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Linking gas-sorption induced changes in coal permeability to directional strains through a modulus reduction ratio

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ABSTRACT

Although coal–gas interactions have been comprehensively investigated, most prior studies have focused on one or more component processes of effective stress or sorption-induced deformation and for resulting isotropic changes in coal permeability. In this study a permeability model is developed to define the evolution of gas sorption-induced permeability anisotropy under the full spectrum of mechanical conditions spanning prescribed in-situ stresses through constrained displacement. In the model, gas sorption-induced coal directional permeabilities are linked into directional strains through an elastic modulus reduction ratio, R_m. It defines the ratio of coal bulk elastic modulus to coal matrix modulus ($0<R_m<1$) and represents the partitioning of total strain for an equivalent porous coal medium between the fracture system and the matrix. Where bulk coal permeability is dominated by the cleat system, the portioned fracture strains may be used to define the evolution of the fracture permeability, and hence the response of the bulk aggregate. The coal modulus reduction ratio provides a straightforward index to link anisotropy in deformability characteristics to the evolution of directional permeabilities. Constitutive models incorporating this concept are implemented in a finite element model to represent the complex interactions of effective stress and sorption under in-situ conditions. The validity of the model is evaluated against benchmark cases for uniaxial swelling and for constant volume reservoirs then applied to match changes in permeability observed in a field production test within a coalbed reservoir.

1. Introduction

Knowledge of changes in coal permeability due to gas sorption-induced effective stress is crucially important for the evaluation of both primary gas production from coalbed reservoirs and for CO_2-enhanced coalbed methane recovery (ECBM) (RECOPOL Workshop, 2005).

For primary gas production, as the gas pressure reduces below the desorption point, methane is released from the coal matrix to the fracture network and the coal matrix shrinks. As a direct consequence of this matrix shrinkage the fractures dilate and fracture permeability correspondingly increases. Thus, a rapid initial reduction of fracture permeability (due to change in effective stress) is supplanted by a slow increase in permeability (with matrix shrinkage). Whether the ultimate, long-term, permeability is greater or less than the initial permeability depends on the net influence of these dual competing mechanisms. ECBM involves the injection of CO_2 into a coal seam to promote the desorption of coalbed methane (CBM) while simultaneously sequestering CO_2 in the coal seam. This process exploits the greater affinity of carbon dioxide (CO_2) to adsorb onto coal relative to methane (CH_4), resulting in the net desorption of methane and its potential recovery as a low-carbon fuel. Laboratory isotherm measurements for pure gases have demonstrated that coal can adsorb approximately twice (or more) as much CO_2 (in moles) by volume as methane (White et al., 2005). Correspondingly, CO_2 injection with concurrent production of methane can cause differential swelling of the coalbed particularly in the near wellbore area. This may play an important role in determining the resulting deformation of the coal matrix, the related permeability change and its impact on both gas diffusion to the cleats and gas flow along the cleat network. Thus, the influence of these distinct but connected changes in deformation, due to both effective stresses and to gas-sorption-induced swelling, are key to unravelling the transient response to gas injection and recovery. The complexity of the response is further increased by the overprinted effects of bedding plane and cleat orientations, which together with directional stresses or displacement restraints impart a further directional heterogeneity to the transient evolution of permeability. Thus understanding the transient and anisotropic characteristics of permeability evolution in fractured coals is of fundamental

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importance to the recovery of methane from CBM reservoirs and equally important for CO_2 storage using ECBM.

1.1. Experimental observations

The potential impacts of the coal sorption and related swelling characteristics of coals have been investigated experimentally. The effects of water content on swelling and sorption have been explored for CO_2 uptake at 298 K (Ceglarska-Stefanska and Czaplinski, 1993) using a gas-flame coal, a gas-coking coal and an anthracite and indicate a reduction in swelling strain for "dry" coal versus "pre-wetted" samples (Ceglarska-Stefanska and Brzoska, 1998). Rates of swelling are controlled largely by diffusive length scales imparted by the cleats. A surrogate of this case is powdered coals where for powdered high volatile bituminous Pennsylvanian coals the adsorption rate decreases with increasing grain size for all experimental conditions (Busch et al., 2004). Similarly, coal type and rank (Robertson and Christiansen, 2007; Prusty, 2007) influences the preferential sorption behavior and the evolution of permeability with these changes is linked to macromolecular structure (Mazumder and Wolf, 2008). Adsorption kinetics may also be determined for various gases (e.g. for CO_2 and CH_4) using confining cells to apply desired pressures and temperatures (Charrière et al., 2010) and using X-ray CT methods to determine the resulting sorption isotherms (Jikich et al., 2009). These experiments have focused on the isotropic characteristics of intact or powdered coals.

Nevertheless, some experiments have focused on the anisotropic characteristic of coal. Water transmission characteristics have been shown to be significantly different Gash et al., 1993) under confining pressures when measured perpendicular to either face cleats, butt cleats, or bedding planes. Directional flow experiments on isotropically compressed samples have similarly confirmed the anisotropy of permeability for gas flows (Li et al., 2004). These results are congruent with optical measurements of coal swelling under in CO_2 and other gases where swelling in the plane perpendicular to the bedding plane was always substantially higher than parallel to the bedding plane (Day et al., 2008). This phenomenon has also been observed in the field well tests in the Warrior Basin (USA) where the anisotropy ratio of permeability in the direction of the bedding plane was as high as 17:1 (Koenig and Stubbs, 1986).

1.2. Permeability models

Based on experimental observations, a variety of models have been formulated to quantify the evolution of permeability during coal swelling/shrinkage. Gray (1987) firstly attempted to quantify the role of stresses on the evolution of coal-reservoir permeability, in which permeability was computed as a function of reservoir pressure-induced coal-matrix shrinkage assumed directly proportional to changes in the equivalent sorption pressure. Since then, a number of theoretical and empirical permeability models have been proposed (Seidle and Huitt, 1995; Palmer and Mansoori, 1996; Pekot and Reeves, 2002; Shi and Durucan, 2004). However, most of these studies are under the assumption of either an invariant total stress or uniaxial strain conditions. These critical and limiting assumptions have been relaxed in new models rigorously incorporating in-situ stress conditions (Zhang et al., 2008; Palmer, 2009; Connell, 2009) and are extended to rigorously incorporate CO_2–CH_4 coal–gas interaction relevant to CO_2–ECBM (Connell and Detournay, 2009; Chen et al., 2010).

Despite the complexity of models applied to represent the evolution of coalbed methane reservoirs, few accommodate feedbacks of both anisotropy and coal–gas interaction on the evolution of permeability — including the important roles of linked stress-deformation and gas flow and adsorption/desorption processes. The effect of stress on the evolution of flow anisotropy in orthogonally fractured media (Sayers, 1990) and in deformable granular media (Du et al., 2004) has been investigated although not with the influence of gas adsorption or desorption effects. The impact of permeability anisotropy and pressure interference on CBM gas production has been investigated specifically to seek any unique performance feature that might distinguish between isotropic or anisotropic permeability of the CBM reservoir or to identify the drainage geometry (Chaianansutcharit et al., 2001). And analytical solutions have been presented for steady-state conditions with anisotropic permeability (Al-Yousef, 2005). More recently, an alternative approach has been proposed to develop an improved permeability model for CO_2-ECBM recovery and CO_2 geo-sequestration in coal seams, integrating the textural and mechanical properties to describe the anisotropy of gas permeability in coal reservoirs under confined stress conditions (Wang et al., 2009).

1.3. This study

In this study, a novel permeability model is developed to define the evolution of gas sorption-induced permeability anisotropy under in-situ stress conditions. Gas sorption-induced coal directional permeabilities are linked to directional strains through the elastic modulus reduction ratio (the ratio of coal mass elastic modulus to coal matrix modulus) that represents the partition of the total strain for an equivalent porous coal medium between the fracture system and the matrix. It is assumed that only the partitioned fracture strains are responsible for the changes in directional permeabilities. These new relations are the key cross couplings that link effective stress-related and sorption-related changes in permeability to fluid pressure and gas content. These constitutive relationships are incorporated into a finite element model to represent the complex interactions of stress and chemistry under in-situ conditions and to project their impact on rates and magnitudes of gas recovery. The validity of the general model is evaluated against results for special cases representing uniaxial swelling, constant volume reservoirs, and for the case of a coalbed methane production well test. The incorporation of gas sorption-induced coal permeability anisotropy into the multiphysics simulation of coal–gas interaction represents a new and important contribution to this subject.

2. Approach

The overall approach is illustrated in Fig. 1. The evaluation of fully coupled deformation and gas transport in the fractured coal is conducted through four integrated steps: (1) Coal deformation analysis; (2) Flow equivalence analysis; (3) Permeability evolution analysis; and (4) Flow equivalence updating. These four steps are detailed in the following sections.

2.1. Coal deformation analysis

The mechanical properties of a discontinuous medium containing orthogonal fractures and orthotropic response can be represented by the properties of an equivalent continuous medium (Amadei and Goodman, 1981). The following assumptions are made:

(a) The coal is a homogeneous, isotropic and elastic continuum, and the system is isothermal.
(b) Strains are infinitesimal.
(c) Gas contained within the pores is ideal, and its viscosity is constant under isothermal conditions.
(d) Gas flow through the coal medium is assumed to be viscous flow obeying Darcy's law.

According to the first assumption (a), the strain–displacement relation is expressed as

$$\varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}) \quad (1)$$

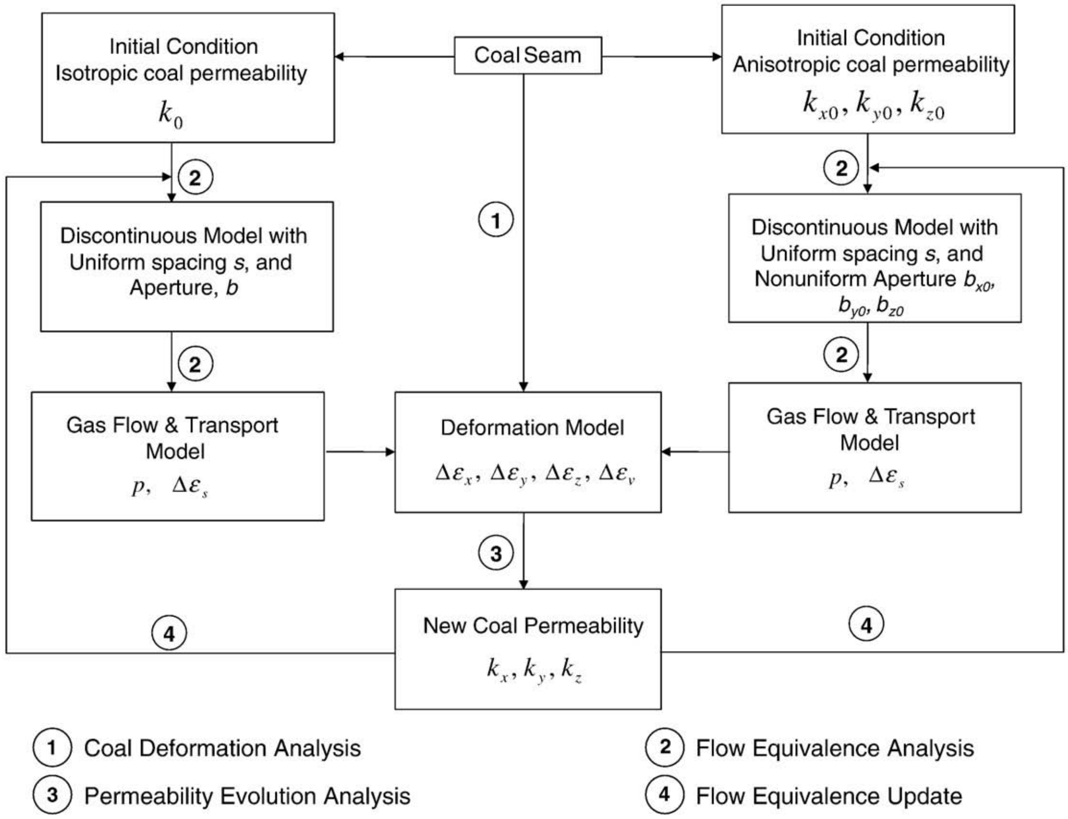

Fig. 1. Flow chart for evaluating coupled deformation and gas transport processes in coal. Circled numbers represent steps of the analysis process.

where ε_{ij} is the component of the total strain tensor and u_i is the component of the displacement. The equilibrium equation is defined as

$$\sigma_{ij,j} + f_i = 0 \tag{2}$$

where σ_{ij} denotes the component of the total stress tensor and f_i denotes the component of the body force.

The gas sorption-induced strain ε_s is assumed to result in only normal strains and these resulting strains are isotropic. The effects of gas sorption on the deformation of coal seams can be treated analogous to the effects of temperature for elastic porous media (e.g., Palmer and Mansoori, 1996), stress–strain relationships for an isothermal gas adsorbing coalbed may be written as (Shi and Durucan, 2004)

$$\varepsilon_{ij} = \frac{1}{2G}\sigma_{ij} - \left(\frac{1}{6G} - \frac{1}{9K}\right)\sigma_{kk}\delta_{ij} + \frac{\alpha}{3K}p\delta_{ij} + \frac{\varepsilon_s}{3}\delta_{ij} \tag{3}$$

where $G = \frac{E}{2(1+\nu)}$, $K = \frac{E}{3(1-2\nu)}$, $E = R_m \cdot E_m$,

$\alpha = 1 - \frac{K}{K_m}, \sigma_{kk} = \sigma_{11} + \sigma_{22} + \sigma_{33}$.

E is the equivalent Young's modulus of the coal-fracture assemblage; K represents the bulk modulus coal-fracture assemblage, and K_m represents the bulk modulus of coal matrixes. G is the shear modulus of coal, ε_s is the sorption-induced strain, E_m is the Young's modulus of the coal matrix, R_m is the modulus reduction ratio, and ν is the Poisson's ratio of the coal-fracture assemblage. α represents the Biot's coefficient, p the gas pressure in the pores and δ_{ij} is the Kronecker delta; 1 for $i=j$ and 0 for $i \neq j$.

Combining Eqs.(1)–(3) yields the Navier-type equation expressed as

$$G\nabla^2 u_i + \frac{G}{1-2\nu}e_{,i} - \alpha p_{,i} - K\varepsilon_{s,i} + f_i = 0 \tag{4}$$

where u_i is the displacement in i direction, e is the volumetric strain, and $p_{,i}$ is the partial derivative of pore pressure with respect to i. Eq. (4) is the governing equation representing deformation of the continuum representation of the fractured coal allowing deformations to be determined if fluid pressures, p, may be determined for both undrained and drained response. Transient fluid pressures are recovered from the flow equation.

2.2. Flow and transport analysis

The mass balance equation for a single component gas is defined as

$$\frac{\partial m}{\partial t} + \nabla \cdot (\rho_g \boldsymbol{q}_g) = Q_s \tag{5}$$

where ρ_g is the gas density, $\boldsymbol{q}_g$ is the Darcy velocity vector and Q_s is the gas source or sink. m is the gas content including both free-phase and absorbed components (Saghafi et al., 2007) and is defined as

$$m = \rho_g \phi_f + \left(1 - \phi_f\right)\rho_{ga}\rho_c \frac{V_L p}{p + P_L} \tag{6}$$

where ρ_{ga} is the gas density at standard conditions, ρ_c is the coal density and ϕ_f is fracture porosity. V_L represents the Langmuir volume constant and P_L represents the Langmuir pressure constant. According to the real gas law, the gas density is proportional to the pore gas pressure and can be described as

$$\rho_g = \frac{M_g}{ZRT} p \tag{7}$$

where M_g is the molar mass of gas, R is the universal gas constant, T is the gas temperature and Z is the correction factor that accounts for the non-ideal behavior of the gas which changes with R and T.

Assuming that the effect of gravity is relatively small and can be neglected, the Darcy velocity may be defined as

$$\boldsymbol{q}_g = -\frac{\vec{k}}{\mu} \nabla p \tag{8}$$

where μ denotes the dynamic viscosity of the gas and $\vec{k}$ denotes the permeability tensor, expressed as

$$\vec{k} = \begin{bmatrix} k_{xx} & k_{xy} & k_{xz} \\ k_{yx} & k_{yy} & k_{yz} \\ k_{zx} & k_{zy} & k_{zz} \end{bmatrix} \tag{9}$$

Substituting Eqs.(6)–(9) into Eq. (5), gives

$$\left[\phi_f + \left(1-\phi_f\right) \frac{\rho_c p_a V_L P_L}{(p + P_L)^2}\right] \frac{\partial p}{\partial t} + \left(p - \frac{\rho_c p_a V_L p}{p + P_L}\right) \frac{\partial \phi_f}{\partial t} - \nabla \cdot \left(\frac{\vec{k}}{\mu} p \nabla p\right) = Q_s \tag{10}$$

where p_a is atmospheric pressure (1 atm or 101.325 kPa). In Eq. (10), the permeability $\vec{k}$ is dependent on the porosity, ϕ_f, while ϕ_f is a function of the volumetric strain, and the sorption-induced strain, ε_s, which will be illustrated in detail in the following sections. Therefore, Eqs. (4) and (10) will be coupled through the porosity–permeability relation and pore pressure evolution.

2.3. Coal permeability analysis

In the analysis of coal permeability the fractured coal mass is treated as a discontinuous medium comprising both matrix and fractures (cleats), as illustrated in Fig. 2. The individual matrix blocks are represented by cubes and may behave isotropically with regard to swelling/shrinkage, thermal expansion, and mechanical deformability. The cleats are the three orthogonal fracture sets and may also have different apertures and mechanical properties ascribed to the different directions.

Changes in coal permeability are determined by the redistribution of effective stresses or strains due to changed conditions such as gas injection. Typically, stresses and strains will evolve at different rates in the different Cartesian directions, i.e., $\Delta\sigma_x$,$\Delta\sigma_y$, $\Delta\sigma_z$ and $\Delta\varepsilon_x$, $\Delta\varepsilon_y$, $\Delta\varepsilon_y$, and result in anisotropic permeabilities, k_x,k_y, k_z. To derive the relationship between stresses/strains and directional permeability, several assumptions and definitions are made:

a) The initial porous coal is substituted either by a discontinuous model with uniform fracture spacing s and aperture b, as shown in Fig. 2(a), or by a discontinuous model with uniform spacing s and non-uniform aperture, b_{x0}, b_{y0}, and b_{z0}, as shown in Fig. 2(b).
b) The coal fracture porosity ϕ_f can be determined by fracture spacing and aperture as follows, $\phi_f = \frac{(b+s)^3 - s^3}{(b+s)^3} \cong 3b/s$. For the two-dimensional case, the areal porosity for x- or y-directions is defined as $\phi_{fx} \cong 2b_y/s$ and $\phi_{fy} \cong 2b_x/s$, respectively.
c) Fracture and matrix deformation are both linear and fully recoverable, and deformations in normal closure or opening are the predominant permeability alteration mode. Therefore, coal permeability changes can be defined as a function of the variation of aperture in corresponding directions i.e., Δb_x,Δb_y, and Δb_z; where the aperture variation partitioned from the porous medium is realized through the elastic modulus reduction ratio, R_m.
d) The coal matrix is functionally impermeable, and the dominant fluid flow within the fractures may be defined by an equivalent parallel plate model. This enables the strain-dependent effective porosity and the strain-dependent permeability field to be determined if induced strains can be adequately partitioned between fracture and matrix.

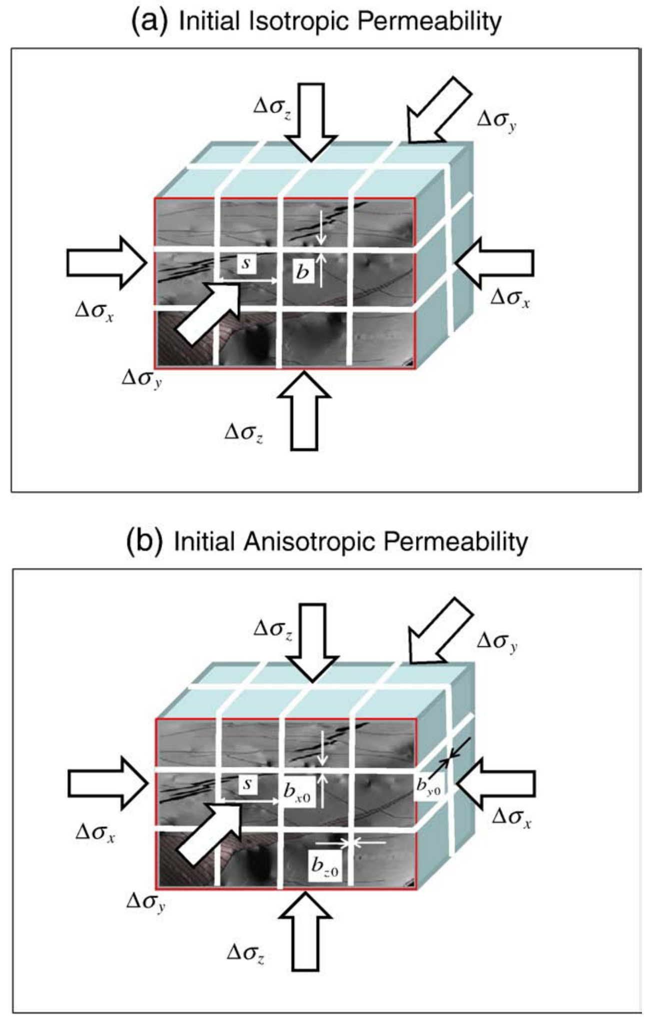

Fig. 2. Substitution of porous coal by discontinuous models.

The schematic diagram regarding the fracture aperture change and the effective stress alteration is shown in Fig. 3. The aperture closure induced by the effective stress change can be calculated by

$$\Delta b_i = (b_i + s) \cdot \frac{\Delta\sigma_{ei}}{E} - s \cdot \frac{\Delta\sigma_{ei}}{E_m} \tag{11}$$

Simplifying this equation, gives

$$\Delta b_i = s \cdot \left(1 - \frac{E}{E_m}\right) \frac{\Delta\sigma_{ei}}{E} + b_i \cdot \frac{\Delta\sigma_{ei}}{E} \tag{12}$$

If assuming $R_m = E/E_m$, $\Delta\varepsilon_{ei} = \Delta\sigma_{ei}/E$, then the above equation can be derived

$$\Delta\varepsilon_{fi} = \frac{\Delta b_i}{b} = \left[\frac{s \cdot (1 - R_m)}{b} + 1\right] \cdot \Delta\varepsilon_{ei} \tag{13}$$

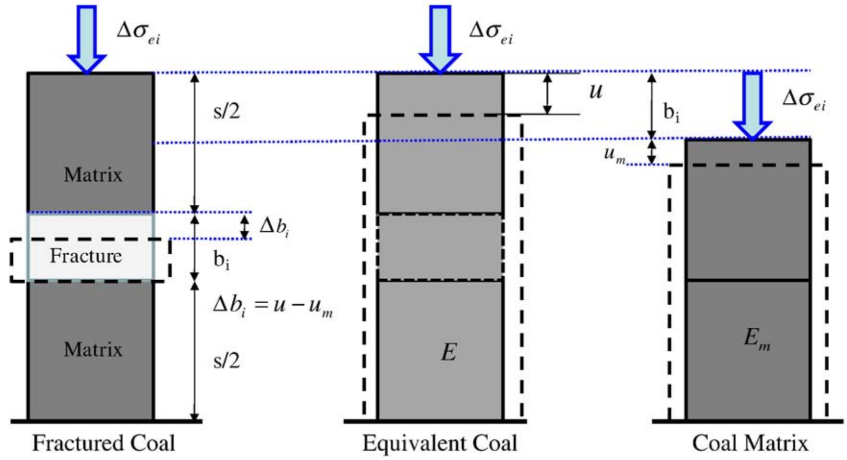

Fig. 3. Schematic diagram of fracture aperture interaction with effective stress.

Because $b \ll s$, Eq. (13) can be simplified into

$$\Delta\varepsilon_{fi} = \frac{\Delta b_i}{b} = \frac{s\cdot(1-R_m)}{b}\Delta\varepsilon_{ei} \tag{14}$$

where R_m is the elastic modulus reduction ratio, $\Delta\varepsilon_{ei}$ is the effective strain change in the i- direction, s is the fracture spacing and b_{i0} is the initial fracture aperture along i- direction.

Based on the above analysis, for the 3D case with three orthogonal sets of fractures, coal directional permeability, k_x, k_y, and k_z are defined as follows (Liu et al., 1999)

$$\frac{k_i}{k_{i0}} = \sum_{i\neq j}\frac{1}{2}\left[1 + \frac{3(1-R_m)}{\phi_{f0}}\Delta\varepsilon_{ej}\right]^3 \tag{15}$$

$$k_{i0} = \sum_{i\neq j}\frac{b_{j0}^3}{12s} \tag{16}$$

where ϕ_{f0} is the initial fracture porosity at reference conditions, i, $j = x,y,z$ for 3D case.

For the 2D case with two orthogonal sets of fractures, coal directional permeability, k_x and k_y are defined as follows

$$\frac{k_i}{k_{i0}} = \left[1 + \frac{2(1-R_m)}{\phi_{f0}}\Delta\varepsilon_{ej}\right]^3, i \neq j \tag{17}$$

$$k_{i0} = \frac{b_{j0}^3}{12s}, i \neq j \tag{18}$$

where $i,j = x,y$ for 2D case.

Results from field and laboratory experiments indicate that coal permeability can change significantly during adsorbable gas injection (e.g. CH_4 and CO_2). The injection gas pressure tends to mechanically open coal cleats and thus enhance the permeability as the initial gas pressure resides only in the fractures and any constrained change in total stress compresses the matrix blocks. The subsequent gas adsorption into the coal matrix induces swelling (volumetric strain) and has two effects: (1) it reduces effective stresses and causes an elastic expansion of the coal bulk due to the increase of gas pressure, overprinted by a (2) sorption-induced swelling of the coal matrix as gas diffuses into coal matrixes. If expansion of the cleat-matrix assemblage is constrained then fracture permeability reduces by narrowing and even closing cleat apertures. When the coal swelling is taken into consideration, the total effective strains in the Eq. (15) can be replaced by the differences between the total strain change, $\Delta\varepsilon_{it}$, in i direction and the free swelling strain change, $\Delta\varepsilon_s$, as follows

$$\Delta\varepsilon_{ei} = \Delta\varepsilon_{it} - \frac{1}{3}\Delta\varepsilon_s \tag{19}$$

Thus for 3D case we have

$$\frac{k_i}{k_{i0}} = \sum_{i\neq j}\frac{1}{2}\left[1 + \frac{3(1-R_m)}{\phi_{f0}}\left(\Delta\varepsilon_{jt} - \frac{1}{3}\Delta\varepsilon_s\right)\right]^3 \tag{20}$$

For the 2D case with two orthogonal sets of fractures, coal directional permeability, k_x and k_y were defined as

$$\frac{k_i}{k_{i0}} = \left[1 + \frac{2(1-R_m)}{\phi_{f0}}\left(\Delta\varepsilon_{jt} - \frac{1}{3}\Delta\varepsilon_s\right)\right]^3, i \neq j \tag{21}$$

2.4. Coupled model

For a system containing a single gas phase the sorption-induced volumetric strain ε_s may be represented by a Langmuir type function (Harpalani and Schraufnagel, 1990; Cui and Bustin, 2005; Robertson and Christiansen, 2007), defined as

$$\varepsilon_s = \varepsilon_L\frac{p}{P_L + p} \tag{22}$$

where ε_L and P_L are the Langmuir-type matrix swelling/shrinkage constants, which represent the maximum swelling capacity and the pore pressure at which the measured volumetric strain is equal to 0.5 ε_L, respectively.

Substituting Eq. (22) into Eq. (4), we rewrite the governing equation for deformation of the coal seam as

$$G\nabla^2 u_i + \frac{G}{1-2\nu}e_{,i} - \alpha p_{,i} - \frac{K\varepsilon_L P_L}{(p + P_L)^2}p_{,i} + f_i = 0 \tag{23}$$

From Eq. (14), we can determine porosity ϕ_f as

$$\phi_f = \frac{b_0 + \Delta b}{3s} = \phi_{f0} + 3(1-R_m)\cdot(\Delta e - \Delta\varepsilon_s) \tag{24}$$

Then, the partial derivative of porosity ϕ_f with respect to time can be expressed as

$$\frac{\partial \phi_f}{\partial t} = 3(1-R_m)\left[\frac{\partial e}{\partial t} - \frac{\varepsilon_L P_L}{(p+P_L)^2}\frac{\partial p}{\partial t}\right] \tag{25}$$

Substituting Eq. (25) into Eq. (10) yields the governing equation for gas flow through a coal seam with the effect of gas sorption incorporated as

$$\left[\phi_f + \left(1-\phi_f\right)\frac{\rho_c p_a V_L P_L}{(p+P_L)^2} - 3(1-R_m)\left(p-\frac{\rho_c p_a V_L p}{p+P_L}\right)\frac{\varepsilon_L P_L}{(p+P_L)^2}\right]\frac{\partial p}{\partial t} - \nabla\cdot\left(\frac{\vec{k}}{\mu}p\nabla p\right) = -3(1-R_m)\left(p-\frac{\rho_c p_a V_L p}{p+P_L}\right)\frac{\partial e}{\partial t} + Q_s \tag{26}$$

In our analysis of coal deformation, the fractured coal mass is represented as an orthotropic fractured medium which is replaced as an equivalent continuous medium. When we conduct flow analysis, we partition the total effective strain from the equivalent medium between coal matrix and the fracture system. Only the partitioned strain for the fracture system contributes to the permeability change. When the rock mass reduction ratio is unity, i.e. $R_m = 1$ then the equivalent modulus of the fractured medium is equal to that of the coal matrix. In other words the coal mass may be considered as unfractured or the fractures are infinitely small. Conversely, in the limit as $R_m = 0$ then the coal matrix is infinitely stiff and the observed deformational response is equivalent to that of the fractures alone. Therefore the parameter $1 - R_m$ represents the ratio of the partitioned strain for the fracture system to the total equivalent strain. If $R_m = 1$, the partitioned strain for the fracture system is due to that of the matrix modulus, which is essentially zero in comparison to the anticipated response of the more compliant fractures; therefore a very small permeability change due to the deformation of the matrix results and this is taken as null. If $R_m = 0$ then the partitioned strain is predominantly due to the fracture deformation. Where the fractures are typically more compliant than the host from which they are derived, then a maximum permeability change results.

The total effective strain is the difference between the total strain, as determined by the constrained boundary conditions, and the free swelling strain. Therefore, the boundary conditions also control the evolution of coal permeability.

In the following sections, we use three examples to illustrate these principles. These are respectively conditions of (1) uniaxial strain; (2) constant reservoir volume; and (3) the behavior of a field case.

3. Uniaxial strain condition

For the case of uniaxial strain, the lateral strains, $\Delta\varepsilon_{tx}$ and $\Delta\varepsilon_{ty}$, are equal to zero. Based on Hooke's law, the relation between stress and strain increments are:

$$\Delta\varepsilon_{ex} = \Delta\varepsilon_{tx} - \frac{1}{3}\Delta\varepsilon_s = \frac{1}{E}[(1-\nu)\Delta\sigma_{ex} - \nu\Delta\sigma_{ez}] = -\frac{1}{3}\Delta\varepsilon_s \tag{27}$$

$$\Delta\varepsilon_{ey} = \Delta\varepsilon_{ty} - \frac{1}{3}\Delta\varepsilon_s = \frac{1}{E}\left[(1-\nu)\Delta\sigma_{ey} - \nu\Delta\sigma_{ez}\right] = -\frac{1}{3}\Delta\varepsilon_s \tag{28}$$

$$\Delta\varepsilon_{ez} = \frac{1}{E}[\Delta\sigma_{ez} - 2\nu\Delta\sigma_{ex}] = \frac{(p-p_0)}{E}\frac{(1+\nu)(1-2\nu)}{1-\nu} - \frac{2\nu}{3(1-\nu)}\varepsilon_s \tag{29}$$

Substituting these Eqs. into Eq. (20) gives

$$\frac{k_x}{k_{x0}} = \frac{k_y}{k_{y0}} = \frac{1}{2}\left[1 + \frac{3(1-R_m)}{\phi_{f0}}\left(-\frac{1}{3}\Delta\varepsilon_s\right)\right]^3 + \frac{1}{2}\left[1 + \frac{3(1-R_m)}{\phi_{f0}}\left(\frac{(p-p_0)}{E}\frac{(1+\nu)(1-2\nu)}{1-\nu} - \frac{2\nu}{3(1-\nu)}\varepsilon_s\right)\right]^3 \tag{30}$$

$$\frac{k_z}{k_{z0}} = \left[1 + \frac{3(1-R_m)}{\phi_{f0}}\left(-\frac{1}{3}\Delta\varepsilon_s\right)\right]^3 \tag{31}$$

As shown in Eqs. (30) and (31), coal permeability in the x-direction is not equal to the permeability in the z-direction. The vertical permeability, k_z, is determined by the swelling strain only while the horizontal permeability, k_x or k_y, is determined both by the swelling strain and by the mechanical deformation. It is obvious that k_z is not equal to k_x even if $k_{x0} = k_{y0} = k_{z0}$. In order to illustrate these conclusions graphically, we use a set of parameters in the Table 1 to quantify the directional permeabilities. The calculated results are shown in Fig. 4. If $R_m = 1$, the partitioned strain for the fracture system is zero; therefore, no permeability change is induced: permeability ratios are equal to unity; If $R_m = 0$, the partitioned strain for the fracture system is 100%; therefore, maximum permeability changes (k_x and k_z) are induced.

4. Displacement controlled condition

For the displacement controlled (or constant reservoir volume) case, strains in all directions, $\Delta\varepsilon_{tx}$, $\Delta\varepsilon_{ty}$, and $\Delta\varepsilon_{tz}$ are equal to zero. Substituting zero value into Eq. (20) gives

$$\frac{k_x}{k_{x0}} = \frac{k_y}{k_{y0}} = \frac{k_z}{k_{z0}} = \left[1 + \frac{3(1-R_m)}{\phi_{f0}}\left(-\frac{1}{3}\Delta\varepsilon_s\right)\right]^3 \tag{32}$$

As shown in Eq. (32), coal permeability ratio in the x- and y-directions is equal to the permeability ratio in the z-direction. All permeability ratios are determined by the swelling strain only. It is apparent that k_z is equal to k_x if $k_{x0} = k_{y0} = k_{z0}$. In order to illustrate these conclusions graphically, we use the parameters in the Table 1 to quantify the directional permeabilities. The calculated results are shown in Fig. 5. We also compare the results for the constant volume case with the ones for the uniaxial strain case in z-direction. For the constant volume case, 100% of the swelling strain contributes to the total effective strain; for the uniaxial strain case, only a portion of the swelling strain contributes to the total effective strain due to the unconstrained condition in the vertical direction. Therefore, maximum permeability changes are induced under the displacement controlled case.

5. Field case

It is generally believed that the in-situ response of a coal gas reservoir to gas production (injection) can be approximated either by

Table 1
Parameters used for the example calculations.

Parameter	Definition	Value
E	Young's modulus	2.7 GPa
ν	Poisson's ratio	0.4
ε_L	Langmuir strain constant	0.03
ϕ_{f0}	Initial fracture porosity	3.0%
p_L	Langmuir pressure constant	3 MPa
R_m	Elastic modulus reduction ratio	0, 0.5, 1

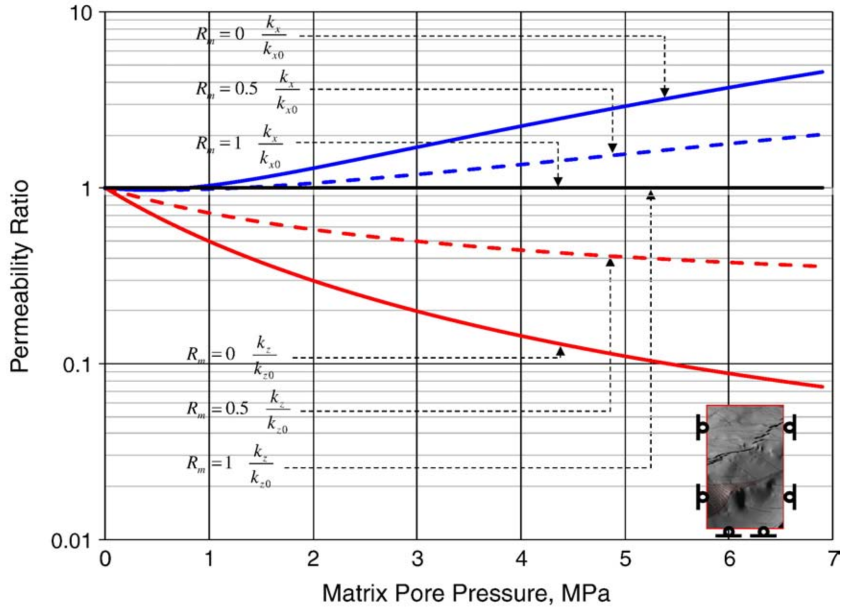

Fig. 4. Coal permeability as a function of matrix pore pressure under uniaxial strain condition and the influence of gas adsorption. Permeability ratios are regulated by the modulus ratio, R_m:$R_m = 1$ represents no fracture influence; $R_m = 0$ represents fracture influence only; $R_m = 0.5$ combined influence of fracture and matrix deformation.

the uniaxial deformation-permeability model (Liu and Rutqvist, 2010) or by the constant volume-permeability model (Massarotto et al., 2009). In this section, we apply both coal permeability models to a field case.

Mavor and Vaughn (1997) reported coal permeability results of three wells in the Valencia Canyon area of the San Juan Basin, and found coal permeability increased between 2.7 and 7.1 times as gas pressure decreased. The initial gas pressures for these wells are 5.35, 6.60 and 6.41 MPa, respectively. Because of the small differences, an average value of 6.12 MPa is used in this evaluation. The following mechanical properties and matrix swelling parameters are taken directly from Liu & Rutqvist (2010): $\nu = 0.3$, $E = 2900$ MPa, $p_L = 2.55$ MPa, $\varepsilon_L = 0.0043$. The initial fracture porosity is 0.05% (Mavor and Vaughn, 1997). These values are representative of the San Juan Basin coalbed.

For the uniaxial strain assumption, Eqs. (30) and (31) were used to evaluate the permeability changes. In this case, the vertical permeability is different from the horizontal permeability. This means that coal shrinkage induces the permeability anisotropy. In our analysis, we match the horizontal permeabilities with the field data.

For the constant reservoir volume assumption, Eq. (32) was used to evaluate the permeability changes. For both assumed conditions,

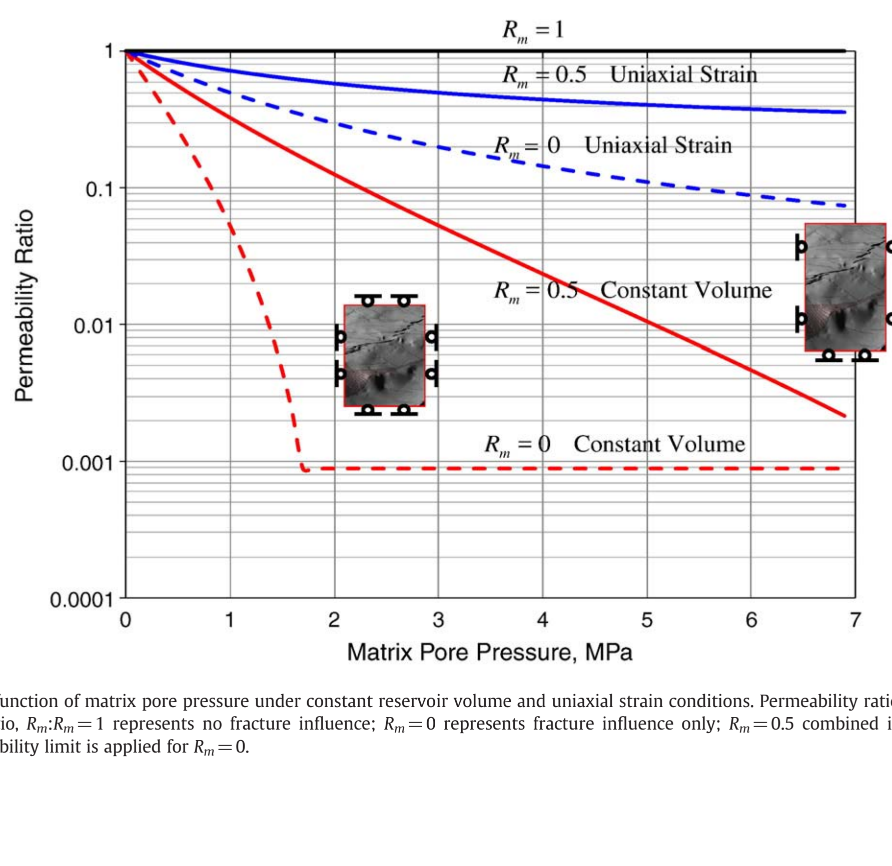

Fig. 5. Coal permeability as a function of matrix pore pressure under constant reservoir volume and uniaxial strain conditions. Permeability ratios are equal in all directions and regulated by the modulus ratio, R_m:$R_m = 1$ represents no fracture influence; $R_m = 0$ represents fracture influence only; $R_m = 0.5$ combined influence of fracture and matrix deformation. A cut-off permeability limit is applied for $R_m = 0$.

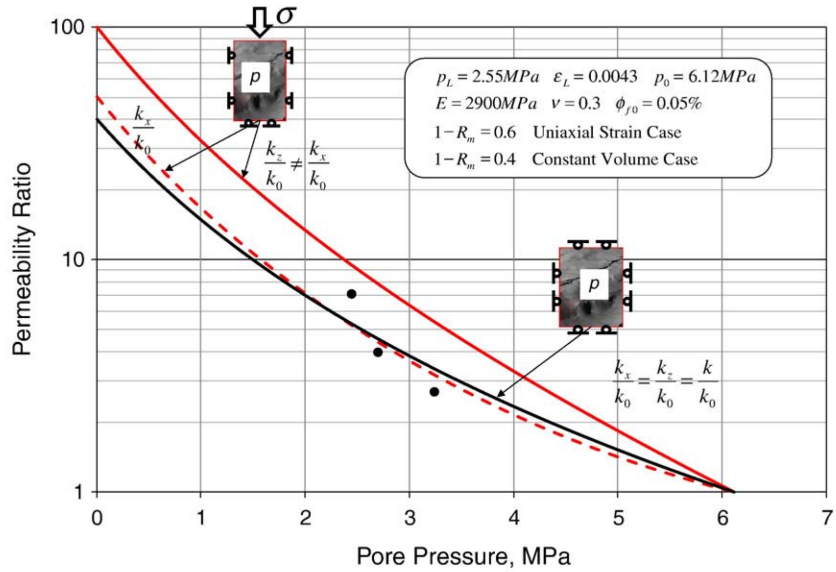

Fig. 6. Matching with field data through use of the uniaxial strain and constant reservoir volume models.

only the modulus reduction ratio, R_m, is adjustable. Best matches were achieved when $R_m = 0.4$ and $R_m = 0.6$, respectively, as shown in Fig. 6. For the uniaxial deformation case, $1 - R_m = 0.6$, representing a partitioned strain of the equivalent porous coal medium for the fracture system of 60%. For the constant volume case, $1 - R_m = 0.4$, representing a partitioned strain of the equivalent porous coal medium for the fracture system of 40%.

6. Evaluation of coupled processes

A field scale model is used to simulate the performance of coalbed methane production under in-situ conditions. Input parameters for this simulation are identical to the parameters used in Section 5. The simulation model geometry is 200 m by 200 m with a methane production well located at the lower left corner. For the coal deformation model, all four sides are constrained in the normal direction. For the gas transport model, the coal is saturated initially with CH_4 and the initial pressure is 6.12 MPa. A condition of atmospheric pressure is applied at the boundary representing the production well. Simulation results are presented in Figs. 7–9.

In this simulation, the reservoir volume remains unchanged throughout the production. This assumption requires that global strains within the coal seam are zero. However, this constraint does not preclude sorption-induced shrinkage (or swelling) of individual coal blocks and complementary opening (or closing) of fractures. The direct consequence of these internal transformations is the isotropic change in permeability defined through Eq. (32).

As shown in that equation, the change in coal permeability is defined only by the swelling strain. This represents the ideal case, i.e., 100% of the swelling strain contributes to the effective stress-induced coal deformation. However, only a portion of the effective stress-induced coal deformation contributes to the permeability change as

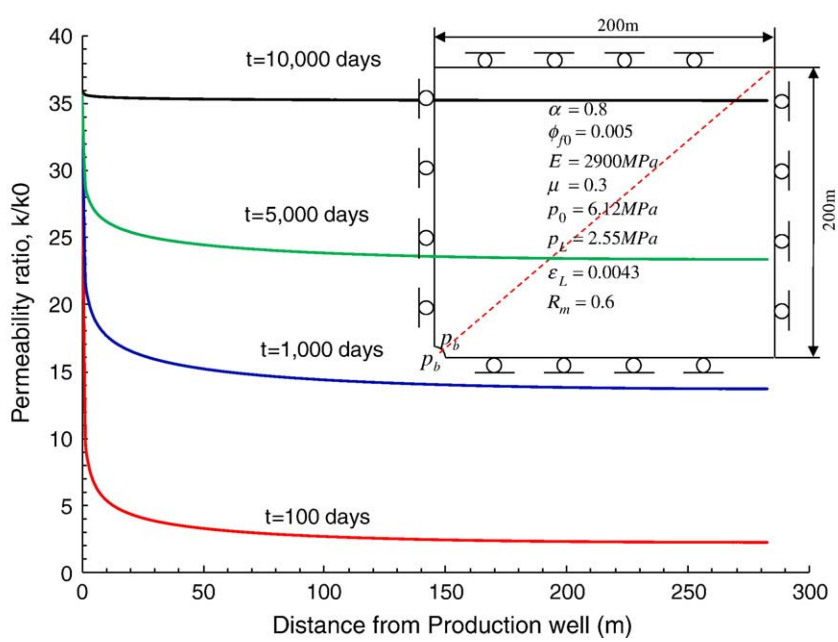

Fig. 7. Spatial and temporal evolution of coal permeability ratios on a diagonal radial traverse from the production well.

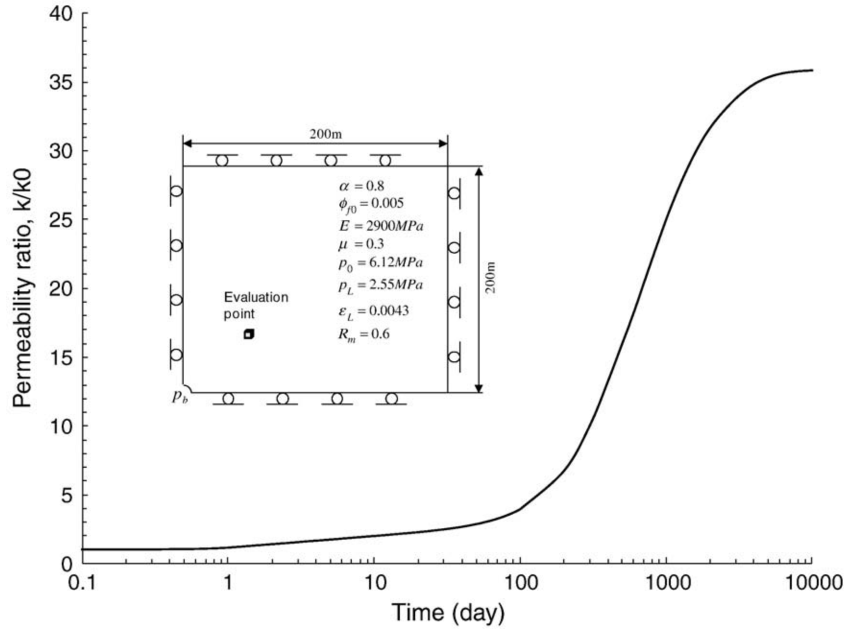

Fig. 8. Evolution of coal permeability at a specific evaluation point.

this is modulated through the parameter$1-R_m$. In this case, $1-R_m$ is equal to 0.4. This means that only ~40% of the total effective stress-induced coal strain (equal to the swelling strain) is directly responsible for the permeability growth, as shown in Figs.7 and 8. Fig. 9 shows the relation of the cumulative gas production and the pore pressure with time. The gas production was calculated based on 5 m height of coal seam, and the nonlinear change trend between cumulative gas production and pore pressure indicates the influence of gas desorption.

7. Conclusions

A novel permeability model has been developed to define the evolution of gas sorption-induced permeability anisotropy under in-situ stress conditions. This was implemented into a fully coupled finite element model of coal deformation and gas flow and transport in a coal seam. Based on the model evaluations and the analysis of coupled processes, the model adequately and consistently reflects the conceptual assumptions:

- The directional permeability of coal is determined by the mechanical boundary conditions, the ratio of coal bulk modulus to coal matrix modulus, the initial fracture porosity, and the magnitude of the coal sorption-induced strain. The boundary conditions control the magnitudes of total strains while the modulus reduction ratio partitions the effective strain (total strain minus the swelling strain) between fracture and matrix.
- For restraint conditions of uniaxial strain and for a constant volume reservoir, changes in coal permeability are determined only by the change of gas pore pressure and the swelling strain. In both cases, the influence of effective stress is substituted by the change of gas pore pressure and the swelling strain.

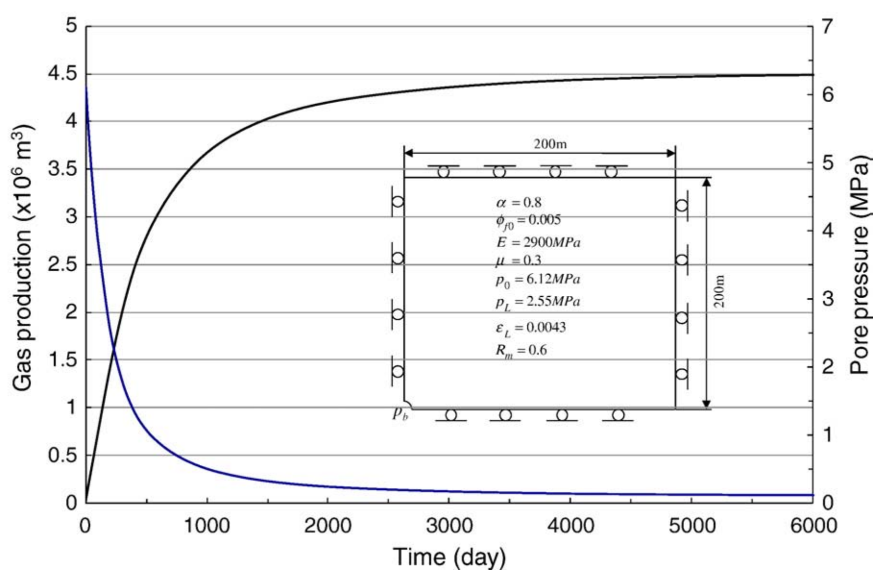

Fig. 9. Evolution of the cumulative gas production and pore pressure.

• Analysis including the effect of the fully coupled processes illustrates how coal permeability evolves both in space and in time. These evolutions are the direct outcomes of feedbacks of coal–gas interaction on the evolution of permeability, stress deformation, gas flow and adsorption/desorption processes.

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