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Numerical simulation of influence of Langmuir adsorption constant on gas drainage radius of drilling in coal seam

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ABSTRACT

To determine reasonable distance of gas pre-drainage drillings in coal seams, a solid–gas coupling model that takes gas adsorption effect into account was constructed. In view of different adsorption constants, the paper conducted the numerical simulation of pre-drainage gas in drillings along coal seam, studied the relationship of adsorption constants and permeability, gas pressure, and effective drainage radius of coal seams, and applied the approach to the layout of pre-drainage gas drillings in coal seams. The results show that the permeability of coal seams is on the gradual increase with time, which is divided into three sections according to the increase rate: the drainage time 0–30 d is the sharp increase section; 30–220 d is the gradual increase section; and the time above 200 d is the stable section. The permeability of coal seams is in negative linear and positive exponent relation with volume adsorption constant V_L and pressure adsorption constant P_L, respectively. The effective drainage radius is in negative linear relation with V_L and in positive exponent relation with P_L. Compared with the former design scheme, the engineering quantity of drilling could be reduced by 25%.

1. Introduction

With the increase in mining depth and mining difficulty, gas emission goes up, respectively. Drainage serves as a fundamental measure to solve the gas problem, and drilling pre-drainage in coal seams is one of the major methods, which can effectively lower the gas content of coal seams and reduce the probability of coal–gas outburst [1]. In the layout of gas drillings in pre-drainage coal seams, drilling distance is an important parameter which is closely related to drainage time, coal seam gas pressure, and especially to permeability of coal seams.

Pre-drainage of gas in coal seams through drillings is a complicated solid–gas coupling process, and permeability of coal seams changes dynamically. Many scholars have studied this area. Yin et al. studied coal mass containing gas mechanics and gas seepage characteristics, obtained the relationship between coal mass volumetric strain and permeability variation, and constructed the solid–gas coupling mathematical model of gas-containing coal mass [2,3]. Zhao et al. have carried out the test and numerical simulation separately from the perspective of effective stress [4–7]. Wei et al. studied the permeability change law of loaded coal mass under different effective stresses and temperatures [8,9]. Liang et al. set up the gas flow coupling model under the non-isothermal condition, and presented the numerical solution [10]. Cao et al. studied mechanical behaviors of coal, such as expansion in gas adsorption and shrinkage in gas desorption [11–13]. Lu et al. calculated the relationship between drainage radius and drilling distance on the basis of Klinkenberg effect [14]. They analyzed the change laws of coal seam permeability and gas pressure in the process of gas drainage from different angles, but little attention has given to the change laws under different the Langmuir adsorption constants.

Based on the Langmuir monomolecular layer adsorption theory and solid–gas coupling theory, and the paper constructs the solid–gas coupling model in the light of coal seam gas seepage flow field equation and coal seam deformation equation, by taking into account coal mass gas adsorption effect in the process of gas drainage. It applies COMSOL Multiphysics to the numerical simulation of pre-drainage gas in drillings along seam, analyzes the change laws of coal seam permeability and gas pressure, obtains the effective drainage radius of coal seam gas under different gas adsorption constants and drainage times, and determines the reasonable distance of drillings. The paper also carries out the on-site verification with a coal mine in Shanxi province as an example, and generates the favorable engineering effect.

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2. Drilling drainage seepage model considering gas adsorption characteristics

In typical seepage mechanics, fluid usually flows through rigid media, but coal mass is virtually deformable, with the major reasons being: (1) effective stress change caused by the change of pore pressure; and (2) coal matrix expansion (shrinkage) caused by gas adsorption (desorption) [15].

2.1. Basic assumptions

(1) Drainage of gas in coal seams is isothermal.
(2) Gas of coal seams is ideal and compressible, and its viscous is constant.
(3) Coal is a homogeneous, isotropic and elastic continuum, and the strains are infinitesimal.
(4) Gas of coal seams conforms to the Langmuir monomolecular layer adsorption theory, and its flowing process abides by the Darcy law.

2.2. Governing equation of coal mass deformation

Coal mass containing gas is chiefly subject to gas pressure, adsorption (desorption), and external load of overlying strata. In the light of the generalized Hooke's law, governing equation of coal mass deformation can be obtained [16].

$$Gu_{i,jj} + \frac{G}{1-2v}u_{j,ji} - \alpha p_{,i} - K\varepsilon_{s,i} + f_i = 0 \tag{1}$$

where G is the shear modulus of coal, MPa; v the Poisson's ratio; α the Biot coefficient; p the gas pressure, MPa; K the bulk modulus of coal, MPa; f_i the body force, N/m^3; ε_s the sorption-induced strain; and i, j the coordinates. Coal mass sorption-induced strain is as follows [17]:

$$\varepsilon_s = \varepsilon_L \frac{p}{p + 1/P_L} \tag{2}$$

where ε_L is the volumetric strain constant; and P_L the pressure adsorption constant, MPa^{-1}.

2.3. Basic equation of gas flow

Gas flow of coal seams conforms to the Darcy, namely [18]:

$$V = -\frac{k}{\mu}\nabla(p + \rho g H) \tag{3}$$

where V is Darcy velocity, m/s; k the permeability of coal seam, m^2; μ the viscous, Pa s; ρ the gas density, kg/m^3; g the gravitational acceleration, m/s^2; and H the height, m.

Gas flow of coal seams conforms to the continuity equation, namely

$$\frac{\partial m}{\partial t} + \nabla \cdot (\rho V) = Q_m \tag{4}$$

where m is the gas content in unit volume, kg/m^3; and Q_m the gas source, kg/m^3 s.

Gas of coal seams exists mainly in the absorbed state and free-state, and gas content in unit volume is

$$m = \rho\varphi + \rho_{ga}\rho_c \frac{V_L p_L p}{1 + p_L p} \tag{5}$$

where φ is the porosity; ρ_{ga} the gas density on the standard conditions, kg/m^3; ρ_c the coal density, kg/m^3; and V_L the volume adsorption constant, cm^3/g.

2.4. Dynamic change equation of permeability of coal seams

In gas drainage of coal seams, permeability is related to porosity. Permeability ratio (k/k_0) is as follows [19–21]:

$$\frac{k}{k_0} = \left(\frac{\varphi}{\varphi_0}\right)^3 \tag{6}$$

where k_0 is the initial permeability of coal; and φ_0 the initial porosity of coal.

With the gas adsorption effect and effective stress of coal mass considered, porosity change equation is

$$\varphi = (\alpha - \varphi_0)\left(\varepsilon_v - \varepsilon_{v0} + \frac{p - p_0}{K_s} + \varepsilon_s - \varepsilon_{s0}\right) \tag{7}$$

where ε_v is the volumetric strain of coal; ε_{v0} the initial volumetric strain of coal; K_s the bulk modulus of the coal grains, Pa; and ε_{s0} the initial sorption-induced strain.

3. Numerical model and simulation scheme of gas pre-drainage in drillings of coal seams

3.1. Overview of the simulated coal face

The No. 401 face is located in No. 4 area of a mine in Shanxi province with the mining length and width being 1435 and 180 m, respectively, and designed mainly No. 15 coal seam. The thickness of coal seam is 4.5 m; average inclination is 7°; burial depth is about 470 m; gas adsorption constants are 40.2 cm^3/g and 0.965 MPa^{-1}; density is 1350 kg/m^3; moisture is 0.96%; ash content is 12.52%; porosity is 0.04; and average gas pressure is 0.70 MPa.

3.2. Establishment of geometrical model

It constructs a 2D geometrical model with the length and width being 20 and 4.5 m, respectively. The drilling is located in the middle of the model, with the drilling diameter being 0.094 m. The grid is divided into 990 triangle units in total (Fig. 1).

3.3. Definite conditions and calculation parameters

(1) Initial conditions

Solve the gas pressure of coal seams in the domain $p(t)|_{t=0} = p_0 = 0.7$ MPa, and the initial displacement of the stress field $u_i = 0$ ($i = x, y$).

(2) Boundary conditions

Seepage boundary: the main roof and bottom of coal seam are gas-tight rock strata, and their upper and lower boundary pressures are zero, and left and right boundary pressures are 0.7 MPa. The negative pressure of drilling wall of drainage is 13 kPa.

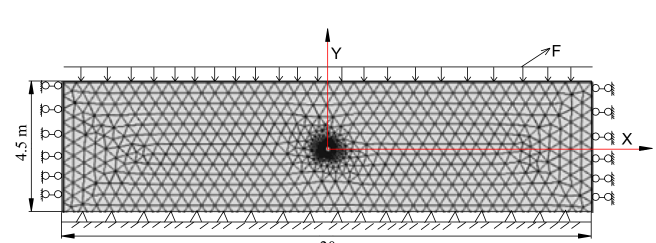

Fig. 1. Geometric model and mesh.