International Journal of Mining Science and Technology 27 (2017) 681–685

Contents lists available at ScienceDirect

International Journal of Mining Science and Technology

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

Numerical simulation of gas migration into mining-induced fracture network in the goaf

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ARTICLE INFO

Article history:
Received 11 December 2016
Received in revised form 17 February 2017
Accepted 17 March 2017
Available online 19 May 2017

Keywords:
Gas migration
Fractures
Mining-induced
Numerical simulation

ABSTRACT

Gas extraction practice has been proven for the clear majority of coal mines in China to be unfavorable using drill holes in the coal seam. Rather, mining-induced fractures in the goaf should be utilized for gas extraction. To study gas migration in mining-induced fractures, one mining face of 10th Mine in Pingdingshan Coalmine Group in Henan, China, has been selected as the case study for this work. By establishing the mathematical model of gas migration under the influence of coal seam mining, discrete element software UDEC and Multiphysics software COMSOL are employed to model gas migration in mining-induced fractures above the goaf. The results show that as the working face advances, the goaf overburden gradually forms a mining-induced fracture network in the shape of a trapezoid, the size of which increases with the distance of coal face advance. Compared with gas migration in the overburden matrix, the gas flow in the fracture network due to mining is far greater. The largest mining-induced fracture is located at the upper end of the trapezoidal zone, which results in the largest gas flux in the network. When drilling for gas extraction in a mining-induced fracture field, the gas concentration is reduced in the whole region during the process of gas drainage, and the rate of gas concentration drops faster in the fractured zone. It is shown that with gas drainage, the gas flow velocity in the mining-induced fracture network is faster.

1. Introduction

The geological conditions of coal seams in China are complex and their permeability is generally low. Gas extraction practice has been proven for the clear majority of coal mines in China to be unfavorable using drill holes in the coal seam. Rather, mining-induced fractures in the goaf should be utilized for gas extraction. In the process of longwall coal mining, the surrounding rock stress is redistributed and generates mining-induced fractures. This is not only favorable for gas desorption off the coal mass, but also it increases the permeability of the coal, thus creating a gas flow channel in the coal and rock mass near the working face. Therefore, research on gas migration into mining-induced fractures above the goaf can provide useful insight, and help optimize the drainage system in terms of pressure-relief and maximize gas extraction rate.

Numerous scholars have carried out research on gas migration laws in mining-induced fracture field above the goaf. Qian and Xu studied the distribution characteristics of mining-induced fractures in the overlying strata by means of model experiments, image analysis and discrete element simulation [1]. They revealed that a two-stage fracture pattern develops due to mining, in the form of an "O-shape" circle in the long wall face. They also provided a guide to drill hole pattern for relieving gas drainage. Li examined mining-induced fracture field formation and characteristics of fractures above the goaf and in front of the working face [2]. Tu and Liu researched the formation, development, closure and variation of cracks in the roof of the coal seam, and the influence of coal mining. They also described the range of fracture development [3]. Liu et al. according to the breakage and fractures developing in overlying strata, defined the layer area where the fracture aperture was more than 10^{-1} mm as a mining gas channel [4]. Other researchers studied coal seam gas migration laws by numerical simulation, but only a few quantitative results have been reported [5–13]. This is mainly due to the lack of better numerical simulation tools, capable of representing not only the space-time evolution of mining-induced fractures, but also the flow rule of gas migration.

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http://dx.doi.org/10.1016/j.ijmst.2017.05.015
2095-2686/

This study takes one mining face of 10th Mine in Pingdingshan Coalmine Group in Henan, China as a case study site. Numerical modelling of different gas flow laws in different zones in the working face is carried out by combining multi-physics software COMSOL and discrete element software UDEC. These are used to examine gas migration rule in mining-induced fractures above the goaf.

2. Mathematical model for gas migration under the influence of mining

The presence of mining fissures renders the medium porous; the gas in the fissures can be regarded as ideal gas mixture, consisting of methane and air. The gas flow follows the continuity equation, momentum equation and mass conservation equation.

2.1. Continuity equation

The gas flow in the coal and rock follows the law of mass conservation. When not considering the mass source (sink), the gas continuity equation is

$$\frac{\partial(\rho_g\phi)}{\partial t}+\nabla\cdot(\rho_g\phi\mathbf{v}_g)=0 \tag{1}$$

where ρ_g is the density of the ideal gas, kg/m^3; ϕ the porosity, %; and $\mathbf{v}_g$ the flow velocity of gas, m/s. The gas transportation in mining fissure should satisfy the law of conservation of the gas quality, i.e. it should consider the mass sources of gas, so the gas continuity equation is

$$\frac{\partial(\rho_g c_g)}{\partial t}+\frac{\partial}{\partial x_i}(\rho_g c_g u_i)=-\frac{\partial}{\partial x_i}(J_g u_i)+S_g \tag{2}$$

where u_i is average flow velocity for porous medium in the i direction; S_g the additional production rate of gas source term; and J_g the gas diffusion flux.

2.2. Momentum conservation equation

In a given fluid system, the time variation of its momentum is equal to the sum of the external forces acting on it. For porous media, the momentum conservation equation of the i direction in the inertial (non-acceleration) coordinate system is

$$\frac{\partial(\rho_g u_i)}{\partial t}+\frac{\partial}{\partial x_j}(\rho_g u_i u_j)=\frac{\partial\tau_{ij}}{\partial x_j}-\frac{\partial p}{\partial x_i}+\rho_g g_i+F_i \tag{3}$$

where τ_{ij} is the stress tensor; $\tau_{ij}=\mu_{eff}\left[\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)-\frac{2}{3}\frac{\partial u_i}{\partial x_i}\delta_{ij}\right]$; δ_{ij} Kroneker delta; $\rho_g g_i$ the gravity force on the i direction; F_i the external volume force on the i direction which is including a custom porous media source term.

2.3. Equation of motion

Because of the complex gas flow channel in coal and viscous effects, the equation of motion of the gas flow in the porous media of coal and rock need to be described per the conditions of different areas. Per previous research, Navier-Stokes equation is appropriate to describe the fluid flow in the roadway, whereas the Brinkman equation focusing on the fracture zone considers the characteristics of the fluid pressure and movement, which is appropriate to describe the fluid flow in the caving zone [14]. Using the two equations can help build a working face air flow model, as shown in Fig. 1. The velocity and pressure on the interface are consistent in the region where the gas flow is in accordance with Navier-Stokes and Brinkman model. The velocity and pressure distribution at the coal face and in the goaf can be predicted by the numerical model.

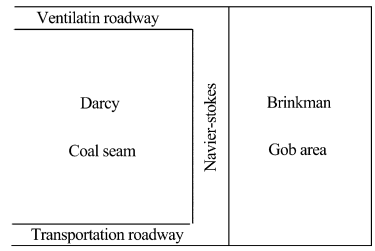

Fig. 1. Schematic plan view showing fluid motion equation in different areas, in front of and behind the working face.

2.3.1. Fluid equation of motion in front of the working face

The Reynolds number, R_e of the gas flow in the coal seam is given by

$$R_e=\frac{q\cdot k}{\upsilon\cdot d_m} \tag{4}$$

where q is the gas flow velocity, m/s; k the permeability, m^2; υ coefficient of kinematic viscosity, m^2/s; and d_m the average particle size, m. When the $R_e\leqslant 2320$, the fluid flow state is laminar flow, it is transition flow when $2320<R_e<4000$, and it is turbulent flow when $R_e\geqslant 4000$ [15].

When the fluid flow state is laminar, the flow in the coal bed is follows Darcy's Law, which is

$$u=-\frac{k}{\mu}\cdot\frac{dp}{dx} \tag{5}$$

where u is the gas flow velocity in coal bed, m/s, k the permeability of coal, m^2; μ the dynamic viscosity of the fluid, Pa/s; and dp/dx the fluid pressure gradient.

When the fluid flow state is turbulent, the gas flow in the coal bed follows Non-Darcy flow, and the fluid pressure gradient can be expressed as

$$-\frac{dp}{dx}=\frac{\mu}{k}u+\beta\rho u^n \tag{6}$$

where n is related to the characteristics of the porous media of coal; and β the β-factor of Non-Darcy flow.

Coal permeability in front of the working face is related to its effective stress, considering the dual effect of gas pressure, mechanical effect and absorption effect. The relationship between permeability and effective stress in coal under the condition of mining, i.e. dynamic loading and unloading is

$$k=ck_0\times\exp\left(d\left\{\Theta-3p\left\{1-\frac{3K(1-2\nu_s)}{E_s}\left[1-\frac{\rho RT\alpha\ln(1+bp)}{p(1-\varphi)}\right]\right\}\right\}\right) \tag{7}$$

where k_0 is the original permeability of coal, m^2; Θ the bulk stress of coal, MPa; K the bulk modulus, MPa; ν_s the Poisson's ratio of the coal skeleton; p the gas pressure, MPa; ρ the density of coal, kg/m^3; a, b the isothermal adsorption constants; R the molar gas constant; $R=8.3143$ J/(mol K); and φ the porosity, %.

2.3.2. Fluid motion equation in working face

Navier-Stokes equation can well describe the fluid flow in the pipeline, the fluid flow is faster in working face, and it can be solved by Navier-Stokes equation.

$$-\nabla\cdot\eta[\nabla u_{ns}+(\nabla u_{ns})^T]-\rho_g(u_{ns}\cdot\nabla)u_{ns}+\nabla p_{ns}=0 \tag{8}$$