Modeling Anisotropic Permeability of Coal and Its Effects on Coalbed Methane Reservoir Simulation

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Abstract: In this study, an alternative permeability model was developed and compared with data from laboratory investigations. The model was further applied for reservoir simulation with several cases in order to evaluate the effects of the anisotropic permeability variation on the CO_2-sequestration and CO_2-sequestration enhanced coalbed methane (CO2-ECBM) recovery. The permeability model developed in this study is based on a discontinuum medium approach, in which coal is treated as a discontinuum medium containing anisotropic matrixes and cleats. The permeability variations and anisotropic permeability ratios under isotropic net stresses were tested with relatively large coal samples. The simulations show good agreements with the experimental data, revealing that the developed model is superior for describing stress- and sorption-induced permeability variations in coals compared with models using constant values for stress-dependent parameters. The results from reservoir simulation incorporating the developed permeability model show the anisotropic permeability exhibit significant effect on CO2-ECBM recovery.

1 INTRODUCTION

Coal is typically an anisotropic porous media consisting of butt and face cleats, featured by anisotropy of the permeability to fluids flowing through the cleats. The anisotropic permeability often varies due to stress change and gas adsorption/desorption occurring during coalbed methane recovery. The deformations of coal and permeability evolution have a significant influence on reservoir performance. Therefore understanding of coal deformation and permeability evolution underlies the use, management and optimization of deep coal as an economic resource for CO_2 sequestration, CBM recovery and underground gasification. So far this phenomenon has not been well understood (Wang et al., 2008; Wei et al., 2007), and it is considered as one of the critical problems for improved CO2-ECBM processes.

In the last several decades many attempts have been made in both the theoretical and experimental studies on the permeability of coal, including the permeability evolution in underground coal reservoirs associated with gas storage and gas production. The currently published permeability models can be generally classified into two types: analytical permeability models (Gray, 1987; Harpalani and McPherson, 1985; Puri and Seidle, 1991; Shi and Durucan, 2004; Somerton, 1975) and coupled permeability models, which include continuum medium coupled (CMC) model and discontinuum medium coupled (DMC) model. Gu and Chalaturnyk (Gu and Chalaturnyk, 2006) compared these models and suggested that the DMC model provides better estimates of permeability and production than analytical models because it includes the influences of many factors, such as discontinuity and anisotropy. While considerable efforts have been made in modelling permeability changes during CO2-ECBM processes, significant limitations exist in these permeability models due to the complexity of the behaviour of coal under dynamically changing stresses. So far there is no model considering the anisotropic permeability evolution associated with CO2-ECBM processes.

This work seeks to investigate anisotropic physical and mechanical properties of in-situ coal and to develop a more practicable and reliable model for reservoir simulations. It will provide a better understanding of structure and anisotropic permeability evolution of coals for prediction and simulation of processes associated with CO_2

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sequestration and CO2-ECBM recovery.

2 PERMEABILITY MODEL

Figure 1 shows the conceptual model of anisotropic permeabilities for a coal core. The anisotropic permeabilities of the coal specimens usually include horizontal permeability and vertical permeability, and the horizontal permeability can be divided into two directional permeabilities of face cleats and butt cleats. The vertical permeability consists of contributions from both face and butt cleats.

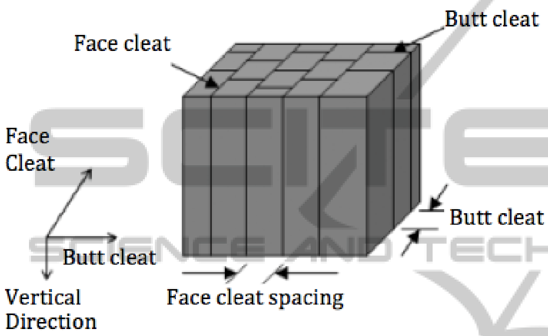

Figure 1: Anisotropic permeability model of a coal specimen.

The 3-dimensional stress and strain relationship for an isotropic specimen can be described as

$$\begin{bmatrix}\sigma_{eB}\\ \sigma_{eF}\\ \sigma_{eV}\end{bmatrix} = \frac{E}{(1+\nu)(1-2\nu)}\begin{bmatrix}1-\nu & \nu & \nu\\ \nu & 1-\nu & \nu\\ \nu & \nu & 1-\nu\end{bmatrix}\begin{bmatrix}\varepsilon_B\\ \varepsilon_F\\ \varepsilon_V\end{bmatrix} \tag{1}$$

where E is Young's modulus, ν is Poison's ratio, σ and ε are effective stress and strain, respectively. The subscripts B, F, and V means butt cleat, face cleat and vertical direction, respectively. σ_{eB}, σ_{eF} and σ_{ev} represent the effective stresses of butt cleat, face cleat and the cleat in vertical direction, respectively

Due to sorption induced dimensional changes (Gilman and Beckie, 2000), Equation (1) can be extended to

$$\begin{aligned}\begin{bmatrix}\sigma_{eB}\\ \sigma_{eF}\\ \sigma_{eV}\end{bmatrix} &= \frac{E}{(1+\nu)(1-2\nu)}\begin{bmatrix}1-\nu & \nu & \nu\\ \nu & 1-\nu & \nu\\ \nu & \nu & 1-\nu\end{bmatrix} \times \left\{\begin{bmatrix}\varepsilon_B\\ \varepsilon_F\\ \varepsilon_V\end{bmatrix} + \begin{bmatrix}\varepsilon_{SB}\\ \varepsilon_{SF}\\ \varepsilon_{SV}\end{bmatrix}\right\}\\ &= \frac{E}{(1+\nu)(1-2\nu)}\begin{bmatrix}1-\nu & \nu & \nu\\ \nu & 1-\nu & \nu\\ \nu & \nu & 1-\nu\end{bmatrix}\begin{bmatrix}\varepsilon_B\\ \varepsilon_F\\ \varepsilon_V\end{bmatrix} + \frac{\alpha}{3(1-2\nu)}E\Delta S\begin{bmatrix}1\\1\\1\end{bmatrix}\end{aligned} \tag{2}$$

where α is the volumetric swelling coefficient, S is the adsorbed mass, ΔS is the variation of the adsorbed mass, ε_{SB}, ε_{SF} and ε_{SV} are the sorption induced strains in three directions.

For the problem of CO2-ECBM recovery from a coal reservoir, we may well assume that overburden stress is constant and uniform. The following assumptions are made

$$\begin{cases}\varepsilon_B = \varepsilon_F = 0\\ \sigma_{eV} = -\Delta P_f\end{cases} \tag{3}$$

where P_f is the pressure in fractures.

Applying Equation (3) to Equation (2), the Equation (2) can be simplified to

$$\sigma_{eB} = \sigma_{eF} = -\frac{\nu}{1-\nu}\Delta P_f + \frac{\alpha}{3(1-2\nu)}E\Delta S \tag{4}$$

For isotropic coal specimens, since the cleats are nearly vertical, we have

$$d\sigma_{eB} = d\sigma_{eF} = -E_f\frac{da}{a} \tag{5}$$

where a is the mean fracture aperture and E_f is the Young's modulus for the fracture. The vertical permeability can be represented as (Wang, et al., 2008)

$$K_V = \frac{a^3}{c\tau_f h} \tag{6}$$

where c is a constant depending on cleat geometry and surface roughness, h is the cleat spacing, and τ_f is the fracture tortuosity. Through calculus and algebraic operations on Equation (6), we obtain

$$\frac{dK_V}{K_V} = \frac{3a^2}{c\tau_f h}\frac{c\tau_f h}{a^3} = 3\frac{da}{a} \tag{7}$$

Substituting Equation (5) to Equation (7) gives

$$\frac{dK_V}{K_V} = -3\frac{d\sigma_{eF}}{E_f} \tag{8}$$

The vertical permeability variations during CO_2

sequestration and enhanced coalbed methane recovery processes can be estimated as

$$K_V = K_{V0} exp\left[\int_{P_{f0}}^{P_f} \frac{3\nu}{(1-\nu)E_f} dP_f\right] exp\left[\int_{S_0}^{S} \frac{\alpha E_m}{(1-\nu)E_f} dS\right] \quad (9)$$

where subscript 0 represents initial condition, and the adsorbed mass *S* can be estimated based on Langmuir isotherm under following assumptions: 1) The adsorbed phase should be in instantaneous equilibrium with the cleat pressure; and 2) The Langmuir isotherm is valid for the determination of the adsorption equilibrium.

For anisotropic coal specimens, the contributions from face cleats and butt cleats can be treated independently. The vertical permeability consists of contributions from both butt and face cleats, represented by

$$\begin{cases} \dfrac{dK_{BV}}{K_{BV}} = -3\dfrac{d\sigma_B}{E_{Bf}} \\ \dfrac{dK_{FV}}{K_{FV}} = -3\dfrac{d\sigma_F}{E_{Ff}} \end{cases} \quad (10)$$

where K_{FV} and K_{BV} are vertical permeability contributions from face and butt cleats, respectively; E_{Ff} and E_{Bf} are Young's moduli for face cleats and butt cleats, respectively. Thus

$$\begin{cases} K_{BV} = K_{BV0}\exp\left(-3\displaystyle\int_{\sigma_{B0}}^{\sigma_B}\frac{1}{E_{Bf}}\right)d\sigma_B \\ K_{FV} = K_{FV0}\exp\left(-3\displaystyle\int_{\sigma_{F0}}^{\sigma_F}\frac{1}{E_{Ff}}\right)d\sigma_F \\ K_V = K_{BV} + K_{FV} \end{cases} \quad (11)$$

Preliminary experimental results obtained from our lab suggested that the variations of anisotropic permeabilities of coals with average net stress, defined by the difference between confined stress acting on a coal sample and fluid pressure in pores, are similar in three directions. Therefore, to simplify the model, we assumed that the permeability variations with average net stress are approximately the same in different directions. Three parameters PAR_{FB}, PAR_{FV} and PAR_{BV} are defined in the model to describe the anisotropic permeability ratios of face cleat to butt cleat, face cleat to vertical direction and butt cleat to vertical direction, respectively. Thus, the horizontal permeabilities, i.e. face cleat and butt cleat permeabilities, can be estimated using the following equations.

$$\begin{cases} K_V = K_V PAR_{FV} \\ K_B = K_V PAR_{BV} \end{cases} \quad (12)$$

3 MODEL PARAMETERS

The model as indicated in Eq. (9) deals with some stress-dependent parameters such as directional permeability, compressibility and Young's modulus for cleats. Those parameters can only be determined experimentally, as shown in Figures. 2-3.

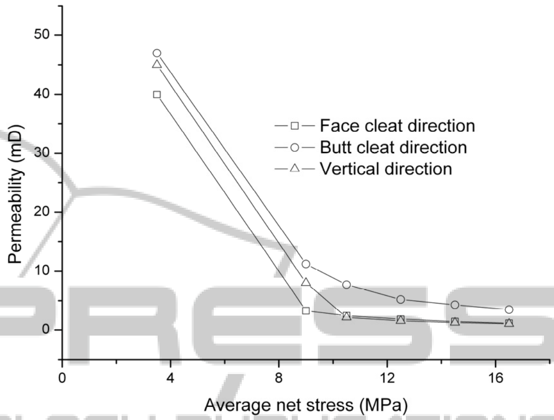

Figure 2: Helium permeabilities through face cleat, butt cleat and vertical directions of a 80 mm cubic coal sample.

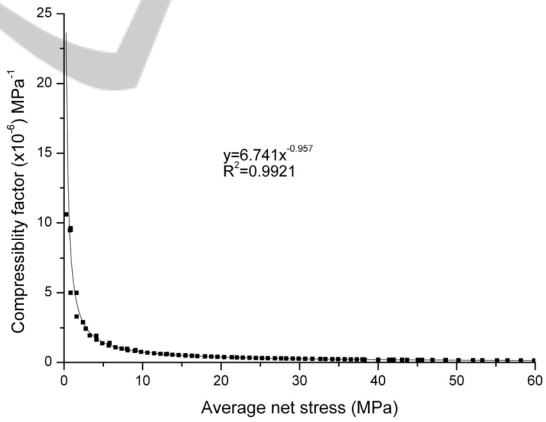

Figure 3: Compressibility factor of coal varying with average net stress.

Mechanical properties of bulk coals such as bulk moduli and total bulk moduli Young's modulus are also stress-dependent and can be estimated as follows.

The bulk modulus is defined as

$$K_{bt} = \frac{1}{C_p} = \frac{E_t}{3(1-2\nu)} \quad (13)$$

where K_{bt} is the total bulk moduli of coal, including the contributions from cleats (or fractures) and matrix; C_p denotes coal compressibility; E_t and ν

represent the Young's modulus and Poison's ratio of coal, respectively. The contributions of cleats and matrix to total bulk moduli of coal are largely depended on the coal compressibility, which can be approximately estimated using the correlation as follows

$$\frac{1}{K_{bt}} = \frac{1-(\sigma/\sigma_{max})}{K_{bf}} + \frac{(\sigma/\sigma_{max})}{K_{bm}} \tag{14}$$

where K_{bf} and K_{bm} are cleat (fracture) and matrix bulk moduli, respectively; σ denotes stress; and σ_{max} is the maximum stress above which the compressibility variation in coal can be negligible, that is, the cleat or fracture contribution to the coal compressibility approaches zero. If the Poison's ratio in Eq. (13) is a constant, the Young's modulus can be estimated by

$$\frac{1}{E_t} = \frac{1-(\sigma/\sigma_{max})}{E_f} + \frac{(\sigma/\sigma_{max})}{E_m} \tag{15}$$

where E_f and E_m are defined as the moduli for cleats and coal matrix, respectively.

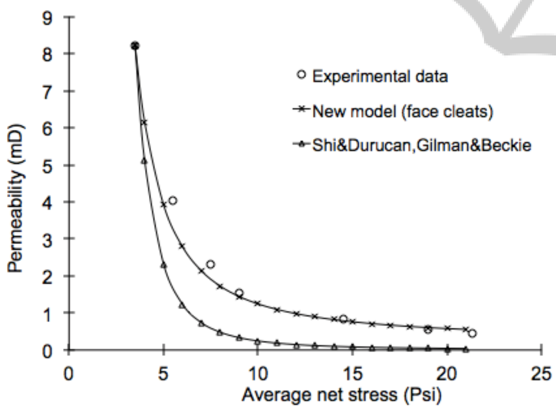

Figure 5: Comparison of methane permeability variations with net stress.

Given the Young's modulus for the coal matrix as 2.82×10^6 MPa, the estimated maximum stress σ_{max} is about 20MPa. Thus the estimated Young's modulus for cleats can be estimated using Eq. (15), as shown in Figure 4. The results show that the Young's modulus for cleats increases remarkably in the lower stress range and then slowly approaches $\sim2.10\times10^6$ MPa at an average net stress of 60 MPa.

4 RESERVOIR SIMULATION

The methane permeability variations with average net stress under constant pore pressure can be comparatively calculated using three permeability models, i.e. the model developed in this study, Shi-Durucan model and Gilman-Beckie model. The calculated results were then compared with the experimental data, as shown in Figure 4. The experimental data of methane permeability variations were measured under constant pore pressure (7.2 MPa) at different average net stresses. Figure 4 shows that the predicted results using the model developed in this study fit the experimental data very well, while the other two models apparently underestimated permeability at higher average net stresses. This is because the values of compressibility factor and Young's modulus for cleats are constant in these two models, ignoring changes in net stresses. In other words, these two models cannot predict the permeability variation with average net stress well by not taking into account the influence of compressibility and Young's modulus for cleats on permeability, particularly at a higher average net stress.

In order to evaluate the effects of the anisotropic permeability variation on the CO_2-sequestration and CO_2-sequestration enhanced coalbed methane (CO_2-ECBM) recovery, a 3-dimensional and two-phase numerical reservoir model was further developed for reservoir simulations by incorporating the developed permeability model to simulate the multi-component gas and water diffusion and flow in coal seams. Details on the reservoir simulation will be reported separately and some results will be discussed later.

5 RESULTS AND DISUSSION

A base case was designed for the reservoir simulations. A five-spot well pattern with one vertical injector in the centre of four horizontal producers was used to represent a pilot-scale project, as shown in Figure 5. The orientation of horizontal producers was assumed to be parallel to the direction of butt cleats. Methane production took place one year before CO_2 injection-ECBM recovery was initiated. The production and injection wells are to be shut-in at the time of CO_2 breakthrough, at which the mole fraction of CO_2 in the gas production stream is equal to 5%. The parameter values used in simulations for the base case are listed in Table 1.

Table 1: Parameter values used in simulations.

Parameter	Value
Reservoir drainage area (ft^2)	25.00×10^6
Coal seam thickness (ft)	10.00
Initial coal seam porosity (%)	2.00
Initial pressure (psia)	800.00
Coal density (g/cc)	1.36
Face, butt and vertical permeability (mD)	1.95, 0.23, 1.35
Poisson's ratio	0.32
Young's modulus for coal matrix (MPa)	2.82×10^6
Micropore diffusion coefficient of CH_4, CO_2 (ft^2/day)	8.37×10^{-5}, 7.44×10^{-4}
Cleat spacing (in)	0.50
Sorption time constant (days)	7.60
Sorption volume (CH_4, CO_2) (scf/ton)	600.00, 1500.00
Sorption pressure (CH_4, CO_2) (psia)	700.00, 300.00
Critical saturation (gas, water) (%)	0.00, 10.00
Initial water saturation (%)	45.00
Initial mole fraction of coal gas (CH_4, CO_2) (%)	100, 0
Reservoir temperature (ºF)	113.00
Wellbore radius (ft)	0.25
Skin factor	0.00

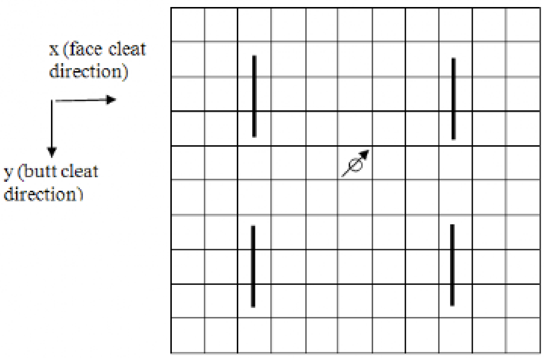

Figure 5: Well patterns for base case (thick lines representing horizontal producers).

5.1 Impact of Anisotropic Permeability

In order to investigate the effects of anisotropic permeabilities on the gas production, six cases were designed based on the experimental measurements. Table 2 lists the cases with different PARs for model simulations.

The values of directional permeabilities used in the six cases were set to be 1.7 times higher or lower than those in base case. The results from the simulations are shown in Figure 6. This forms two groups of data for a better comparative study, i.e. the first three cases comparing with the base case, and Cases 4-6 forming the other group, which will be discussed in details as follows.

Table 2: Cases designed for simulations.

Cases	$K_{vertical}$ (mD)	K_{butt} (mD)	K_{face} (mD)	PAR_{FB}	PAR_{FV}	PAR_{BV}
Base case	1.35	0.23	1.95	8.48	1.44	0.17
Case 1	1.35	0.39	1.95	5.00	1.44	0.29
Case 2	2.28	0.23	1.95	8.48	0.86	0.10
Case 3	1.35	0.23	1.15	5.00	0.85	0.17
Case 4	0.80	1.44	4.32	3.00	5.40	1.80
Case 5	0.80	2.45	4.32	1.76	5.40	3.06
Case 6	0.80	1.44	2.54	1.76	3.18	1.80

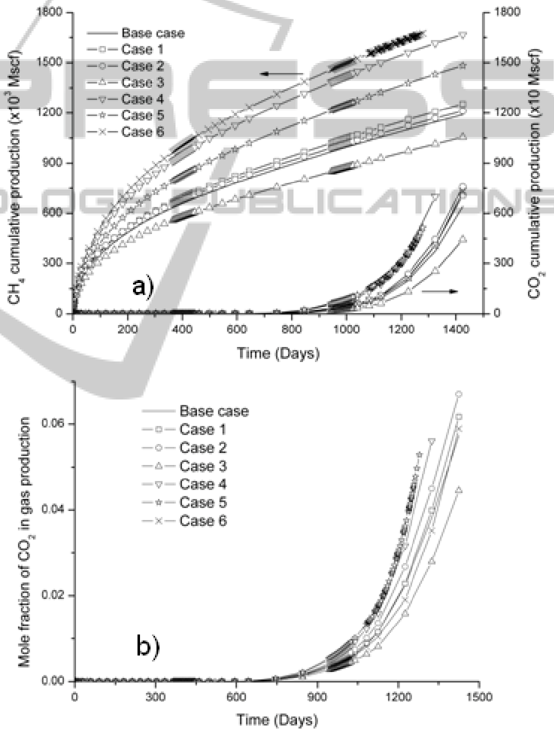

Figure 6: The effects of anisotropic permeability ratios on gas productions.

The comparison of base case and first three cases suggested that face cleat permeability has major effect on CH_4 and CO_2 production. The vertical permeability has major effect on CO_2 injection, but little influence on methane production. For coal reservoir with lower PAR_{BV}, the influence of directional permeabilities on CO_2 breakthrough time deceases in the order of face cleat permeability, vertical permeability and butt cleat permeability. For the cases with higher PAR_{BV}, i.e. Cases 4-6, the face cleat permeability has major effect on CH_4

production and CO_2 injection, while butt cleat has major effect on CO_2 production. Increasing butt cleat permeability may expedite CO_2 breakthrough in produced gas.

5.2 Influence of Permeability Variation

Figure 7 shows the cumulative productions of CH_4 and CO_2 and associated mole fraction of CO_2 in gas production predicted in the designated base case using three permeability models, i.e. model developed in this study, Shi & Durucan model and Gilman & Beckie model.

In fact, the latter two models are essentially one model in which the isotropic permeability is used. In this comparison study, an initial isotropic permeability used in Shi & Durucan model and Gilman & Beckie model was 1.35 mD.

Permeability variation of coal reservoirs is not only affected by the changing stress during the gas production but also, maybe more importantly, controlled by permeability anisotropy of coal. It can be seen from Fig. 8 that the anisotropic permeability clearly has some effect on CH_4 and CO_2 productions using the model developed in this study, compared with Shi & Durucan model and Gilman & Beckie model. The new model predicts that cumulative CH_4

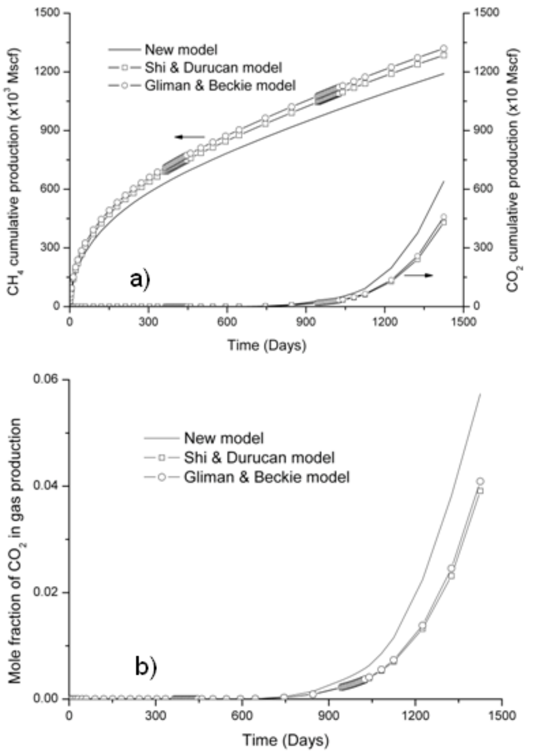

Figure 7: The calculated results of three permeability models for the base case.

production will be lower, but cumulative CO_2 production will be higher than results predicted by the other two models. Additionally, CO_2 breakthrough time will be shorter. These comparison results suggest that the permeability anisotropy has major effects on gas flow dynamics in coal reservoirs, although stress- and sorption-induced permeability variations also affect gas productivity to some extent.

6 CONCLUSIONS

An alternative permeability model was developed to describe anisotropic permeability variations of coal due to stress change and gas sorption. The model has unique features by taking into account separate Young's moduli for coal matrix and cleats, stress-dependent Young's modulus for cleats, and anisotropic permeability ratios etc. These make the model more practicable and reliable to be incorporated into reservoir simulations for the gas and water flow in coal reservoirs. The simulations provide further information to investigate the effects of anisotropic permeability variations on CO_2-ECBM recovery. The results suggested that anisotropic permeability has significant effects on gas production and CO_2 breakthrough time, implying it is a critical parameter in determining well pattern and orientation of horizontal wells.

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