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Investigation of the Klinkenberg effect on gas flow in coal matrices: A numerical study

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ABSTRACT

The Klinkenberg effect may significantly impact gas flow behavior, especially in low permeability materials (e.g., coal matrices). The estimation of permeability in coal matrices with respect to the Klinkenberg effect has significant implications for the production of coal bed methane (CBM), impacting factors such as production rates and reservoir issues. In our study, a coal permeability model consisting of seepage and the stress field is constructed. This model considers the stress–strain equation, porosity dynamic evolution equation, and permeability equation with Klinkenberg effects. The primary focus was that the Klinkenberg effect, which is linked to variable porosity in coal, was treated as a dynamic parameter affecting the permeability of the coal matrix. A numerical model, based on the COMSOL software package, was employed for this coal permeability model. A physical experiment was used to validate the numerical simulations. The results show that Klinkenberg effect-based permeability now has an improved agreement with the physical experiment. The Klinkenberg effect is influenced by the stress magnitude, gas pressure distribution, and boundary conditions. Specifically, an increase in effective stress induced by the reduction of the gas pressure improves the compressive deformation of the coal matrix, thereby changing the porosity and permeability of the coal seam. The Klinkenberg effect affects gas pressure permeability. Under fixed boundary conditions for a small change in outlet conditions, the gas pressure gradient is significantly reduced; however, under the inlet conditions, the gas pressure gradient increases.

1. Introduction

As an unconventionally clean gas resource, coal bed methane (CBM) is of interest for potential energy production and is generally explored and enhanced by CO_2 injection (Perera, M.S.A. et al., 2015). This gas usually infiltrates the micro-pores of the coal matrix (Kuuskraa and Boyer, 1993; Perera, M.S.A. et al., 2013; Ranathunga, A.S et al., 2014). The micro-pores, fractures, and faults in the coal matrix construct the main paths for gas transport (Lu and Connell, 2007; Pan and Connell, 2010). One of main factors influencing CBM exploration, the permeability of a coal matrix, is typically determined based on the coal-pore characteristics and stress-strain field of the coal (Tsang, 1984; Brown, 1987; Laubach et al., 1998). The shrinkage of a coal matrix due to the desorption of gas opens the pores and improves the coal permeability. Additionally, a decrease in effective stress due to an increase in gas pressure, to some degree, may lead to an increase in coal permeability (Harpalani and Chen, 1997; Gorucu et al., 2005). Lin et al. (2008) demonstrated that coal permeability is a function of pore pressure and injected-gas types under certain effective stress conditions using physical experiments. Injection of absorbable gases, including CO_2, CH_4, and N_2, leads to an increase in coal permeability (Mazumder et al., 2006; Mazumder and Wolf, 2008). To accurately describe the mechanism of gas flow in porous materials, a number of theoretical and empirical permeability models have been proposed (Gray, 1987; Seidle and Huitt, 1995; Palmer and Mansoori, 1996; Gilman and Beckie, 2000; Pekot and Reeves, 2002; Shi and Durucan, 2004; Cui and Bustin, 2005). These studies assume constant total stress or uniaxial stress as the loading conditions. In newer models, in-situ stress conditions are rigorously incorporated (Zhang et al.,

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Nomenclature

a	the maximum adsorption quantity at infinite pore pressure, m^3/kg
p	gas pressure, MPa
α	Biot's coefficient, 1
Δp	gas pressure variation, MPa
b	the adsorption equilibrium constant, Pa^{-1}
ρ_g	the real-time density of the gas, kg/m^3
b'	the Klinkenberg factor, MPa
ρ_c	the coal density, kg/m^3
c	Klinkenberg coefficient, 1
q	Darcy velocity of gas, m^3/s
d_m	the effective diameter of coal matrixes, m
Q	the gas content per unit volume of coal mass, $kg/(m^3 \cdot s)$
d_{m0}	the initial effective diameter of coal matrixes, m
r	the effective pore radius, m
d	the gas molecular diameter, m
T	coal temperature, K
ε_p	matrix/system strain on account of gas adsorption/desorption, 1
T_n	coal temperature in standard condition, K
ε_i	strain in the i direction, 1
u_i	the component of the displacement, m
ε_{ps}	matrix/system strain induced by gas pressure, 1
ν	the Poisson's ratio of the coal body, 1
ε_{ij}	the component of the total strain tensor, 1
V_B	volumetric of the coal bulk, m^3
ε_L	the maximum volumetric swelling strain at infinite pore pressure, 1
ΔV_B	volumetric variation of the coal bulk, m^3
e	bulk strain of coal body, 1
V_S	volumetric of the coal matrix, m^3
E	elasticity modulus of the coal body, MPa
ΔV_S	volumetric variation of the coal matrix, m^3
Es	elasticity modulus of the coal matrix, MPa
V_P	volumetric of the pore space, m^3
F_i	the component of the body force, MPa/m
ΔV_P	volumetric variation of the pore space, m^3
G	the shear modulus of coal, MPa
β	effective stress coefficient, 1
K_P	the bulk modulus for the pore volumetric strain, MPa
φ	porosity of the coal, 1
K	the bulk modulus of coal body, MPa
φ_0	initial porosity of the coal, 1
KS	the bulk modulus of coal matrix, MPa
σm	average value of three-dimensional stress, MPa
k_∞	absolute permeability of coal matrix under very large gas pressure, m^2
σ_i	the stress in i direction, MPa
k_0	initial absolute permeability of coal matrix, m^2
σ_j	the stress in j direction, MPa
κ	Boltzmann gas constant, $1.3806505 \times 10^{-23}$ J/K
σ_k	the stress in k direction, MPa
L	length of coal body, m
λ	the mean free path of gas molecular, m
n	the number of pores along one direction, 1
δ_{ij}	the Kronecker delta, 1
p_L	the pore pressure at which the measured volumetric strain is equal to 0.5 ε_L, 1
μ	viscosity coefficient of gas, Mpa·s
p_m	the average gas pressure, MPa

2008; Connell and Detournay, 2009; Palmer, 2009) and the CO_2–CH_4 interaction is coupled (Connell and Detournay, 2009; Chen et al., 2010). The most widely used permeability models include the Palmer and Mansoori model (P&M Model), the Shi and Durucan model (S&D), the Cui and Busitinmodel (C&B) model, and the Advanced Resources International (ARI) model (Palmer and Mansoori, 1996; Shi and Durucan, 2005; Cui and Bustin, 2005; Pekot and Reeves, 2002). Unfortunately, the Klinkenberg effect (Klinkenberg, 1941) has not been considered in most models to date, despite the error of permeability in porous media that is introduced by ignoring the Klinkenberg effect (Baehr and Hult, 1991). This effect was investigated by damage to gas wells induced by the non-Darcy flow and stress (Tavares et al., 2006), although only a few studies address this phenomenon. Zeng et al. (2003) found that the Klinkenberg coefficient increased with incremental stress, which has an adverse effect on coal permeability. Similar results were also achieved by Chin et al. (2000), Reda (1987), Persoff and Hulen (1996), and Jones (1972). The Klinkenberg effect may have significant impacts on gas flow behavior, especially in low permeability materials. Pan et al. (2010) briefly considered the role of the Klinkenberg factor in gas flow in coal seams, but modeling of the Klinkenberg factor is still lacking. Zhu et al. (2007) developed a numerical code for solving the gas flow equation that considers the Klinkenberg effect as an empirical parameter; this approach was validated by comparison with available analytical solutions. In our study, we aim to establish a coal permeability model considering the gas flow in isotropic and porous coal components that include the Klinkenberg effect. The model is strain-based, and the Klinkenberg effect is treated as a dynamic parameter (not an empirical parameter) that is affected by the deformation of the coal matrix or/and fracture due to desorption-induced shrinkage and effective stress changes in the coal matrix. The model is then implanted into the simulation software COMSOL to evaluate the gas flow in coal matrices.

The remainder of the paper is organized as follows: Section 2 describes the modified permeability prediction model, which includes the coal deformation model and the hydrodynamic model. Section 3 introduces the numerical computing results compared with physical experiments and evaluates the parameter evolution under different gas pressure and effective stress conditions. The results and discussion are presented in Section 4. The conclusions are detailed in Section 5.

2. Modified coal permeability model

2.1. Basic assumptions of the model

In this study, the following assumptions are necessary:

1) The coal matrix is continuously saturated with single-phase methane.
2) The porous materials are homogeneous, and the pores in the coal matrix are isotropic.
3) Methane gas is stored in the pores of coal and can be absorbed by the surface of coal particles.
4) The inertial and volume forces produced by gas seepage in the coal matrix are neglected.