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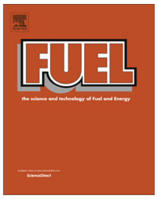

Full Length Article

Impact of coal matrix strains on the evolution of permeability

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ABSTRACT

The goal of this study is to investigate how coal matrix strains affect the evolution of coal permeability. In previous studies, this impact was quantified through splitting the matrix strain into two parts: one contributes to the internal swelling while the other to the global strain. It was assumed that the difference between the internal swelling strain and the swelling strain of matrix determines the evolution of fracture permeability through a constant splitting factor. This assumption means that the impact of internal swelling strain is always same during the whole gas injection/production process. This study extends this concept through the introduction of a strain splitting function that defines the heterogeneous distribution of internal swelling. The distribution function changes from zero to unity. Zero means that the internal swelling strain has no impact on permeability evolution while unity means 100% of the internal strain contributes to the evolution of coal permeability. Based on this approach, a new permeability model was constructed and a finite element model was built to fully couple the coal deformation and gas transport in coal seam reservoirs. The model was verified against three sets of experimental data under the condition of a constant confining pressure. Model results show that evolution of coal permeability under the condition of a constant confining pressure is primarily controlled by the internal strain at the early stage, by the global strain at the later stage, and by the strain splitting function in-between, and that the impact of the heterogeneous strain distribution on the internal swelling strain vanishes as the swelling capacity of matrix increases.

1. Introduction

Coal permeability significantly affects coalbed methane (CBM) production and long-term storage of CO_2 in coal reservoirs. Coal permeability is sensitive to two factors: effective stress and sorption-induced strain. For CBM production, the reduction of gas pressure increases the effective stress which in return reduces the permeability [1,2]. Meanwhile, the reduction of gas pressure decreases sorption-induced strain which in return increases the permeability [3]. The behavior of coal permeability change depends on the net influence of these two competing mechanisms [4,5].

A broad variety of models have been developed to represent the effects of sorption-induced strain and effective stress on the dynamic evolution of coal permeability over the last few decades [6]. The coal permeability models with the effect of effective stress were firstly proposed [1,7,8], and then the effect of sorption-induced strain on coal permeability evolution was introduced into coal permeability models [9–12]. In the field, it is usually assumed that the coal seam reservoir is under the uniaxial strain condition. The permeability models dealing with the permeability evolution in the field consider the effect of the horizontal effective stress rather than the volumetric effective stress [2,4,12–14]. In laboratory, the condition on the samples is different from the in-situ condition. Many permeability models with different assumptions and empirical parameters were proposed to analyze the experimental data [8,15,16]. Based on the poroelasticity theory, Zhang et al. [17] developed a strain-based porosity model and a permeability model under variable stress conditions.

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Nomenclature

A	constant for β (fraction)
E	Young's modulus of coal (GPa)
G	shear modulus of coal (GPa)
K	bulk modulus of coal (GPa)
K_f	bulk modulus of fracture (GPa)
K_s	bulk modulus of matrix (GPa)
P_0	initial pressure (MPa)
P_{in}	injection pressure (MPa)
P_L	Langmuir pressure constant (MPa)
P_{con}	confining pressure (MPa)
P_c	pressure constant for β (MPa)
P_{Low}	constant for β_p (MPa)
P_a	atmosphere pressure (MPa)
P_w	Wellbore pressure (MPa)
V_b	volume of coal bulk (m^3)
V_f	fracture volume (m^3)
V_m	matrix volume (m^3)
V_L	Langmuir sorption capacity (m^3/kg)
b	fracture aperture (m)
$b0$	initial fracture aperture (m)
c_f	compressibility (MPa^{-1})
c_{fA}	compressibility of Anderson coal (MPa^{-1})
c_{fG}	compressibility of Gilson coal (MPa^{-1})
k_0	initial permeability of the dry coal (m^2)
k_f	fracture permeability (m^2)
k_{f0}	initial fracture permeability (m^2)
k_{m0}	initial matrix permeability (m^2)
p	pressure (MPa)

Greek symbols

α	biot coefficient (fraction)
β	strain splitting function (fraction)
β_p	strain splitting function for production process (fraction)
δ_i	index indicating whether internal strain is valid in *i*th matrix
ε	strain (fraction)
ε_{in}	internal swelling strain (fraction)
ε_v	volumetric strain of coal (fraction)
ε_s	gas adsorption-induced swelling strain of the whole coal (fraction)
ε_L	overall Langmuir strain constant for coal (fraction)
ε_{LI}	Langmuir strain constant for region I (fraction)
ε_{LII}	Langmuir strain constant for region II (fraction)
ε_{Lm}	Langmuir strain constant of matrix (fraction)
$\overline{\varepsilon_{Lm}}$	average Langmuir strain constant for matrix (fraction)
ε_{fs}	gas adsorption-induced strain of fracture (fraction)
ε_{ms}	gas adsorption-induced strain of matrix (fraction)
μ	viscosity (Pa s)
μ_{CO2}	CO_2 Viscosity (Pa s)
μ_{CH4}	CH_4 Viscosity (Pa s)
v	Poisson's ratio of coal (fraction)
ρ_c	coal density (kg/m^3)
σ_c	overburden pressure (MPa)
$\bar{\sigma}$	mean compressive stress (MPa)
ϕ_0	initial porosity for dry coals (percentage)
ϕ_{m0}	initial matrix porosity (percentage)
ϕ_{0A}	initial porosity of Anderson coal (percentage)
ϕ_{0G}	initial porosity of Gilson coal (percentage)

In our recent review paper [18], it was concluded that current coal permeability models are unable to describe results from stress-controlled shrinkage/swelling laboratory tests [19–22]. It was suggested that the reason is that the impact of coal matrix-fracture interactions inside coals has not been taken into consideration. This impact could induce the internal swelling strain inside coal affecting permeability evolution [23]. The internal swelling strain was assumed as a portion of the free swelling strain of the whole coal [23,24]. This statement may be not always true. Other study illustrated that the internal swelling strain could be approximately 50 times larger than the swelling strain of coal bulk because of the low fracture porosity [25]. Currently, many models use a constant coefficient to account for the effect of internal swelling strain on permeability [23–26]. Although the characteristics of internal swelling strain were not fully studied, these models could match experimental data much better than traditional coal permeability models [23,26].

In order to investigate the evolution of internal swelling strain, a conceptual model comprised of a matrix and a fracture is usually used [27–31]. It was concluded that the internal swelling strain results from the gas transport between matrix and fracture [27]. The effects of temperature and boundary condition on the evolution of internal swelling strain were also investigated [28,29]. Based on those above studies, a dual porosity model with the effect of internal swelling strain due to gas transport between matrix and fracture was proposed [32]. All properties of the matrix in this model are homogeneous. In this ideal case, the internal swelling strain disappears when the equilibrium state between matrix and fracture is achieved [27–29]. This ideal case is different from the reality that a coal matrix contains several types of organic materials with different percentage. It was observed in laboratory that the swelling strain is unevenly distributed inside coal matrices [33,34]. The distribution of organic materials inside coal matrices may significantly affect the distribution of internal swelling strain. Currently, the characteristics of internal swelling strain in coal matrices and how to consider the effect of heterogeneous distribution of internal swelling strain on the coal permeability have been rarely investigated.

In this paper, a conceptual geometry comprised of a fracture and a matrix including two regions with different minerals was first built to illustrate the effect of internal swelling strain on permeability. Secondly, a variable representing the effect of heterogeneous distribution of internal swelling strains on permeability was introduced into permeability model for a coal bulk. This variable was proposed based on some published experimental observations and our understanding about the internal swelling strain from the above conceptual geometry. Thirdly, this new model was testified through three sets of experimental data and then implemented into a numerical simulation model fully coupling the coal deformation and gas transport in coal seam reservoirs.

2. Effect of internal swelling strain on permeability evolution

In this section, a conceptual geometry representing the matrix-fracture system of coal was built to illustrate the obvious effect of internal swelling strain inside coal on permeability evolution. Then new models would be developed in the next section to consider the effect of internal swelling strain on permeability evolution. In this study, the adsorption-induced strain around fracture is called as the internal swelling strain. The matrix of coal as shown in Fig. 1 is divided into two regions with different adsorption capacities. This conceptual geometry is under the condition of free swelling