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3D numerical simulation of boreholes for gas drainage based on the pore–fracture dual media

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ABSTRACT

A gas migration controlling equation was formulated based on the characteristics of the dual pore–fracture media of coal mass and in consideration of the matrix exchange between pores and fractures. A model of permeability dynamic evolution was established by analyzing the variation in effective stress during gas drainage and the action mechanism of the effect of coal matrix desorption on porosity and fracture in the coal body. A coupling model can then be obtained to characterize gas compressibility and coal deformability under the gas–solid coupling of loading coal. In addition, a 3D model of boreholes was established and solved for gas drainage based on the relevant physical parameters of real mines. The comparison and analysis results for the law of gas migration and the evolution of coal body permeability around the boreholes before and after gas extraction between the dual media and the single-seepage field models can provide a theoretical basis for further research on the action mechanism of gas drainage.

1. Introduction

Gas drainage can considerably reduce the gas content of a single coal seam as well as the occurrence probability of dynamic gas accidents. The gas extracted from coal seams can also be used as a type of clean energy. Constructing boreholes can break the initial stress state of the coal body around the drilling holes; moreover, the permeability of the surrounding coal body also changes with stress. The stress and the gas flow fields are two important components of the mechanical environment of the coal body around boreholes. These two fields interact with each other, and their coupling effect should be considered. The fluid–solid coupling effect of the loaded coal that contains gas has recently been studied to enhance gas drainage theory. By adopting the basic theory of coal mass deformation and gas seepage, Yang established a solid–gas coupling model that considers coal adsorption–desorption to simulate and analyze coal permeability and gas pressure during gas drainage under different confining pressures [1]. Yin adopted the gas–solid coupling model and studied the effect of gas drainage given various extraction pressures, apertures, and extraction times by applying the related physical parameters of the coal in the 10# mine of Pingdingshan Coal Group [2]. Si followed a series of assumptions regarding coal bed methane, formulated the porosity and the permeability equations of the coal body, presented a fluid–solid coupling model, and simulated the law of gas migration under the drainage condition [3]. Ding considered the mass conservation law and gas flow theory, established a gas drainage flow model, and drilled boreholes for gas drainage along a coal seam to compare and analyze the difference between the results of numerical simulation and the actual conditions of gas drainage in coal mines [4]. This researcher also identified the gas drainage parameters that fitted the coal seam. Xiao established a gas seepage model and studied gas migration law through numerical calculation in consideration of the Klinkenberg effect [5]. Hu derived the dynamic fluid–solid coupling model of coal with low permeability and generated the numerical solution of the coupled model according to the setting conditions of the gas-containing coal mass and the model parameters [6]. This researcher determined that the simulation results are consistent with the experimental results.

In conclusion, previous research established a gas flow equation based on Darcy's law and mass conservation law; nonetheless, these works consider only a single-seepage flow field and take into account the effect of the amounts of pore compression and adsorption expansion on coal permeability [7–14]. A coal body is a porous media containing porous matrix with cracks. The pores and cracks play significant roles in gas storage, migration, and production. Thus, the flow-solid coupling model of the coal body around a

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borehole is developed based on the characteristics of the dual-porosity media of the coal body given the mass exchange between the pores and cracks. In the present study, a 3D physical model was established based on the actual condition of coal seams in a sample coal mine of Yi'an. A numerical simulation is performed to analyze the influence of the existing mass exchange capacity between pores and fractures on the gas migration and permeability evolution characteristics of the coal body around boreholes. The results of this analysis provide a scientific, theoretical basis for borehole gas drainage.

2. Fluid–solid coupling model of dual porosity media

2.1. Gas migration equation

Gas-containing coal can be considered a dual-porosity media composed of a coal particle system and a fracture splitting system. The coal particle system primarily contains pores. Fig. 1 presents Warrant-Root's dual media model; once the original coal seam is disturbed by external factors, the initial state of the adsorption dynamic equilibrium of coal is disrupted. Thus, the free state gas in the fracture system flows to the excavation space as seepage and can induce differences in pore pressure. Finally, the gas adsorbed in the pore system continuously desorbs and flows to the fracture system through diffusion. The speed of gas seepage is significantly greater than the velocity of gas diffusion; therefore, the gas desorbed from the pore system continuously flows to the fracture system. In the process, gas mass exchange q_m occurs between the pore system and the fracture system. Based on the aforementioned analysis and the fact that gas-containing coal is a dual-porosity media, this work develops a fluid–solid coupling model for dual-porosity media in consideration of the gas mass exchange q_m between the pore system and the fracture system. This model is based on the mechanism of gas desorption–diffusion–flow.

2.1.1. Gas migration equation in the pore system

According to the mass conservation principle, the outflow quantity from the micro-body is subtracted from the inflow quantity to the interior of the body per unit time for any micro-body within a pore system. The matter exchange quantity q_m is subtracted from the above resultant value, whose value is equal to the amount of quality change in the pore micro-body per unit time:

$$\frac{\partial C}{\partial t} = -\nabla M - q_m \quad (1)$$

where C is the mass concentration of gas in the adsorption state, kg/m^3; ∇ is the Hamiltonian operator; M is the diffusion flux vector of adsorbed gas; and q_m is mass exchange, kg/(m^3 s).

In the pore system, gas flows through diffusion because of the concentration gradient. According to Darcy's law, the gas migration equation in the pore system is expressed as follows:

$$\frac{\partial C}{\partial t} = D\nabla^2 C - q_m \quad (2)$$

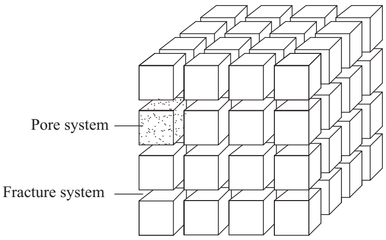

Fig. 1. Warrant-Root's dual media model.

where D is the diffusion coefficient, m^2/s.

In the pore system, the content of gas in the adsorbed state fits the Langmuir isothermal adsorption equation. Considering the effect of moisture and ash on adsorption gas content, this content can be expressed as follows per unit volume:

$$C = \frac{abcp_n p}{(1+bp)RT} \quad (3)$$

where a is the adsorption capacity limit of unit coal mass, m^3/kg; b is the adsorption constant of coal, MPa^{-1}; c is the quantity of combustible material in coal per unit volume, kg/m^3; p_n is air pressure (101,325 Pa) under the standard condition; p is the gas pressure in the free state, Pa; R is the gas constant (8.3145 J/(kg K)) of methane; and T is the temperature of the coal body, K.

The gas migration equation can be obtained as follows by simultaneously calculating Eqs. (1)–(3) and omitting the two-order trace:

$$\frac{\partial p}{\partial t} = D\nabla^2 p - \frac{(1+bp)^2 RT}{abc\rho_n} q_m \quad (4)$$

2.1.2. Gas migration equation in the fracture system

According to the mass conservation principle, the outflow quantity from the micro-body is subtracted from the inflow quantity to the interior of the body per unit time for any micro-body within the fracture system. The resultant value is added to matter exchange quantity q_m, whose value is equal to the amount of quality change in the pore micro-body per unit time:

$$\frac{\partial(\varphi\rho)}{\partial t} = -\nabla(\rho v) + q_m \quad (5)$$

where φ is the porosity of the coal body; ρ is the density of gas in the free state, kg/m^3; and v is the seepage velocity of gas, m/s.

Gas flows through seepage in the fracture system. Seepage velocity can be determined as follows by considering the Klinkenberg effect [15] and Darcy's law:

$$v = -\frac{k}{\mu}\left(1+\frac{m}{p}\right)\nabla p \quad (6)$$

where k is the permeability of the coal rock mass, m^2; μ is the dynamic viscosity of gas, Pa s; and m is the Klinkenberg coefficient, Pa.

According to the ideal gas state equation,

$$\rho = \frac{p}{RT} \quad (7)$$

When the influence of pore pressure and strain on porosity is considered, the porosity variation in the porous media during the isothermal process can be expressed as follows [16]:

$$\frac{\partial\varphi}{\partial t} = (1-\varphi)\left(\frac{\partial\varepsilon_v}{\partial t} + \frac{1}{K_s}\frac{\partial p}{\partial t}\right) \quad (8)$$

where ε_v is the volumetric strain of the coal body and K_s is the bulk modulus of coal.

The gas migration equation in the fracture system can be obtained as follows by simultaneously calculating Eqs. (5)–(8):

$$p(1-\varphi)\frac{\partial\varepsilon_v}{\partial t} + \left[\frac{p(1-\varphi)}{K_s} + \varphi\right]\frac{\partial p}{\partial t} = \nabla\left[\frac{k}{2\mu}\left(1+\frac{m}{p}\right)\nabla p^2\right] + RTq_m \quad (9)$$

2.1.3. Mass exchange q_m

According to the analysis above, the initial adsorption equilibrium state is disrupted when the coal seam is affected by coal min-