Fuel 207 (2017) 522–532

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Impact of matrix–fracture interactions on coal permeability: Model development and analysis

Ting Liu, Baiquan Lin *, Wei Yang

Key Laboratory of Coal Methane and Fire Control, Ministry of Education, China University of Mining and Technology, 221116, People's Republic of China
School of Safety Engineering, China University of Mining & Technology, Xuzhou 221116, People's Republic of China

HIGHLIGHTS

- A new permeability model considering the matrix–fracture interaction is developed.
- The influencing factors of internal swelling coefficient are discussed.
- The effect of internal swelling coefficient on coal permeability is explored.

ARTICLE INFO

Article history:
Received 27 April 2017
Received in revised form 16 June 2017
Accepted 28 June 2017

Keywords:
Coal permeability
Matrix–fracture interaction
Internal swelling coefficient
Coalbed methane recovery
CO_2 geological sequestration

ABSTRACT

In this study, we develop a new permeability model that incorporates the matrix–fracture interactions. In addition, a newly defined internal swelling coefficient (f) has been introduced to quantify the contribution of adsorption-induced matrix deformation to fracture aperture and coal permeability. The model is independent of the boundary conditions and has been verified with the data tested under the conditions of uniaxial strain, constant external stress, constant effective stress, and constant pore pressure. Besides, a comparison between the commonly used models and our model shows that our model can cover most of the variation trends of the other models. The influencing factors and the mechanisms controlling the internal swelling coefficient have been comprehensively discussed. The results show that under the conditions of uniaxial strain and constant effective stress, f shows a downward trend with a reduction of the pore pressure, whereas under the constant external stress condition, f presents an opposite variation trend. The gas type has an effect on the internal swelling coefficient and f decreases in the order of N_2, CH_4, and CO_2. In addition, the coal type also affects the internal swelling coefficient. All the factors indirectly affect the internal swelling coefficient by changing the effective stress and adsorption-induced matrix deformation. We have also investigated the controlling mechanism of the internal swelling coefficient on permeability, which indicated that the permeability shows an opposite variation trend with the internal swelling coefficient. It is suggested that the internal swelling coefficient can be set as a value in the range of 0–0.2 for the prediction of coal seam permeability during CBM recovery and CO_2 geological sequestration.

1. Introduction

Coalbed methane (CBM) is not only a kind of clean energy, but also a kind of greenhouse gas and a hazard to the coal mining. Therefore, its release during underground coal mining poses a significant threat to the environment and the mining safety [1,2]. The global CBM reserves have been estimated to be 84–262 trillion m^3 [3]. Therefore, emphasizing the intensity of CBM recovery and improving the efficiency can not only mitigate the energy crisis, but also reduce environmental pollution and ensure mining safety. At present, the most commonly used method for commercial CBM production is the reservoir-pressure depletion. However, due to the low permeability of coal seams, this method is considered inefficient [4]. Recently, enhanced CBM recovery technique, which enhances the methane desorption from the coal matrix by injecting CO_2 into the coal seams [5,6], has been postulated as another viable option. The injection of CO_2 into the coal seams can not only enhance CBM recovery, but also realize the geological sequestration of CO_2. Both CBM production and CO_2 injection will in-turn trigger a series of coal–gas interactions, which will further alter

---

* Corresponding author at: School of Safety Engineering, China University of Mining & Technology, Xuzhou 221116, People's Republic of China.
E-mail address: lbq21405@126.com (B. Lin).

http://dx.doi.org/10.1016/j.fuel.2017.06.125
0016-2361/© 2017 Elsevier Ltd. All rights reserved.

Nomenclature

L_m	size of matrix block (m)
L_f	fracture aperture (m)
ΔL_m^S	matrix deformation caused by gas adsorption (m)
ΔL_f^S	fracture deformation caused by gas adsorption (m)
ΔL_b^S	coal mass deformation caused by gas adsorption (m)
f	internal swelling coefficient
$\Delta \varepsilon_m^S$	matrix strain caused by gas adsorption
ε_L	Langmuir strain constant
p_L	Langmuir pressure constant
$\Delta \varepsilon_f^S$	fracture strain caused by gas adsorption
$\Delta \varepsilon_b^S$	coal mass strain caused by gas adsorption
$\Delta \varepsilon_f^E$	fracture strain caused by effective stress
p_m	gas pressure in matrix
p_f	gas pressure in fracture
$\Delta \sigma_z^E$	increment of effective stress in z direction
$\Delta \sigma_z$	increment of external stress in z direction
$\Delta \varepsilon_{mx}^S$	matrix adsorption strain in x direction
$\Delta \varepsilon_{my}^S$	matrix adsorption strain in y direction
$\Delta \varepsilon_{mz}^S$	matrix adsorption strain in z direction
p_m	initial gas pressure in matrix
p_f	initial gas pressure in fracture
α,β	Biot coefficients
K	bulk modulus of coal
K_f	bulk modulus of fracture
K_m	bulk modulus of matrix
E	elastic modulus of coal
E_m	elastic modulus of matrix
ν	Poisson's ratio of coal
σ_e	effective stress
σ	external stress
σ_0	initial external stress
δ_{ij}	Kronecker delta
ϕ_f	fracture porosity
ϕ_{f0}	initial fracture porosity
$\Delta \varepsilon_{bx}$	coal mass strain in x direction
$\Delta \varepsilon_{by}$	coal mass strain in y direction
k_f	fracture permeability
k_{f0}	initial fracture permeability

the coal seam permeability [6,7]. For example, the main mechanism for CO_2 geological sequestration is adsorption [8].The adsorption of CO_2 into the coal seams leads to matrix swelling, which inevitably results in permeability reduction. In real-world scenarios, permeability loss of coal seams is a major problem encountered during CBM recovery and CO_2 geological sequestration [7]. Therefore, it is necessary to study the permeability evolution of coal seams and its controlling mechanisms.

Modeling coal permeability during CBM production and CO_2 injection is an active research area with numerous models being presented [6,9]. Based on the assumption of uniaxial strain, Gray [10] first incorporated matrix shrinkage into a coal permeability model. Palmer and Mansoori [11] built another widely used P&M model, which incorporated the effects of matrix shrinkage and effective stress. However, this model failed to match the field data from San Juan basin for the overestimated matrix compressibility [26]. An additional parameter (g) was then introduced to modify the model [12]. Assuming that the change in cleat permeability was dominated by the effective stress normal to the cleats, Shi and Durucan [4] developed a model (SD model) for pore pressure-dependent permeability. Cui and Bustin [13] derived a stress-dependent permeability model (CB model) by quantifying the effects of reservoir pressure and volumetric strain caused by gas adsorption on coal seam permeability. One critical difference between the CB model and the SD model is that the former considers the effect of horizontal stress while the latter considers the effect of normal stress. Pan and Connell [14] applied the anisotropic coal swelling model to the SD model to describe permeability behavior for primary and enhanced coalbed methane recovery. By applying the elasticity theory to the fractured rocks, Perera et al. [7] modeled the relationship between permeability and gas-injecting pressure, confining pressure, axial load, and gas adsorption in triaxial tests.

It is believed that gas adsorption on coal will result in coal matrix swelling. This deformation alters the fracture aperture and thus changes the coal seam permeability, a process termed as "matrix–fracture interaction". Although a certain degree of success has been achieved in the prediction of coal permeability using previously developed models, some problems do exist: for example, (1) the interactions between the matrix and fractures have not been considered; (2) in previous models, it was assumed that the matrix deformation caused by gas adsorption is equal to that of the fracture, but this is inconsistent with the laboratory test results [15,16]. To address these problems, Liu and Rutqvist [15] proposed a modified matchstick model, in which the coal matrix was connected by "matrix bridge." Furthermore, to quantify matrix–fracture interactions, the concept of "internal swelling coefficient" was introduced to develop permeability models under conditions of uniaxial strain and constant external stress. After that, Connell et al. [17] developed two analytical permeability models for matching the permeability data in the laboratory. In these models, a coefficient, which is the ratio of the adsorption-induced fracture strain to the adsorption-induced bulk coal strain, was introduced to characterize the matrix–fracture interactions. Assuming that only part of the adsorption-induced matrix deformation was used to change the fracture volume, Guo et al. [18] developed a permeability model under triaxial stress conditions. Based on the research results of Guo et al. [18], Lu et al. [19] developed a boundary condition–independent permeability model, which also explicitly considered the matrix–fracture interactions. In a separate study, Wang et al. [20] developed an anisotropic permeability model with a modified cube model. Similar to that in the study by Liu and Rutqvist [15], in this model, the coal matrix was also assumed to be connected by "matrix bridge", and a coefficient was also introduced to characterize the matrix–fracture interactions.

Although the matrix–fracture interactions have been explicitly considered in these studies, some issues remain that have not been fully addressed. It is well-known that the fracture gas pressure is generally lower than the matrix gas pressure [21]; however, in the aforementioned models, the matrix gas pressure and the fracture gas pressure are not separately accommodated, and this leads to an error while evaluating the matrix–fracture interactions. In addition, in the previous models, the coefficient, which was introduced to characterize the matrix–fracture interactions, was generally viewed as a constant, and the influencing factors and their controlling mechanisms have not yet been studied. Zang et al. [22] studied the variation of the internal swelling coefficient with the pore pressure under different boundary conditions, but its controlling mechanisms need to be discussed further.