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Coal permeability evolution with the interaction between nanopore and fracture: Its application in coal mine gas drainage for Qingdong coal mine in Huaibei coalfield, China

Leilei Si[a,b], Zenghua Li[a,b,*], Yongliang Yang[a,b]

[a] Key Laboratory of Gas and Fire Control for Coal Mines (China University of Mining and Technology), Ministry of Education, Xuzhou, 221116, China
[b] School of Safety Engineering, China University of Mining and Technology, Xuzhou, 221116, China

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ABSTRACT

Permeability plays a significant role on CBM. However, the gas flow mode in nanopore and fracture is different, resulting in the confusion of gas flow mechanism. In this work, a dual-permeability model was constructed with the nanopore permeability and fracture permeability. Then, the impact of adsorption layer, elastic modulus reduction ratio, adsorption effect and stress on the evolution of pore parameters were investigated to reveal the interaction mechanism between nanopore and fracture. Finally, this model was carried out to analyze the coal mine gas drainage of Qingdong coal mine. Results show that, the adsorption layer primarily controls the effective pore radius and thus impacts the nanopore permeability and total permeability. The elastic modulus reduction coefficient can affect the fracture porosity and thus change the fracture permeability, gas mobility and equilibrium pore pressure. Then, the effective pore radius, nanopore porosity and nanopore permeability are affected. For the adsorption effect, it can notably affect the effective pore radius, nanopore porosity and fracture porosity. It is noticed that its effect focuses on the evolution process. Furthermore, the effective pore radius, nanopore porosity and fracture porosity are controlled by stress and the fracture porosity is more sensitive to the stress. Finally, the permeability model can match the field test results well, indicating that our model can be used to estimate gas drainage effect and relief zone for gas pressure. In addition, for the different reservoirs, once the coal basic parameters were determined, the gas production and gas permeability can be estimated by using this model. Therefore, it is important for guiding the gas drainage in coal mine gas prevention and control.

1. Introduction

Coal mine gas is regarded as a kind of clean energy source, which is widely used as the fuel and industrial raw materials (Pan and Connell, 2011; Peng et al., 2017; Qin et al., 2017; Sharma et al., 2017; Vishal et al., 2013; Ziarani and Aguilera, 2011). However, in the process of mining, mine gas disaster is one of the most serious disasters, which is called the “first killer” of coal mine safety. Further, coal, natural porous media, possesses complex heterogeneous pore/fracture structure, leading to the dimness of gas flow mechanism. In addition, the gas flow in coal seam is also controlled by the effective stress, sorption-induced swelling deformation and variable porosity. Moreover, for different reservoirs, the proportion of pore or fracture is different, causing the traditional single porosity is unable to evaluate the gas permeability (Ashrafi Moghadam and Chalaturnyk, 2014; Brunauer et al., 1938; Cheng et al., 2017; Vishal, 2017; Wang et al., 2014b). Therefore, it is significant to construct a cross-coupled gas flow model and investigate the effect of these factors on the gas flow.

As we all know, coal contains lots of the pore and fracture. Over the past few decades, many works have been carried out to investigate the evolution of gas permeability in fracture (Hu et al., 2018; Wang et al., 2014a; Zhai et al. 2016, 2018;Zhang et al. 2012, 2018; Zhu et al., 2007). Palmer and Mansoori (1996) constructed a permeability model with the sorption-induced swelling deformation and stress-induced compression deformation, and investigated the evolution of porosity and permeability. Shi and Durucan (2005) used a compression coefficient to describe the coal deformation, and then constructed a permeability model with the effect of effective stress. Robertson and Christiansen (2006) proposed a permeability model with variable fracture width, and then investigated the gas permeability evolution under different conditions (constant pore pressure conditions and constant stress conditions). These models only considered the gas flow in fracture while the gas flow in pore was neglected. More recently, a series of dual-porosity permeability models were constructed. Liu et al.

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[*] Corresponding author. Key Laboratory of Gas and Fire Control for Coal Mines (China University of Mining and Technology), Ministry of Education, Xuzhou, 221116, China.
E-mail address: lizenghua@cumt.edu.cn (Z. Li).

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List of symbols

k_m	Gas permeability in nanopore (m^2)
k_e	Total gas permeability (m^2)
k_f	Fracture permeability (m^2)
ϕ_m	Nanopore porosity
ϕ_{m0}	Initial nanopore porosity
ϕ_f	Fracture porosity
ϕ_{f0}	Initial fracture porosity
r_e	Effective pore radius (m)
r_0	Initial nanopore radius (m)
r	Nanopore radius (m)
d_g	Gas diameter (m)
a	Initial matrix width (m)
b	Initial fracture width (m)
τ	Pore tortuosity
α	Biot's coefficient
K	Bulk modulus of coal (MPa)
K_s	Bulk modulus of the coal grains (MPa)
E_m	Young's modulus of the coal matrix (MPa)
$\overline{\sigma}$	Average stress (MPa)
p	Pore pressure (MPa)
σ_e	Effective stress (MPa)
P_L	Langmuir pressure constant (MPa)
G	Shear modulus (MPa)
ε_s	Sorption-induced volumetric strain
ε_L	Langmuir volumetric strain constant
ε_v	Volumetric strain of the coal matrix
ψ	Modification coefficient of adsorption layer
R_m	Elastic modulus reduction coefficient
m	Gas mass (kg)
ρ	Gas density (kg/m^3)
q	Darcy's velocity (m/s)
μ	Dynamic viscosity (Pa·s)
ρ_{ga}	Gas density at standard conditions (kg/m^3)
M_a	Molar mass of methane (kg/mol)
T	Gas temperature (K)
ρ_c	Coal density (kg/m^3)
V_L	Langmuir volume constant (m^3/kg)
υ	Poisson's ratio
δ_{ij}	Kronecker delta

(2015) constructed a dual-porosity model and then analyzed the evolution of pore pressure and fracture pressure. A non-equilibrium permeability model was built by Liu et al. (2017b), who investigated the gas permeability evolution under non-equilibrium state. Liu et al. (2010) proposed a stress-controlled dual-permeability model based on the cubic model, and deemed that the matrix swelling would not affect coal permeability because of the complete separation between matrix blocks caused by through-going fractures. However, these works ignored the pore permeability is different from the fracture permeability. Coal is composed of complex pore/fracture system. Therefore, it is very important to construct a model with pore permeability and fracture permeability.

In addition, many studies investigated the effect of different influencing factors on the gas permeability, such as effective stress, matrix swelling, Klinkenberg's effect, variable porosity and so on (Cai et al., 2017; Chareonsuppanimit et al., 2014; Connell, 2016; Hou et al., 2017; Seomoon et al., 2015; Wang et al., 2017; Yang et al., 2017; Yu et al., 2017). For the fracture permeability, some works deemed that matrix swelling plays a significant role in the gas permeability, and found that the gas permeability is decreased with the pore pressure because the swelling deformation leads to the reduction in fracture width (Chen et al., 2011). Zhou et al. (2016) proposed a fracture permeability model with variable Klinkenberg's factor, and thought that Klinkenberg's effect can notably improve the gas permeability. Liu et al. (2017a) investigate the impact of matrix–fracture interactions on the gas permeability, and studied the effect of internal swelling on the evolution of gas permeability under different conditions. However, these works ignored the effect of nanopore porosity on the fracture porosity. For the gas flow in nanopore, Wang et al. (2015) constructed a nanopore permeability model, and analyzed the effect of the gas diffusion and adsorption layer on the gas permeability. However, the sorption-induced variable porosity is neglected. Therefore, Cao et al. (2016) proposed a nanopore permeability with adsorption effect, and then investigated the gas permeability under different reservoirs and constructed a general gas permeability model for porous media. However, for all these model ignored the interaction between nanopore and fracture.

In this work, we tried to constructed a coal porosity model with nanopore and fracture. Then, the nanopore permeability model and fracture permeability model were proposed, respectively. Further, the effect of adsorption layer thickness, elastic modulus reduction coefficient, sorption-induced swelling deformation and stress on the evolution of effective pore radius, nanopore porosity and fracture porosity were investigated to reveal the interaction between nanopore permeability and fracture permeability. Finally, the permeability model was carried out to analyze the gas drainage of 824 working face in Qingdong coal mine, Huaibei coalfield.

2. Modeling

In this paper, we constructed a dual-permeability model, considering the gas permeability in nanopore and fracture. For the nanopore, the effective stress, sorption-induced swelling deformation and adsorption layer thickness is considered. For the fracture, it is only affected by the effective stress. The detailed modeling process is described as follows.

2.1. Gas permeability in nanopore

Some studies showed that the gas permeability in nanopore can be defined as (Cao et al., 2016; Wang et al., 2015):

$$k_m = \frac{\phi_m r_e^2}{8\tau} \tag{1}$$

where k_m is the gas permeability in nanopore (m^2), ϕ_m is the nanopore porosity, r_e is the effective pore radius, (m), and τ is the pore tortuosity.

For coal seam, the porosity is affected by stress, gas pressure and sorption-induced swelling. Therefore, the porosity can be defined as (Zhang et al., 2008):

$$\phi_m = \phi_{m0} - \frac{\alpha}{K}(\Delta\overline{\sigma} - \Delta p) - \Delta\varepsilon_s \tag{2}$$

where ϕ_{m0} is the initial nanopore porosity, α is the Biot's coefficient; $\alpha = 1 - K/K_m$, where K is the Bulk modulus of coal (MPa), and K_s is the Bulk modulus of the coal grains (MPa), where $K = \frac{E}{3(1-2\upsilon)}$ and $K_m = \frac{E_m}{3(1-2\upsilon)}$, where E_m is the Young's modulus of the coal matrix (MPa), $\overline{\sigma}$ is the average stress (MPa), and $\overline{\sigma} = \frac{\sigma_{kk}}{3}$, where σ_{kk} is the stress component in the positive direct, and $\sigma_{kk} = \sigma_{11} + \sigma_{22} + \sigma_{33}$, p is the pore pressure (MPa), and ε_s is the sorption-induced volumetric strain, where $\varepsilon_s = \frac{\varepsilon_L p}{P_L + p}$, where ε_L is the Langmuir volumetric strain constant, and P_L is the Langmuir pressure constant (MPa).

Then, Eq. (2) can be converted to be a strain-controlled type:

$$\phi_m = \frac{\phi_{m0}(1 + \varepsilon_{v0} + p_0/K_m - \varepsilon_{s0}) + \alpha(\Delta\varepsilon_v + \Delta p/K_m - \Delta\varepsilon_s)}{1 + \varepsilon_v + p/K_m - \varepsilon_s} \tag{3}$$