Journal of Natural Gas Science and Engineering xxx (2016) 1–9

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

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

Quantitative study on coal permeability evolution with consideration of shear dilation

Mingyao Wei [a, b, *], Jishan Liu [a], Xiating Feng [a], Chunguang Wang [c], Kai Fang [c], Fubao Zhou [b], Shouwen Zhang [a], Tongqiang Xia [a, b]

[a] *State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan 430071, China*
[b] *State Key Laboratory of Coal Resources and Safe Mining, China University of Mining and Technology, Xuzhou 221116, China*
[c] *Department of Engineering Mechanics, Shandong University of Science and Technology, Qingdao 266590, China*

ARTICLE INFO

Article history:
Received 15 December 2015
Received in revised form
27 April 2016
Accepted 4 May 2016
Available online xxx

Keywords:
Coal permeability
Gas sorption
Coal swelling
Shear dilation
Effective stress

ABSTRACT

Although coal permeability has been largely investigated, its changes caused by shear dilation of fractures are rarely reported possibly because it's often underestimated by many models. This work develops a new model of coal permeability with consideration of fracture deformation under influences of both normal and shear stresses. It is coupled with the existing models of coal deformation in the matrix system as well as gas flow and transport in the fracture system. Lastly, the fully coupled mode is applied to calculate the evolution of coal permeability during coalbed gas production. The results show that coal permeability increases with the decreasing reservoir pressure, while the fracture permeability decreases nonlinearly with the increasing normal stress and increases with the increasing shear dilation, all of which are well consistent with field data. The application of this model in a case study also indicates that the fully coupled model with consideration of shear dilation is superior to previous models.

1. Introduction

Permeability is a key parameter that controls mass and energy transport in a geologic reservoir. As coal is commonly represented as a typical dual porosity system that consists of porous matrix and fracture network (Harpalani and Schraufnagel, 1990; Warren and Root, 1963), both matrix and fracture contribute to the evolution of coal permeability. The pore system within the coal matrix ultimately determines the matrix permeability (Moore, 2012). Similarly, the permeability of a single fracture is primarily determined by the fracture aperture. Therefore, both matrix and fracture contribute to the resultant permeability of fractured coal.

Both matrix permeability and fracture permeability are highly sensitive to the change in effective stresses (Izadi et al., 2011; Wu et al., 2010). In the past few decades, significant experimental efforts have been made to investigate factors affecting gas permeability and its evolution in coal at various confining stresses and pore pressures (Harpalani and Schraufnagel, 1990; Viete and Ranjith, 2006; Shi and Durucan, 2004). Investigation on gas flow in coal indicated that gas permeability is sensitive to stress because the fractures and pores of coal tend to close under external normal force (Somerton et al., 1975; Pan et al., 2010). Laboratory measurements show that coal permeability decreases exponentially with the increase of effective stress, which is a relationship supported by extensive laboratory (Somerton et al., 1975) and field studies (Enever and Henning, 1997). Permeability reduction shows a steep gradient followed by a gentle gradient as the applied effective stress increases (Durucan and Edwards, 1986). At the beginning the steep gradient was believed to be attributed to the immediate closure of existing microfractures subject to stresses (Durucan and Edwards, 1986). Later, an exponential permeability variation was presented on the basis of assumption that the solid grains are incompressible (Seidle and Huitt, 1995).

The effect of gas adsorption induced coal swelling on permeability is also considered as a well-known phenomenon. The potential impacts of sorption-induced swelling on the evolution of coal permeability have been investigated through experimental and analytical studies (Pan et al., 2010; Robertson and Christiansen, 2005). Under the constant total stress, gas permeability decreases

---

* Corresponding author. State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan 430071, China.
E-mail address: mywei@whrsm.ac.cn (M. Wei).

http://dx.doi.org/10.1016/j.jngse.2016.05.007
1875-5100/© 2016 Elsevier B.V. All rights reserved.

Please cite this article in press as: Wei, M., et al., Quantitative study on coal permeability evolution with consideration of shear dilation, Journal of Natural Gas Science and Engineering (2016), http://dx.doi.org/10.1016/j.jngse.2016.05.007

with the increase in pore pressure due to the coal swelling (Pan et al., 2010; Robertson and Christiansen, 2005), and increases with the decrease in pore pressure due to the matrix shrinkage (Cui and Bustin, 2005; Harpalani and Schraufnagel, 1990; Seidle and Huitt, 1995).

Based on experimental observations, a broad variety of theoretical and empirical models have been developed to represent the effects of sorption, swelling and effective stresses on the evolution of coal permeability (Cui and Bustin, 2005; Izadi et al., 2011; Palmer and Mansoori, 1998; Seidle and Huitt, 1995; Shi and Durucan, 2004). In the latest review (Liu et al., 2011), these models were classified into two groups: those under uniaxial strain conditions and those under triaxial stress conditions. It has been demonstrated in the most recent studies (Izadi et al., 2011) that the previous studies have not incorporated the impact of coal matrix–fracture compartment interactions into coal permeability models appropriately.

Fracture systems in coal seam are geometrically complex, and can exert fundamental control on fluid flow. It has been commonly recognized that a rock fracture subjected to quasi-static (normal or shear) loads exhibits highly nonlinear deformational behavior (Liu et al., 2012). Zeng et al. (2011) reported that the permeability of coal samples under triaxial compression tends to decrease with the increase in effective stress in each loading direction, and is controlled by the evolution of cracks development in coal. Hangx et al. (2010) has performed triaxial compression experiments together with permeability measurements using argon gas. Dynamic permeability measurements showed the coal permeability was largely controlled by the permeability of developed shear faults. The static, post-failure permeability decreased with the effective mean stress.

A number of empirical and theoretical constitutive models have been proposed to describe the observed relationship between effective stress and fracture aperture through laboratory tests under monotonic or cyclic loading conditions. Among them, two types of empirical models are usually used: one is the hyperbolic models presented by Goodman (1976), Bandis et al. (1983), Barton et al. (1985) and others; the other is the logarithmic models proposed by Swan (1983), Brown and Scholz (1986), and others. Somerton et al. (1975) investigated the permeability of fractured coal and presented a correlation equation to predict the relationship between permeability and mean stress. Gray (1987) considered the changes in fracture permeability, which is related to changes in prevailing effective horizontal stresses. Seidle and Huitt (1995) developed a permeability model by considering the effects of coal-matrix swelling/shrinkage only to explain the coal permeability decrease with increasing effective stress. Robertson and Christiansen (2006) described the derivation of a new equation that can be used to model the permeability behavior of a fractured, sorptive-elastic medium, such as coal, under variable stress conditions based on the cubic geometry. Liu et al. (2009) concluded that porous and fractured coal is inherently heterogeneous with a variety of geometric shapes. Therefore, it is important to accurately describe the deformation of coal for coupled mechanical and hydrological processes.

Coal permeability is influenced not only by the normal stress, but also by the shear stress. Experimental data have demonstrated that an elastic deformation of the asperity is initially caused by the shear stress during shearing process along a fracture surface (Gentier et al., 1997). Shear deformation can induce an increase in fracture opening as a result that the asperities on the opposed sides of a fracture slide over each other. The prediction of dilation phenomenon of fractures subject to shear loading has been investigated by numerous researchers such as Barton et al. (1985) and Bandis et al. (1983). Many researchers have studied the shear dilation, but almost exclusively for rocks. Nevertheless, few data are available on coal, even though a small shear deformation can increase the permeability by 1–2 orders of magnitude in fractured rock (Lee et al., 2001).

In all the previous coal permeability models, the influence of shearing on the evolution of coal permeability is rarely considered. In this study, a coal permeability model that includes the combined impact of both normal stress and shear dilation is developed to evaluate the dynamic evolution of coal permeability. The effect of shear dilation was represented by a fractal-based model (Wei et al., 2013). The permeability model is extended to define the evolution of gas sorption-induced permeability anisotropy under variable stress conditions including normal stress and shear stress, and implemented into a fully coupled coal deformation, gas flow and transport in the matrix system, and gas flow and transport in the fracture system model. This model represents important non-linear responses due to the effects of effective stress that cannot be recovered where mechanical influences are not rigorously coupled with the transport system.

2. Model of coal permeability

2.1. Basic assumptions

In this study, following basic assumptions are made:

(1) Coal is a homogeneous, isotropic, and dual poroelastic continuum, and the system is isothermal.
(2) The deformation of coal seam and natural gas flow process within both cleats and coal matrix are all pseudo-static.
(3) Gas flow through the coal matrix is assumed to be viscous flow obeying Darcy's law.
(4) Gas contained within the pores is ideal, and its viscosity is constant under isothermal conditions.
(5) Matrix swelling is linearly related to the change in adsorbed concentration.
(6) Gas absorption/adsorption can be described by Langmuir isotherm. Gas adsorption only takes place in matrix.
(7) Spatial distributions of fracture roughness has fractal character.

2.2. Model of the permeability in coal matrix

The porosity and permeability of coal matrix under the influence of effective stress are not constants. Based on Liu's work (Liu et al., 2011), the porosity of coal matrix can be defined as a function of effective stress as follows:

$$\phi_m = \phi_{m0} - \alpha \frac{\Delta\sigma - \Delta p_m}{K} \tag{1}$$

where $\Delta\sigma$ is the increment in mean stress, namely, the stress responsible for a change in permeability; m_0 is the initial porosity of matrix system, K is the bulk modulus, and α is the Biot coefficient. Further, a widely used relationship between the porosity and permeability of coal matrix (e.g. Cui and Bustin, 2005; Palmer and Mansoori, 1998) is

$$\frac{k_m}{k_{m0}} = \left(\frac{\phi_m}{\phi_{m0}}\right)^3 \tag{2}$$

where k_m is the matrix permeability, and k_{m0} the initial matrix permeability. Based on Eq. (1), k_m is also the function of the effective stress. Obviously, the effects of gas sorption, coal deformation,

Please cite this article in press as: Wei, M., et al., Quantitative study on coal permeability evolution with consideration of shear dilation, Journal of Natural Gas Science and Engineering (2016), http://dx.doi.org/10.1016/j.jngse.2016.05.007