basically conforms to the linear seepage law.

Darcy's law can describe the gas flow under the effect of fluid pressure gradients in fluid potential field for porous media. The seepage of gas in coal therefore can be demonstrated by Darcy's law. In terms of physics, pressure is dependent variable. The free gas in porous media is found having linear seepage motion under non-equilibrium pressure state. The seepage motion follows Darcy's law and is expressed as

$$u_g = -\frac{K_g}{\mu_g}(\nabla p + \rho_g g D) \tag{2}$$

K_g represents the seepage amount of gas of coal mass under the effects of gas pressure, m^2: μ_g is the absolute viscosity of gas in coal seams, Pa·s; P is the gas pore pressure of coal seams, Pa; g denotes gravity acceleration, m·s^{-2} and D is rectangular coordinate, m.

2.3. 3. Langmuir adsorption equation

Gas usually exists in pores and cracks within coal mass at two types of states (adsorption and free states), among which, 80%–90% of total gas is present in adsorption state, while the rest of 10%–20% gas exists in free state in pores and cracks of coal seams. The gas content of coal rocks satisfies the Langmuir equation (Gao, 2013):

$$M = \beta\left(\frac{\phi}{p_0} + \frac{ab\rho_s}{1 + bp}\right)p^2 \tag{3}$$

Where ϕ denotes the porosity of coals, %; P_0 is the air pressure boundary, Pa; a refers to extreme adsorption amount of coal rocks, m^3/kg; b is the adsorption equilibrium constant of coal rocks, Pa^{-1}; ρ_s denotes the density of coals, Kg·m^{-3}; β represents compressibility factor and p is the gas pore pressure of coal seams, Pa.

2.4. 4. Klinkenberg equation of coal gas

The linear distance that refers to an individual gas molecule's motion trajectory from the region ranging between two adjacent collision points to outside is defined as the free path of gas molecules in motion state. In the test, when the measured mean free path value of gas molecules was close to the diameter of test tube, slippage phenomena occur to molecules, which is called as slippage effect, namely, Klinkenberg effect (Klinkenberg, 1941). The permeability of coal is expressed as:

$$k_g = k_\infty\left(1 + \frac{\alpha_k K_\infty^{-0.36}}{p}\right) \tag{4}$$

Where k_g represents the seepage amount of gas under current gas pressure, m^2; K_∞ refers to the absolute seepage amount of gas under larger gas pressure when the effect of Klinkenberg is negligible, m^2; α_k is an effective coefficient and P denotes the gas pore pressure of coal seams, Pa.

By substituting equation (4) into equation (2), and then equations. (2) and (3) were substituted into equation (1) to derive the coupling equation of gas seepage (Yang et al., 2010):

$$\beta\left[\frac{\phi}{p_0} + \frac{ab\rho_s}{1+bp} - \frac{ab^2\rho_s}{2(1+bp)^2}\cdot p\right]\frac{\partial p^2}{\partial t} - \nabla\cdot\left[\beta\frac{K_\infty}{\mu_g}\left(1 + \frac{\alpha_k K_\infty^{-0.36}}{p}\right)\nabla p^2\right] = Q_p \tag{5}$$

2.5. 5. Effective stress equation

Coal rocks containing gas were seen as elastic-plastic media, while coal containing gas was a type of porous medium and the stress state of coal skeleton follow Terzaghi's effective stress principle

$$\sigma'_{ij} = \sigma_{ij} + \alpha p \delta_{ij} \tag{6}$$

Where σ_{ij} is total stress, MPa; σ'_{ij} refers to effective stress, MPa; p is the pore pressure, MPa; α represents equivalent pore pressure coefficient, $0^<\alpha^<1$; δ_{ij} is the symbol of Kronecker, $\delta ij = \begin{cases} 0 & (i = j) \\ 1 & (i \neq j) \end{cases}$.

In the establishment of the mathematical model based on coal rocks containing gas, coal rocks were assumed to be isotropic perfect elastoplastic body so as to facilitate simplifying the mathematical model with