Fuel 210 (2017) 398–409

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Modeling of gas migration in water-intrusion coal seam and its inducing factors

Leilei Si[a,b], Zenghua Li[a,b,*], Yongliang Yang[a,b], Jun Zhou[a,b], Yinbo Zhou[a,b], Zhen Liu[c], Liwei Liu[a,b]

[a] Key Laboratory of Coal Methane and Fire Control, Ministry of Education, China University of Mining and Technology, Xuzhou 221008, China
[b] School of Safety Engineering, China University of Mining and Technology, Xuzhou 221116, China
[c] College of Mining and Safety Engineering, Shandong University of Science and Technology, Qingdao, Shandong 266590, China

ARTICLE INFO

Keywords:
Water-saturated coal seam
Diffusion
Seepage
Henry's law
Numerical simulation
Dissolution

ABSTRACT

Formation water intrusion into the coal seam through cross drainage boreholes seriously affects the gas extraction efficiency. Particularly in the downward boreholes, the formation water cannot be discharged through the drain. Using the conventional seepage model to estimate the effect of gas drainage will cause that the coal seam residual gas pressure is underestimated. In this paper, we construct the gas migration models in a water-intrusion coal seam, which include the gas seepage in original coal seam and the gas diffusion in water-saturated coal seam. By comparing with the field data, the mathematical models are authenticated. Then, the influences of diffusion coefficient, permeability, Henry's constant and the radius of water-saturated coal seam on the residual gas pressure and gas production are analyzed by numerical calculations. The results show that the gas pressure decreases with the increase of the diffusion coefficient, while increases with the increase of Henry's constant and the radius of the water-saturated coal seam. The impact of permeability is more complex. In the high permeability coal seam, the overall pressure relief effect is better. However, in the low permeability coal seam, the pressure relief effect around the borehole is better. Finally, the influence mechanism of each factor is analyzed to revel the gas production in the water-intrusion coal seam. The results of the work are of great significance to enrich the theory of gas migration and the prevention and control of mine gas disaster.

1. Introduction

Mine gas disaster is one of the most serious disasters [1–3]. Cross boreholes are often used for gas drainage to prevent gas disaster. However, in China, the mine hydrogeological conditions are very difficult. There is usually an aquifer in the roof or floor of the coal seam. During the gas extraction process, the formation water in the aquifer will intrude into the coal seam through cross boreholes [4–8]. The pores of coal around the borehole were totally filled with water. In the original coal seam, the gas flow follows Darcy's law. However, in the water-saturated coal seam, the gas is dissolved in the formation water due to the fact that the pores of coal are completely filled with water. In the water-saturated zone, the gas migration in pore water follows the Fick's law. Now, few studies about gas migration in the water-intrusion coal seam have been reported [9]. Therefore, it is urgent to carry out the research on the mechanism and characteristics of gas migration in the water-intrusion coal seam.

Many studies about gas seepage in the coal seam have been carried out [10,11]. However, in the water-intrusion coal seam, there is a water-saturated zone around borehole. Unlike coalbed methane (CBM) extraction, the formation water is relatively static during the mine gas extraction. The gas in the coal seam is dissolved in the pore water under the action of gas pressure.

The gas dissolution in the water is the first step for the gas diffusion in the pore water. Dissolution is a complex geochemical changes [12]. As is known, the composition of formation water is complex, different mineral ions have different effects. Duan et al. [13,14] proposed a gas solubility model in the multi-component solution according to thermodynamic theory, which could calculate the gas solubility in the different mineral solutions. For the influencing factors of solubility, Duan et al. [15] tested the solubility of methane in the mineral solution at 0–250 °C, and the results showed that the methane solubility decreased with increasing temperature at low temperature (0–120 °C), and the solubility of methane increased gradually after 120 °C. In summary, under a certain pressure, the gas can be dissolved in the formation water, and its solubility is affected by the solution properties and the external environment.

Gas migration in the coal seam is a complex problem of multiphase coupling. It is generally believed that gas migration in the coal seam follows Darcy's law, which is driven by the pressure gradient. However,

* Corresponding author at: Key Laboratory of Coal Methane and Fire Control, Ministry of Education, China University of Mining and Technology, Xuzhou 221008, China.
E-mail address: lzh6512@126.com (Z. Li).

http://dx.doi.org/10.1016/j.fuel.2017.08.100
Received 21 June 2017; Received in revised form 24 August 2017; Accepted 29 August 2017
Available online 23 September 2017
0016-2361/

the dissolved gas migration in the water-saturated coal seam follows Fick's law, which is driven by the concentration gradient.

Some works about the influencing factors for gas diffusion in the water have been carried out. The mathematical model of gas diffusion was constructed by Zhang et al. [16,17], who tested the diffusion coefficient of CO_2 at different temperatures and deemed that the diffusion coefficient increased with the increasing temperature. Zhang et al. [16] tested the diffusion coefficient of gas in brine at pressures from 0.5 MPa to 2 MPa, the results showed that diffusion coefficient increased with the increasing pressure. For the effect of the solution properties on diffusion coefficient, the diffusion coefficient of gas in different mineral water was investigated by Jafari et al. [18], who argued that the gas diffusion coefficient is closely related to the size, charge and concentration of metal ions. In addition to the diffusion of gas in the water, Martins [19–22] tested the diffusion coefficient of the gas in the ionic liquid and heavy oil. The experimental results showed that the diffusion coefficient of the gas in the aqueous solution was 2–3 orders of magnitude smaller than that in the ionic liquid, but it was slightly larger than the diffusion coefficient in the heavy oil.

Unlike the diffusion of gas in the water, the diffusion of gas in the pore water is also affected by factors such as porosity and tortuosity of coal. At present, the work on gas diffusion in the water-saturated porous media was primarily focused on the test method of diffusion coefficient. Song et al. [23] used Magnetic Resonance Imaging (MRI) to test the gas diffusion coefficient in a water-saturated porous media and validated the reliability of this method. Jacops et al. [24,25] used a double-chamber method to test the gas diffusion coefficient in a water-saturated boom clay. Li et al. [26] proposed a mathematical model for diffusion coefficient, used a pressure-decay method to test the gas diffusion coefficient, and analyzed the effects of temperature, pressure and permeability on the diffusion coefficient. All the results show that the gas in the coal seam can be dissolved in the pore water under the action of the pressure. Then, the dissolved gas diffuses in the pore water under the action of concentration gradient.

In summary, the gas migration in the water-intrusion coal seam is affected by many influencing factors, such as gas solubility, diffusion coefficient, porosity and permeability. However, few studies focused on the gas migration in the water-intrusion coal seam and environmental consequences [27–32]. In this paper, the mathematical model of gas migration in the water-intrusion coal seam was constructed. Using numerical calculations, we investigated the effect of various factors on the gas production to reveal the gas migration characteristics and mechanism in a water-intrusion coal seam.

2. Modeling and experimental

2.1. Physical model

In the water-intrusion coal seam, the formation water constantly overcomes the gas pressure of microporous in the coal and eventually reaches a steady state. Then, the coal surrounding the borehole is wetted and divided into 3 zones: water-saturated coal seam, water-unsaturated coal seam and original coal seam. It is generally believed that the water-saturated zone only accounts for a very small part of the wetting area [33]. The physical model for gas migration in the water-intrusion coal seam is shown in Fig. 1. After formation water reaches a steady state, the gas in the coal seam is dissolved into the pore water under the action of pore pressure. Then, the dissolved gas gradually diffuses in the pore water. Finally, the dissolved gas is released due to a decrease in pressure. The gas migration in the water-intrusion coal seam comprise two parts: in the original coal seam and water-unsaturated coal seam, gas migration follows Darcy's law. But in the water-saturated coal seam, gas migration follows Fick's law.

2.2. Mathematical models

In order to construct the mathematical models of gas migration in the water-intrusion coal seam, a series of equations are defined to describe the deformation of the coal body, the gas seepage in the original coal seam, and the gas diffusion in the water-saturated coal seam. These equations are based on the following assumptions: (a) Gas migration in the water-saturated coal seam is defined by Fick's law. (b) The density change of water in the pore is ignored. (c) The radius of water-saturated coal seam is constant. (d) Gas diffusion in the water-filled borehole is ignored. (e) Gas flow in the original coal seam and water-unsaturated coal seam follows Darcy's law, and the effect of water is ignored. (f) Conditions are isothermal. (g) Coal is a homogeneous, isotropic and elastic continuum. In summary, the gas transport in water-intrusion coal seam is composed of 2 parts: gas seepage in original seam and gas diffusion in water-saturated coal seam. Moreover, the effects of temperature and heterogeneity on the gas transport were ignored. Based on these assumptions, the detailed equations are as follows:

2.2.1. Mathematical model for coal seam deformation

Many studies have investigated the coal seam deformation, which is affected by stress, gas pressure and sorption-induced strain. Based on the poroelasticity, the constitutive equation of coal seam can be described as [34–36]:

$$\varepsilon_{ij} = \underbrace{\frac{1}{2G}\sigma_{ij} - \left(\frac{1}{6G} - \frac{1}{9K}\right)\sigma_{kk}\delta_{ij}}_{A} + \underbrace{\frac{\alpha}{3K}p\delta_{ij}}_{B} + \underbrace{\frac{\varepsilon_s}{3}\delta_{ij}}_{C} \tag{1}$$

where A is the stress-induced deformation, B is the gas pressure-induced deformation, C is the gas sorption-induced deformation, ε_{ij} is the strain tensor component, σ_{ij} is the total stress (MPa), G is the shear modulus (MPa), $G = 2/E(1 + \upsilon)$, where E is the Young's modulus of coal (MPa), and υ is the Poisson's ratio, σ_{kk} is the stress component in the positive direction, $\sigma_{kk} = \sigma_{11} + \sigma_{22} + \sigma_{33}$, p is the gas pressure (Pa), α is the Biot's coefficient; $\alpha = 1-K/K_s$, 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 $K_s = \frac{E_s}{3(1-2\upsilon)}$, where E_s is the Young's modulus of the coal grains (MPa). δ_{ij} is the Kronecker delta tensor, and ε_s is the sorption-induced volumetric strain. $\varepsilon_s = \frac{\varepsilon_L p}{P_L + p}$, where ε_L is the Langmuir volumetric strain constant, and P_L is the Langmuir pressure constant, (Pa).

Eq. (1) can be transformed into a Navier-type equation:

$$Gu_{i,kk} + \frac{G}{1-2\upsilon}u_{k\cdot ki} - \alpha p_{,i} - K\varepsilon_{s,i} + f_{,i} = 0 \tag{2}$$

2.2.2. Mathematical model for gas seepage in the coal seam

According to the mass conservation equation of gas, the gas flow in the coal seam can be defined as [10]:

$$\frac{\partial m}{\partial t} + \nabla(\rho q) = Q_s \tag{3}$$

where m is the gas mass (kg), ρ is the gas density (kg/m^3), Q_s is the mass source, t is the time (s), and q is the Darcy's velocity (m/s), it can be defined as;

$$q = -\frac{k}{\mu}(\nabla p) \tag{4}$$

Gas in the coal includes free-phase gas and adsorbed gas. Therefore, m can be defined as [37]:

$$m = m_{free} + m_{adsorption} \tag{5}$$

where m_{free} and $m_{adsorption}$ are the free-phase gas and adsorbed gas, respectively. They can be defined as:

$$m_{free} = \rho_g \phi \tag{6}$$