International Journal of Coal Geology 87 (2011) 175–189

Contents lists available at ScienceDirect

International Journal of Coal Geology

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

Interactions of multiple processes during CBM extraction: A critical review

Jishan Liu [a,*], Zhongwei Chen [a], Derek Elsworth [b], Hongyan Qu [a], Dong Chen [a]

[a] *School of Mechanical and Chemical Engineering, the University of Western Australia, WA 6009, Australia*
[b] *Energy and Mineral Engineering and G3 Center, Pennsylvania State University, University Park, PA 16802, USA*

ARTICLE INFO

Article history:
Received 21 March 2011
Received in revised form 5 June 2011
Accepted 6 June 2011
Available online 15 June 2011

Keywords:
Coal permeability models
Coupled processes
Coal shrinking
CBM extraction

ABSTRACT

Coal permeability models are required to define the transient characteristics of permeability evolution in fractured coals during CBM recovery. A broad variety of models have evolved to represent the effects of sorption, swelling and effective stresses on the dynamic evolution of permeability. In this review, we classify the major models into two groups: permeability models under conditions of uniaxial strain and permeability models under conditions of variable stress. The performance of these models is evaluated against analytical solutions for the two extreme cases of either free shrinking/swelling or constant volume. For the case of free shrinking/swelling none of the swelling/shrinking strain contributes to the change in coal permeability because effective stresses do not change. Conversely, for the case of constant volume the full swelling/shrinking strain contributes to the change in coal permeability because the coal is completely constrained from all directions. Therefore, these two solutions represent the lower bound and the upper bound behaviors of permeability evolution, respectively.

Review of laboratory observations concludes that although experiments are conducted under conditions of free shrinking/swelling the observed response is closest to that for constant volume condition. Similarly, review of in-situ observations concludes that coal gas reservoirs behave close to the constant volume condition although these observations are made under undefined in-situ stress and constraint conditions anticipated to be intermediate between free swelling and constant volume (i.e. for uniaxial strain). Thus comparison of these laboratory and field observations against the spectrum of models indicates that current models have so far failed to explain the results from stress-controlled shrinking/swelling laboratory tests and have only achieved some limited success in explaining and matching in situ data. Permeability models under uniaxial strain are more appropriate for the overall behavior of coal gas reservoirs under typical in situ conditions while models representing variable stress conditions are more appropriate for behavior examined under typical laboratory conditions. Unlike permeability models under the uniaxial strain condition, models under the constant volume condition are effective-stress based and can be used to recover the important non-linear responses due to the effective stress effects when mechanical influences are rigorously coupled with the gas transport system. Almost all the permeability models are derived for the coal as a porous medium, but used to explain the compound behaviors of coal matrix and fracture. We suggest that the impact of coal matrix-fracture compartment interactions has not yet been understood well and further improvements are necessary.

Contents

---

* Corresponding author.
E-mail address: jishan@cyllene.uwa.edu.au (J. Liu).

0166-5162/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.coal.2011.06.004

1. Introduction

Advances in our understanding of coal–gas interactions have changed the manner in which we treat coalbed methane: from mitigating its dangers as a mining hazard to developing its potential as an unconventional gas resource recovered as a useful by-product of CO_2 sequestration.

As found in nature, coal is a typical dual porosity/permeability system (Harpalani and Schraufnagel, 1990; Lu and Connell, 2007; Warren and Root, 1963) containing porous matrix surrounded by fractures. These natural fractures form a closely-spaced, orthogonal network called cleats. The main set of fractures, termed face cleats, is comprised of well-developed, extensive, roughly planar fractures that run parallel to one another. Butt cleats are orthogonal to face cleats and often terminate at them. Butt cleats are also roughly planar but are not as well-developed or as continuous as face cleats. The cleat system provides an essential and effective flow path for gas. Much of the measured bulk or "seam" permeability is due to the cleat system, although the presence of larger scale discontinuities such as fractures, joints, and faults can also make a significant contribution. The coal matrix is isolated by the fracture network and is the principal medium for storage of the gas (of the order of 98%), principally in adsorbed form and with low permeability in comparison to the bounding cleats (Gray, 1987). The remaining gas is stored in the natural fractures, or cleats, either as free gas or dissolved in water. The surface area of the coal on which the methane is adsorbed is very large (20 to 200 m^2/g) (Patching, 1970) and gas is stored at near-liquid densities.

The production of CBM dates back to the early 1930s. Yet, it was not until the early 1980s that research and development projects began to show the enormous potential of this energy resource. Major reserves exist in many countries and more than 90% of the estimated reserves are in Canada, Russia, China, the United States and Australia. Kuuskraa et al. (1992) defined global CBM reserves through a detailed study of coalbed basins around the world. This work was further updated by different researchers before the final form was presented (Boyer, 1994; Kuuskraa et al., 1992; Murray, 1996; Palmer, 2008; White et al., 2005). Estimates of the global coalbed methane (CBM) reserve defined in volume of CH_4 are summarized in Table 1.

Compared to conventional gas reservoirs, coal reservoirs have low effective porosity and high compressibility and are dominated by gas desorption. CBM recovery triggers a series of coal–gas interactions. For primary gas production, the reduction of gas pressure increases effective stress which in turn closes fracture apertures and reduces the permeability. 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 may dilate (zero volume change condition) and fracture permeability correspondingly increases. Thus a rapid initial reduction in fracture permeability (due to an increase in effective stress) is supplanted by a slow increase in permeability (indexed to 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 (Chen et al., 2008; Connell, 2009; Liu et al., 2010b,c,d; Shi and Durucan, 2004). Therefore, understanding the transient characteristics of permeability evolution in fractured coals is of fundamental importance to CBM recovery.

CBM extraction induced complex interactions between stress and sorptive chemistry exert strong influence on the transport and sorptive properties of the coal. These include influences on gas sorption and flow, coal deformation, porosity change and permeability modification. We label this chain of reactions as "coupled processes" implying that one physical process affects the initiation and progress of another. The individual processes, in the absence of full consideration of cross couplings, form the basis of very well-known disciplines such as elasticity, hydrology and heat transfer. Therefore, the inclusion of cross couplings is the key to rigorously formulate the behavior for coupled processes of coal–gas interactions. The complexity of these interactions is reflected in the extensive suite of coal permeability models available in the literature — with many of these models implemented into computer simulators to quantify coal–gas interactions. The primary goal of this paper is to review and evaluate the performance of these disparate models of coal permeability evolution and to define principal physical conditions where they, and their application in simulators, can be most successful.

2. Fundamental principles and scope of the review

In this section, stress–strain relationships for a linear elastic porous medium are derived. The derivation makes use of an analogy between thermal contraction and matrix swelling/shrinkage associated with

Table 1
Coalbed methane reserves around the world.

Country	CBM reserves (Tcf)			
	Boyer (1994)	Murray (1996)	Kuuskraa et al. (1992)	Palmer (2008)
Canada	200–2700	300–4260	570–2280	200–2700
Russia	600–4000	600–4000	550–1550	600–4000
China	1060–1240	1060–2800	350–1150	1060–1240
United States	343–414	275–650	500–1730	400
Australia	300–500	300–500	310–410	300–500
Indonesia	–	–	210	–
Germany	100	100	120 (Western Europe)	100
Poland	100	100	70	100
United Kingdom	60	60	–	60
Ukraine	60	60	50	60
Kazakhstan	40	40	40	40
Southern Africa[a]	30	40	100	30
India	30	30	90	30
Turkey	–	–	50	–
Total	2953–9304	2976–12640	3010–7840	2980–9260

[a] Includes South Africa, Zimbabwe and Botswana.

gas adsorption/desorption in coalbeds. Stress–strain relationships for a thermoelastic porous medium can be readily found in the literature (Bear and Corapcioglu, 1981; Nowacki, 1995). In a non-isothermal body, if the temperature drops the fabric shrinks, leading to a potential change in the porosity of the porous medium. This is directly analogous to matrix swelling in coalbeds, where cleat porosity changes as gas adsorbs during injection (Palmer and Mansoori, 1996). Assuming thermal expansion/contraction and matrix swelling/shrinkage are isotropic, the stress–strain relationships for a non-isothermal coalbed may be written as (negative in compression)

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

where $G = \frac{E}{2(1+\nu)}$, $K = \frac{E}{3(1-2\nu)}$, $\alpha = 1-\frac{K}{K_s}$, $\sigma_{kk}=\sigma_{11}+\sigma_{22}+\sigma_{33}$. K represents the bulk modulus of coal and K_s represents the bulk modulus of coal grains. G is the shear modulus of coal comprising the Young's modulus (E) and Poisson's ratio (ν) of the coal. α is the Biot coefficient. δ_{ij} is the Kronecker delta with 1 for $i=j$ and 0 for $i\neq j$. p is the gas pressure within the pores, ε_s is the sorption-induced volumetric strain, T is reservoir temperature and α_T is the coefficient of volumetric thermal expansion.

From Eq. (1), we obtain

$$\Delta\varepsilon_v = -\frac{1}{K}(\Delta\overline{\sigma}-\alpha\Delta p) + \Delta\varepsilon_s + \alpha_T\Delta T \tag{2}$$

where $\varepsilon_v=\varepsilon_{11}+\varepsilon_{22}+\varepsilon_{33}$ is the volumetric strain of coal and $\overline{\sigma} = -\sigma_{kk}/3$ is the mean compressive stress.

Considering a porous medium containing solid volume of V_s and pore volume of V_p, we assume the bulk volume $V=V_p+V_s$ and the porosity $\phi=V_p/V$. According to Eq. (2), the volumetric evolution of the porous medium with a load of total stress $\overline{\sigma}$ and p can be described in terms of $\Delta V/V$ and $\Delta V_p/V_p$, the volumetric strain of the coal and volumetric strain of the pore space, respectively. The relations are

$$\frac{\Delta V}{V} = -\frac{1}{K}(\Delta\overline{\sigma}-\alpha\Delta p) + \Delta\varepsilon_s + \alpha_T\Delta T \tag{3}$$

$$\frac{\Delta V_p}{V_p} = -\frac{1}{K_p}(\Delta\overline{\sigma}-\beta\Delta p) + \Delta\varepsilon_s + \alpha_T\Delta T \tag{4}$$

where $\beta=1-K_p/K_s$.

We assume that the sorption-induced strain for the coal is the same as that for the pore space. Without the gas sorption effect, the volumetric variation of the porous medium satisfies the Betti–Maxwell reciprocal theorem, $\frac{\partial V}{\partial p}|_{\overline{\sigma}} = \frac{\partial V_p}{\partial\overline{\sigma}}|_p$, (Hudson et al., 1993) and we obtain

$$K_p = \frac{\phi}{\alpha}K. \tag{5}$$

Using the definition of porosity, the following expressions can be deduced as (Detournay and Cheng, 1993)

$$\frac{\Delta V}{V} = \frac{\Delta V_s}{V_s} + \frac{\Delta\phi}{1-\phi} \tag{6}$$

$$\frac{\Delta V_p}{V_p} = \frac{\Delta V_s}{V_s} + \frac{\Delta\phi}{\phi(1-\phi)}. \tag{7}$$

Solving Eqs. (3)–(7), we obtain the relationship as

$$\Delta\phi = \phi\left(\frac{1}{K}-\frac{1}{K_p}\right)(\Delta\overline{\sigma}-\Delta p). \tag{8}$$

Substituting Eqs. (2), (5) into Eq. (8) yields

$$\phi-\phi_0 = -(\alpha-\phi)\frac{(\Delta\overline{\sigma}-\Delta p)}{K}. \tag{9}$$

Rearranging the above equation gives

$$\phi = \frac{\phi_0}{\left(1-\frac{\Delta\overline{\sigma}-\Delta p}{K}\right)} - \frac{\alpha}{\left(1-\frac{\Delta\overline{\sigma}-\Delta p}{K}\right)}\frac{\Delta\overline{\sigma}-\Delta p}{K} \tag{10}$$

Because generally $(\Delta\overline{\sigma}-\Delta p)/K<<1$, the above equation can be simplified into

$$\frac{\phi}{\phi_0} = 1-\frac{\alpha}{\phi_0}\frac{\Delta\overline{\sigma}-\Delta p}{K} = 1 + \frac{\alpha}{\phi_0}\Delta\varepsilon_e \tag{11}$$

where $\Delta\varepsilon_e = -(\Delta\overline{\sigma}-\Delta p)/K$ is defined as the total effective volumetric strain.

The free-swelling volumetric strain $\Delta\varepsilon_s$ and the coal grain compressive volumetric strain $\Delta p/K_s$ produce no shear strain. Their effects on all three normal components of strain are equal (Robertson, 2005). By these definitions, rearranging Eq. (2), the total effective volumetric strain can be given as

$$\Delta\varepsilon_e = \Delta\varepsilon_v + \frac{\Delta p}{K_s} - \Delta\varepsilon_s - \alpha_T\Delta T \tag{12}$$

Only $\Delta\varepsilon_e$ is responsible for the coal porosity and permeability change. It is determined by four components: total volumetric strain, $\Delta\varepsilon_v$, coal compactive strain, $\frac{\Delta p}{K_s}$, gas sorption-induced volumetric strain, $\Delta\varepsilon_s$, and thermal strain, $\alpha_T\Delta T$. Both coal porosity and permeability can be defined as a function of $\Delta\varepsilon_e$

$$\phi = \phi(\Delta\varepsilon_e) \tag{13}$$

$$k = k(\Delta\varepsilon_e) \tag{14}$$

Relations, $\phi(\Delta\varepsilon_e)$ and $k(\Delta\varepsilon_e)$, are defined as the coal porosity model and coal permeability model, respectively. It is these two models that link different physical processes together as illustrated in Fig. 1.

When coal is recovered by mining, or fluid recovered or injected, complex interactions of stress and chemistry have a strong influence on the properties of coal. These include influences on gas sorption and flow, coal deformation, porosity change and permeability modification. In this review, we define this chain of reactions as "coupled processes" implying that one physical process affects the initiation and progress of another. The individual process, in the absence of full consideration of cross couplings, forms the basis of very well-known disciplines such as elasticity, hydrology and heat transfer. Therefore, the inclusion of cross couplings is the key to rigorously formulate the full mechanics of coal–gas interactions. This defines the scope of the review: (1) to define coal porosity and permeability models; (2) to understand the interaction of multiple processes; and (3) to define important knowledge gaps.

3. Coal porosity and permeability models

It is clear that there is a relationship between porosity, permeability and the grain-size distribution in porous media. Chilingar (1964) defined this relationship as

$$k = \frac{d_e^2\phi^3}{72(1-\phi)^2} \tag{15}$$

where k is the permeability, ϕ is porosity and d_e is the effective diameter of grains. Based on this equation, we obtain

$$\frac{k}{k_0} = \left(\frac{\phi}{\phi_0}\right)^3\left(\frac{1-\phi_0}{1-\phi}\right)^2. \tag{16}$$

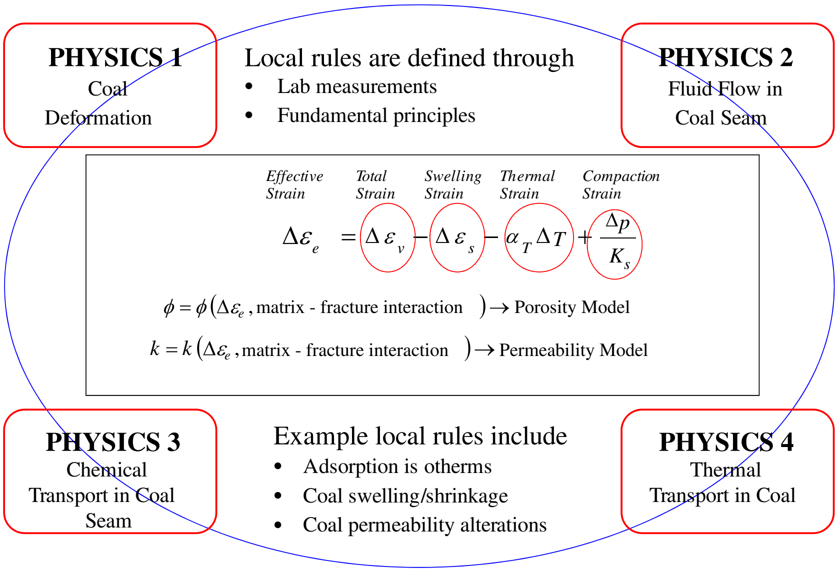

Fig. 1. Interactions of multiple coupled processes through a stress-controlled coal porosity model and coal permeability model defined as a function of the effective strain, $\Delta\varepsilon_e$, during CBM extraction.

When the porosity is much smaller than 1 (normally less than 10%), the second term of the right-hand side asymptotes to unity. This yields the cubic relationship between permeability and porosity for the coal matrix

$$\frac{k}{k_0} = \left(\frac{\phi}{\phi_0}\right)^3 \tag{17}$$

Therefore, coal porosity and permeability can be defined as

$$\frac{\phi}{\phi_0} = 1 + \frac{\alpha}{\phi_0}\Delta\varepsilon_e \tag{18}$$

$$\frac{k}{k_0} = \left[1 + \frac{\alpha}{\phi_0}\Delta\varepsilon_e\right]^3 \tag{19}$$

$$\Delta\varepsilon_e = \Delta\varepsilon_v + \frac{\Delta p}{K_s} - \Delta\varepsilon_s - \alpha_T\Delta T \tag{19a}$$

or

$$\Delta\varepsilon_e = -\frac{\Delta\overline{\sigma} - \Delta p}{K} \tag{19b}$$

Eqs. (18) and (19) are models for coal porosity and permeability that are derived based on the fundamental principles of poroelasticity. They can be applied to the evolution of coal porosity and permeability under variable boundary conditions.

As shown in Eqs. (18) to (19), coal porosity and permeability can be defined as a function of either effective strain (19a) or effective stress (19b). However, coal porosity and permeability models may have a variety of forms when specific conditions are imposed. Examples include:

- When the change in total stress is equal to zero, $\Delta\overline{\sigma} = 0$, both coal porosity and permeability are independent of the total stress. Under this condition, they can be defined as a function of gas pressure and temperature only.
- Assuming the coal sample is under conditions of uniaxial strain and the overburden load remains unchanged, they can also be defined as a function of gas pressure and temperature only.
- When the impact of coal fractures and gas compositions is considered, coal porosity and permeability models can be linked to fracture parameters and gas concentrations.

In this paper, we review two important forms of coal permeability models: coal permeability models under conditions of uniaxial strain and coal permeability models representing conditions of variable stress.

3.1. Permeability models under uniaxial strain condition

An equation for permeability and porosity of a collection of matchsticks are discussed by Reiss (1980) together with an equation for collections of slabs and cubes. As the coal deposit is idealized as a collection of matchsticks, flow in the core sample is along the axis of the matchsticks. Permeability for this geometry is given by Reiss (1980) as

$$k = \frac{1}{48}a^2\phi_f^3 \tag{20}$$

where a is cleat spacing, and ϕ_f is cleat porosity.

Differentiating with respect to hydrostatic stress and combining the relationship between coal physical properties gives (Pan et al., 2010; Seidle et al., 1992)

$$\frac{\partial k}{\partial \sigma_h} = k\left[\frac{2}{E}(1-2\nu) - 3c_f\right] \tag{21}$$

where c_f is coal cleat compressibility defined as $\frac{1}{\phi_f}\frac{\partial \phi_f}{\partial p}$, σ_h is the horizontal stress. E and ν are coal Young's Modulus and Poisson's ratio respectively.

The first term in parentheses represents the contribution of changes in the coal matrix to the stress dependence of permeability. This term is analogous to grain compaction in conventional reservoir rocks. The second term represents the cleat volume contribution to the stress–permeability relation, which is normally two to three orders of magnitude larger than the coal matrix term (Reiss, 1980). Therefore, simplifying and integrating the above equation gives

$$\frac{k}{k_0} = exp\left[-3c_f(\sigma_h - \sigma_{h0})\right] \tag{22}$$

where σ_{h0} is the initial horizontal stress.

Gray (1987) considered the changes in the cleat permeability to be primarily controlled by the prevailing effective horizontal stresses that act across the cleats. Under the assumption of uniaxial strain, the influence of matrix shrinkage on changes in coal permeability was first incorporated into a permeability model. The horizontal stress incorporating matrix shrinkage was expressed as

$$\sigma_h - \sigma_{h0} = -\frac{\nu}{1-\nu}(p-p_0) + \frac{E}{1-\nu}\frac{\Delta\varepsilon_s}{\Delta p_s}\Delta p_s \tag{23}$$

where Δp_s refers to equivalent sorption pressure.

By assuming that an individual fracture reacts as an elastic body upon a change in the normal stress component, Gilman and Beckie (2000) proposed a simplified mathematical model of methane movement in a coal seam taking into account the following features: a relatively regular cleat system, adsorptive methane storage, an extremely slow mechanism of methane release from the coal matrix into cleats and a significant change of permeability due to desorption. Using the uniaxial strain assumption and Terzaghi formula, the effective stress in horizontal plane, $\Delta\sigma_e^h$, was expressed as below, which is similar to Gray's (1987) result:

$$\Delta\sigma_e^h = -\frac{\nu}{1-\nu}\Delta p + \frac{E}{1-\nu}\gamma\Delta S. \tag{24}$$

where ΔS is the change of the adsorbate mass and γ is the volumetric welling/shrinkage coefficient.

The exponential relation was used for the permeability calculation

$$\frac{k}{k_0} = \exp\left(-\frac{3\Delta\sigma_e^h}{E_f}\right) = \exp\left[-\frac{3}{E_f}\left(-\frac{\nu}{1-\nu}\Delta p + \frac{E}{1-\nu}\gamma\Delta S\right)\right] \tag{25}$$

where E_f is an analogous Young's modulus for the fracture.

Seidle and Huitt (1995) calculated the permeability increase due to matrix shrinkage alone by assuming that coal sorption-induced strain is proportional to the amount of gas sorbed and that the sorbed gas is related to pressure by Langmuir's equation. Their porosity and permeability models were defined as

$$\frac{\phi}{\phi_0} = 1 + \frac{\varepsilon_L}{3}\left(1 + \frac{2}{\phi_0}\right)\left(\frac{p_0}{P_L + p_0} - \frac{p}{P_L + p}\right) \tag{26}$$

$$\frac{k}{k_0} = \left[1 + \frac{\varepsilon_L}{3}\left(1 + \frac{2}{\phi_0}\right)\left(\frac{p_0}{p_L + p_0} - \frac{p}{p_L + p}\right)\right]^3 \tag{27}$$

where ε_L and p_L are the maximum volumetric strain and gas pressure at which the matrix strain is half of the maximum value, respectively.

This model considered the effects of coal-matrix swelling/shrinkage only, ignoring the impact of coal compressibility. Therefore, their model is limited to specific conditions in which sorption-induced strain (matrix swelling or shrinkage) dwarfs pressure-induced, elastic changes in cleat permeability (Robertson, 2005).

Based on the matchstick geometry model and the relation between permeability and porosity developed by Seidle and Huitt (1995), Shi and Durucan (2004) presented a model for pore pressure dependent cleat permeability for gas-desorbing, linear elastic coalbeds under uniaxial strain conditions. In this model, it was assumed that changes in the cleat permeability of coalbeds were controlled by the prevailing effective horizontal stresses normal to the cleats. Variations in the effective horizontal stresses under uniaxial strain conditions are expressed as a function of pore pressure reduction during drawdown, which includes a cleat compression term and a matrix shrinkage term that have competing effects on cleat permeability, as expressed below

$$\sigma_h - \sigma_{h0} = -\frac{\nu}{1-\nu}(p-p_0) + \frac{E}{3(1-\nu)}\varepsilon_L\left(\frac{p}{p+p_L} - \frac{p_0}{p_0+p_L}\right) \tag{28}$$

$$k = k_0\exp[-3c_f(\sigma_h - \sigma_{h0})]. \tag{29}$$

Based on the theory of linear elasticity for strain changes, Palmer and Mansoori (1996) developed another widely used theoretical coal permeability model as a function of effective stress and matrix shrinkage under the uniaxial strain condition. In this model, the incremental pore volume strain, $d\varepsilon_p$, can be defined as a result of a simple volumetric balance between the bulk rock, the grains, and the pores

$$d\varepsilon_p = \frac{d\varepsilon_r}{\phi} - \left(\frac{1-\phi}{\phi}\right)d\varepsilon_g \tag{30}$$

where $d\varepsilon_r$ is the incremental rock volume strain, $d\varepsilon_g$ and ϕ are incremental grain volume strain and porosity, respectively.

By assuming the uniaxial strain condition, $\phi << 1$, and no change in overburden stress results in

$$\frac{\phi}{\phi_0} = 1 + \frac{c_m}{\phi_0}(p-p_0) + \frac{\varepsilon_L}{\phi_0}\left(\frac{K}{M} - 1\right)\left(\frac{p}{P_L + p} - \frac{p_0}{P_L + p_0}\right) \tag{31}$$

The cubic relation between porosity and permeability was used for this derivation, as shown below

$$\frac{k}{k_0} = \left[1 + \frac{c_m}{\phi_0}(p-p_0) + \frac{\varepsilon_L}{\phi_0}\left(\frac{K}{M} - 1\right)\left(\frac{p}{P_L + p} - \frac{p_0}{P_L + p_0}\right)\right]^3 \tag{32}$$

where $c_m = \frac{1}{M} - \left(\frac{K}{M} + f - 1\right)\gamma'$, $M = \frac{1-\nu}{(1+\nu)(1-2\nu)}$, γ' is grain compressibility and f is a fraction between 0 and 1.

An improved P&M model has been developed, and is summarized in Palmer et al. (2007). The model now includes (1) cleat anisotropy and potential suppression of pressure-dependent permeability, (2) modulus changes with depletion, and (3) undersaturated coals.

Similarly, the Advanced Resources International (ARI) group developed another permeability model (Pekot and Reeves, 2002). This model does not have a geomechanics framework, but instead extracts matrix strain changes from a Langmuir curve of strain versus reservoir pressure, which is assumed to be proportional to the gas concentration curve. The matrix shrinkage is proportional to the adsorbed gas concentration change, multiplied by shrinkage compressibility C_m (a free parameter). The ARI model has been compared to the P&M model, and the conclusion was that the two models are essentially equivalent in saturated coals, and where the strain versus pressure function is proportional to the Langmuir isotherm (Palmer et al., 2007).

Following the above work, Cui and Bustin (2005) investigated quantitatively the effects of reservoir pressure and sorption-induced volumetric strain on coal-seam permeability with constraints from the adsorption isotherm and associated volumetric strain and derived a stress-dependent permeability model. Initially the authors used poroelasticity to achieve the relation between porosity change and effective stress change, as shown below

$$\frac{\phi}{\phi_0} = \exp\left\{-\frac{1}{K_p}[(\sigma - \sigma_0) - (p - p_0)]\right\} \tag{33}$$

where K_p is the bulk modulus for pore system.

The cubic relation between permeability and porosity was used to calculate coal cleat permeability change.

$$\frac{k}{k_0} = \left(\frac{\phi}{\phi_0}\right)^3 = \exp\left\{-\frac{3}{K_p}[(\sigma - \sigma_0) - (p - p_0)]\right\}. \tag{34}$$

By assuming constant overburden stress and uniaxial strain conditions, this permeability model was extended to be

$$\frac{k}{k_0} = \exp\left\{-\frac{3}{K_p}\left[\frac{(1+\nu)}{3(1-\nu)}(p-p_0) - \frac{2E}{9(1-\nu)}(\varepsilon_s - \varepsilon_{s0})\right]\right\}. \tag{35}$$

Recently, Pan and Connell (2007) developed a theoretical model for sorption-induced strain and applied to single-component adsorption/strain experimental data. Clarkson et al. (2008) expanded this theoretical model to calculate the sorption-strain component of the P&M model (Palmer et al., 2007). The expressions for sorption-induced strain and permeability calculation are given as

$$\Delta\varepsilon_s = RTL\ln(1+B\cdot p)\frac{\rho_s}{E_s}f(x,\nu_s) - \frac{p}{E_s}(1-2\nu_s) \tag{36}$$

$$\frac{k}{k_0} = \left[1+\frac{c_m}{\phi_0}(p-p_0)+\frac{1}{\phi_0}\left(\frac{K}{M}-1\right)\Delta\varepsilon_s\right]^3 \tag{37}$$

where E_s is the modulus of the solid phase, ν_s is Poisson's ratio for solid phase and ρ_s is the density for solid phase. R is the gas constant (8.314 J mol^{-1} K^{-1}), T is the temperature (K), L is Langmuir sorption constant (mol/kg), and B is Langmuir pressure constant (Pa^{-1}).

3.2. Permeability models under variable stress conditions

Robertson and Christiansen (2006) described the derivation of a new equation that can be used to model the permeability behavior of a fractured, sorptive-elastic medium, such as coal, under variable stress conditions. The model is derived for cubic geometry rather than matchstick geometry under biaxial or hydrostatic confining pressures, and it is also designed to handle changes in permeability caused by adsorption and desorption of gasses from the matrix blocks.

In this model, the effective porosity of the matrix block is assumed to be zero, leaving the fracture system to provide the only interconnected void space. The permeability model was expressed as

$$\frac{k}{k_0} = \exp\left\{-3c_f\frac{1-\ \exp[\alpha_c(p-p0)]}{\alpha_c}+\frac{9}{\phi_0}\left[\frac{1-2\nu}{E}(p-p_0) - \frac{\varepsilon_L}{3}\left(\frac{P_L}{P_L+p_0}\right)\mathrm{In}\left(\frac{P_L+p}{P_L+p_0}\right)\right]\right\} \tag{38}$$

where α_c is the change rate of fracture compressibility.

Based on the theory of poroelasticity, a general porosity and permeability model was developed by Zhang et al. (2008), where the expression of permeability for the matrix system is defined as

$$\frac{k_m}{k_{m0}} = \left(\frac{1}{1+S}[(1+S_0)\phi_0+\alpha(S-S_0)]\right)^3 \tag{39}$$

where $S=\varepsilon_v+\frac{p}{K_s}-\varepsilon_s$ and $S_0=\varepsilon_v+\frac{p_0}{K_s}-\varepsilon_{s0}$.

Similarly, Connell et al. (2010) presented two new analytical permeability model representations for standard triaxial strain and stress conditions, derived from the general linear poroelastic constitutive law, including the effects of triaxial strain and stress for coal undergoing gas adsorption induced swelling. A novel approach is presented to distinguish between the sorption strain of the coal matrix, the pores (or cleats) and the bulk coal.

Contrary to previous models developed for field conditions, their model mainly deals with variable stress conditions commonly used during measurement of permeability in the laboratory.

When experimental results from these tests are interpreted, a matchstick or cubic coal model is typically assumed with the matrix blocks completely separated from each other in a stacked structure. Under this assumption, matrix swelling does not affect coal fracture permeability under conditions of constant confining (total) stress, because, for a given pore pressure, p, the coal matrix swelling results in block swelling, rather than changes in fracture aperture (Connell et al., 2010; Liu, et al., 2011; Liu and Rutqvist, 2010). The effective stress is also decoupled from matrix swelling due to the complete separation between matrix blocks caused by through-going fractures. Therefore, the permeability should not change. However, this is not consistent with laboratory observations (Harpalani and Chen, 1997; Pan et al., 2010; Pini et al., 2009), which show dramatic reduction in permeability with the injection of an adsorbing gas. Liu and Rutqvist (2010) believed that in reality coal matrix blocks are not completely separated from each other by fractures but connected by the coal-matrix bridges, and developed a new coal-permeability model, which explicitly considered fracture–matrix interaction during coal-deformation processes based on the internal swelling stress concept. For example, the effective stress under uniaxial strain conditions can be calculated by the following equations

$$\Delta\sigma_e = \frac{\nu}{1-\nu}\Delta P+\frac{E}{1-\nu}\Delta\varepsilon_s-\Delta\sigma_{in} \tag{40}$$

$$\Delta\sigma_{in} = \frac{E}{2(1-\nu)}\phi_{f0}\left(1-e^{-C_f\Delta\sigma_e}\right) \tag{41}$$

where $\Delta\sigma_{in}$ is the internal swelling stress, and ϕ_{f0} is the fracture porosity. The above coupled equations are solved to obtain the effective stress and strain.

An alternate reasoning has been applied by Liu et al. (2010a) on this issue, considering that the reason for the above phenomena may be the internal actions between coal fractures and matrix have not been taken into consideration. A model capable of replicating this apparently anomalous behavior is developed by considering the interactions of the fractured coal mass where cleats do not create a full separation between adjacent matrix blocks, but where solid rock bridges are present. The role of swelling strains is accommodated both over contact bridges that hold cleat faces apart and over the non-contacting span between these bridges. The effects of swelling act competitively over these two components: increasing porosity and permeability due to swelling of the bridging contacts but reducing porosity and permeability due to the swelling of the intervening free-faces.

The fracture permeability was expressed as

$$\frac{k_f}{k_{f0}} = \left(1+\frac{\Delta b}{b}\right)^3 = \left[1+\frac{(1-R_m)}{\phi_{f0}}(\Delta\varepsilon_v-\Delta\varepsilon_s)\right]^3 \tag{42}$$

where b and Δb are fracture aperture and fracture aperture change, respectively. $\Delta\varepsilon_v$ is the volumetric strain.

This study also considered the resultant change in coal permeability, which combined the outcome of the reduction in fracture opening due to coal matrix swelling and effective stress change as well as the decrease in effective stress due to changes in fluid pressure and confining stress for the matrix system, defined as

$$\frac{k}{k_0} = \frac{k_{m0}}{k_{m0}+k_{f0}}\left(1+\frac{R_m}{\phi_{m0}}\frac{p_m}{K}\right)^3+\frac{k_{f0}}{k_{m0}+k_{f0}}\left[1+\frac{(1-R_m)}{\phi_{f0}}(\Delta\varepsilon_v-\Delta\varepsilon_s)\right]^3 \tag{43}$$

where ϕ_{f0} is initial fracture porosity, and R_m is elastic modulus reduction ratio, defined as E/E_m. E_m is Young's modulus for coal matrix. k_{m0} and k_{f0} are initial coal matrix permeability and coal fracture permeability respectively. Subscripts m and f refer to matrix and fracture system respectively.

Izadi et al. (2011) proposed a mechanistic representation of coal as a collection of unconnected cracks in an elastic swelling medium. The cracks are isolated from each other but swells within a homogeneous but cracked continuum resulting in a reduction in crack aperture with swelling, and a concomitant reduction in permeability. In the limit, this behavior reduces to a change in permeability defined as a fully constrained model (zero volume change) as

$$\frac{k}{k_0} = \left(1+\frac{\varepsilon_s s^3}{lb_0}\right)^3 = \left[1+\left(\frac{\varepsilon_L s^2}{lb_0}\right)\frac{p}{p+p_L}\right]^3 \tag{44}$$

where l is the crack length, s is the cleat spacing, b_0 is the initial aperture and ε_L is the Langmuir strain coefficient.

Ma et al. (2011) developed a model, which was based on the volumetric balance between the bulk coal, solid grains and pores, using the constant volume theory (Massarotto et al., 2009). It incorporates primarily the changes in grain and cleat volumes and is, therefore, different from other models that lay heavy emphasis on the pore volume/cleat compressibility. In this study, the overall matchstick strain resulting from matrix shrinkage and decrease in pressure is given as

$$\frac{\Delta a}{a} = -1 + \sqrt{1 + \varepsilon_L\left(\frac{p_0}{p_0 + p_L} - \frac{p}{p + p_L}\right)} + \frac{1-\nu}{E}(p - p_0). \tag{45}$$

The permeability change can be calculated by the following expression

$$\frac{k}{k_0} = \frac{\left(1 + \frac{2}{\phi_0}\frac{\Delta a}{a}\right)^3}{1 - \frac{\Delta a}{a}} \tag{46}$$

where a and Δa are the matrix width and width change, respectively. ϕ_0 is the porosity at virgin reservoir pressure.

3.3. Anisotropic permeability models

The permeability models as reviewed above do not reflect the directional behavior of permeability change. The anisotropic characteristics of a coal matrix-fracture structure suggests that the evolution of coal permeability should be direction-dependent. With cubic coal cores, Pomeroy and Robinson (1967) found that the flow rates of water (corresponding to permeability) were significantly different when the confining pressures were perpendicular to main cleats (face cleats), cross cleats (butt cleats) or bedding planes. From field well tests, Koenig and Stubbs (1986) reported the anisotropy ratio of permeability in the plane of bedding was as high as 17:1 in the Rock Creek coalbeds of the Warrior Basin of the USA. Permeability anisotropy of coal was also confirmed by other experimental results of Gash et al. (1992). Using coal samples from the San Juan Basin and under a confining stress of 6.9 MPa (1000 psi) they found that the permeability parallel to bedding planes was 0.6–1.7 mD in the direction of the face cleat and 0.3–1.0 mD in the direction of the butt cleat, but only 0.007 mD in the direction vertical to the bedding planes. A few of coal permeability models have been developed to accommodate the anisotropy, as summarized below.

Wong (2003) developed a model for deformable granular media, which quantifies the anisotropic changes in permeability when the material experiences shear deformation. In this study, the directions of the principal permeability magnitudes are governed by the induced strains, so the effects of stress paths and stress levels are implicitly considered through effective stress–strain constitutive laws. This strain-induced permeability model is written as:

$$\begin{bmatrix} k_1 \\ k_2 \\ k_3 \end{bmatrix} = \begin{bmatrix} k_{10} \\ k_{20} \\ k_{30} \end{bmatrix} + \begin{bmatrix} a' & b' & b' \\ b' & a' & b' \\ b' & b' & a' \end{bmatrix} \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \end{bmatrix} \tag{47}$$

where, a' and b' are material constants and can be experimentally measured; k_{i0} and k_i denote initial and current permeability, respectively; ε_i is current principal strains.

Following this Al-Yousef (2005) presented an analytical solution for the steady-state flow problem for anisotropic permeability measurements. Gu and Chalaturnyk (2005) developed another permeability model. In this model, coalbeds are considered as naturally fractured reservoirs, and represented with a collection of matchsticks. The permeability is expressed as

$$\frac{k_i}{k_0} = \left(1 + \frac{a}{b}\Delta\varepsilon_{li}\right)^3 \tag{48}$$

$$\Delta\varepsilon_{li} = \Delta\varepsilon_{lEi} + \Delta\varepsilon_{lPi} + \Delta\varepsilon_{lDi} + \Delta\varepsilon_{lTi} \tag{49}$$

where $\Delta\varepsilon_{li}$ is the directional effective strain and each term represents in order the mechanical deformation due to stress change, the mechanical deformation due to pressure change, matrix shrinkage/swelling due to desorption/sorption, and thermal contract/expansion due to temperature changes.

Recently, they extended their work by considering discontinuous coal masses as an equivalent elastic continuum. The implementation procedure of an explicit-sequential coupled simulation using such permeability models in industrial simulators is complex but feasible for coupled simulation in pressure depleting CBM reservoirs (Gu and Chalaturnyk, 2010). The total change of cleat aperture is defined as

$$\Delta b_m = \begin{cases} a\Delta\varepsilon_f & (\mathrm{u_s}/\mathrm{u_s^{\it p}} < 0.3) \\ a\left(\Delta\varepsilon_f + \Delta\gamma_f \tan\psi^m\right) & (\mathrm{u_s}/\mathrm{u_s^{\it p}} \geq 0.3) \end{cases} \tag{50}$$

The total change of matrix block is defined as

$$\Delta a = \begin{cases} a\left(\Delta\varepsilon_L^t - \Delta\varepsilon_f\right) + b_m\Delta\varepsilon_L^t & (\mathrm{u_s}/\mathrm{u_s^{\it p}} < 0.3) \\ a\left(\Delta\varepsilon_L^t - \Delta\varepsilon_f - \Delta\gamma_f \tan\psi^m\right) + b_m\Delta\varepsilon_L^t & (\mathrm{u_s}/\mathrm{u_s^{\it p}} \geq 0.3) \end{cases} \tag{51}$$

The following expression is used for the permeability calculation

$$\frac{k_i}{k_{i0}} = \frac{\left[1 + \frac{(\Delta b_m)_j}{(b_m)_j}\right]^{3n_j}}{1 + \frac{\Delta a_j}{a_j}} \tag{52}$$

where a is the width of the coal matrix block, $\Delta\varepsilon_f$ is the change of normal strain within the fracture (cleat), $\mathrm{u_s}$ and $\mathrm{u_s^{\it p}}$ are shear displacements of the fracture and peak shear displacement of the fracture respectively. $\Delta\gamma_f$ is the change of the shear strain of a fracture, and ψ^m is the mobilized dilation angle. $\Delta\varepsilon_L^t$ is the total change of linear strain of a composite unit including a matrix block and a fracture, and b_m is the mechanical aperture of a fracture.

Wang et al. (2009) developed a model that incorporates the anisotropic structural and mechanical properties to describe the directional permeability of coal. In this model, the mechanical and non-mechanical deformations of coal under confined stress conditions that imitate coal reservoirs were taken into account. The mechanical deformation was the stress-dominated deformation that was described using the general stress–strain correlation and nonmechanical deformation was sorption-induced matrix swelling/shrinkage that was treated using a thermal expansion/contraction analogy. A strain factor, depended on coal properties and sorption characters such as coal type and rank, and sorbent gas, was introduced to correct the strains theoretically obtained for better interpretations of laboratory strain data under unconstrained conditions that are widely used for tests of coal permeability.

Liu et al. (2010b) developed a permeability model 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, which represents the partitioning of total strain for an equivalent porous coal medium between the fracture system and the matrix. Verification of this model has been conducted by Chen et al. (2010b).

The directional permeability expression is defined as follows

$$\frac{k_i}{k_{i0}} = \sum_{i \neq j} \frac{1}{2}\left[1 + \frac{3(1-R_m)}{\phi_{f0}}\Delta\varepsilon_{ej}\right]^3 \tag{53}$$

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

Recently, Pan and Connell (2011) developed an anisotropic swelling model based on the Pan and Connell (2007) swelling model, which applies an energy balance approach where the surface energy change caused by adsorption is equal to the elastic energy change of the coal solid. This new model also incorporated anisotropic coal properties.

3.4. Dual porosity and permeability models

Dual permeability or multiple permeability models have been developed to represent the porosity and permeability of all constituent components (Bai et al., 1993), including the role of sorption (Bai et al., 1997), and of multiple fluids (Douglas et al., 1991). Moreover, several models have been applied to represent the response of permeability evolution in deforming aquifers and reservoirs (Bai et al., 1995; Elsworth and Bai, 1992; Liu and Elsworth, 1997; Ouyang and Elsworth, 1993), to accommodate gas flow and other mechanical influences (Zhao et al., 2004).

Wu et al. (2010a) developed a dual poroelastic model (dual solid media — coal matrix and fracture) for single gas under variable stress conditions. The model allows exploration of the full range of mechanical boundary conditions from invariant stress to restrained displacement. Wu et al. (2010b) extended their previous work (Wu et al., 2010a) to define the evolution of gas sorption-induced anisotropic permeability. In this study, dual permeabilities are used which is different from Gu and Chalaturnyk's work (2010). The expression of anisotropic permeability for cleat system is defined as

$$\frac{k_i}{k_{i0}} = \sum_{i\neq j}\frac{1}{2}\left[1-\frac{1}{\phi_{f0}+\frac{3K_f}{K}}\left(\frac{1}{3}\alpha_T\Delta T+\frac{1}{3}\Delta\varepsilon_s-\frac{1}{K}\Delta\sigma_{ei}\right)\right]^3 \tag{54}$$

where ϕ_{f0} is the initial fracture porosity at reference conditions, $i, j=x,y,z$. ΔT, $\Delta\varepsilon_s$, $\Delta\sigma_{ei}$ refer to the change in temperature, sorption-induced strain and mechanical effective stress. The permeability model for the matrix system is same as that of Zhang et al. (2008).

4. Evaluation of current permeability models

As reviewed in the previous chapter, there is a large variety of coal permeability models. These span conditions represent constant stress through variable stress conditions. In this section, these models are evaluated through comparing laboratory and in-situ measurements with theoretical solutions of the two extreme cases, as illustrated in Fig. 2 for the bounding behaviors of free shrinkage/swelling models to the constant volumetric model.

A matchstick or cubic coal model is typically assumed with matrix blocks completely separated from each other in a coal sample. In this arrangement matrix swelling will not affect coal fracture permeability under the constant confining (total) stress conditions. When an adsorptive gas is injected, the gas occupies the fracture and the gas pressure in the fracture reaches the injection pressure almost instantly. At this stage, the maximum imbalance between fracture pressure and matrix pressure is achieved. However, this imbalance diminishes as the gas diffuses into the coal matrix. The pore pressure in the matrix increases which in turn reduces the effective stress in the matrix. As a consequence of the diffusion, coal matrix swells due to both the matrix pore pressure increase and the gas sorption. Because the effective stress in the fracture remains unchanged throughout the whole process, the coal matrix swelling will result in swelling of the blocks alone, rather than changes in fracture aperture. The ambient effective stress also exerts no influence on matrix swelling, due to the complete separation between matrix blocks caused by through-going fractures. Therefore, the permeability should not change. In other words, 0% of the swelling/shrinking strain contributes to the coal permeability change, which can be seen from Eq. (11). However, when the coal sample is completely constrained from all directions, the coal matrix swelling will be completely transferred to the reduction in fracture apertures. In this situation, 100% of the swelling/shrinking strain contributes to the coal permeability change provided that the fractures are much more compliant than the coal matrix.

The theoretical solutions for these two cases are derived as

$$\frac{k}{k_0} = \left[1+\frac{\alpha}{\phi_{f0}}\left(\frac{\Delta p}{K}\right)\right]^3 \rightarrow \text{Free Shrinking/Swelling Model} \tag{55}$$

$$\frac{k}{k_0} = \left[1+\frac{\alpha}{\phi_{f0}}(\Delta\varepsilon_s)\right]^3 \rightarrow \text{Constant Volumetric Model} \tag{56}$$

Solutions of these two cases are illustrated in Fig. 3. If we apply these solutions to laboratory measurements, experimental observations should lie within the zone of real behaviors bounded by these limiting responses. If we look at the overall behavior of a coal gas reservoir, the reservoir permeability should also be within this zone.

In the following sections, we briefly review experimental observations of coal permeability under the influence of gas adsorption/desorption, in-situ observations of a coal gas reservoir during gas production, and compare them with the bounds of their behaviors as shown in Fig. 3. These comparisons will provide the basis for the evaluation of the current coal permeability models.

4.1. Laboratory observations versus theoretical solutions

Early studies (Dabbous et al., 1974; Durucan and Edwards, 1986; Gray, 1987; Mckee et al., 1988; Patching, 1965; Rose and Foh., 1984; Seidle et al., 1992; and Somerton et al., 1975) have observed significant dependences of coal permeability both on the stress conditions and on the type of gasses. In these studies, the influence of gas-sorption-induced deformation was avoided by using non-adsorptive gasses or by keeping the gas pressure constant. Harpalani and Schraufnagel (1990) made direct observations on the influence of matrix shrinkage and compressibility on coal permeability change through the injection of helium, CH_4 and CO_2 injection under hydrostatic stress conditions. The confining stress was kept constant during testing, and different effective stresses were achieved by varying pore pressure. They observed that the coal permeability decreases with decreasing gas pressure for the case of helium desorption, but increases for the case of CO_2 desorption. A permeability rebound was also observed for the case of methane desorption: permeability initially decreases with decreasing gas pressure, then increases at a certain value of gas pressure. Seidle and Huitt (1995) conducted experimental measurements of coal matrix shrinkage due to gas desorption under free expansion, and found a close relation between matrix shrinkage and gas content. Based on the monitored data and using a matchstick geometry model, equations were derived for permeability change due to matrix shrinkage.

Assuming all of these observations were made under controlled stress conditions and the applied confining stresses were maintained constant during the tests, the influences of these external stresses on the coal permeability change could be eliminated. Under hydrostatic stress condition, 0% of coal shrinkage would contribute to changes in coal permeability. This may represent the free shrinkage case. Assuming the experiments were conducted under completely constrained condition then the bulk volume of a coal sample would not change during the experiment. Under this assumption, 100% of coal shrinkage would contribute to the enhancement of coal permeability, which represents the constant volumetric case. Because most of the experimental observations were made under conditions of controlled stress, they should be equal to or close to the theoretical solution under the free shrinkage condition. As shown in Fig. 4, this has not been the case: the observations are close to the constant volumetric case even though they are made under conditions of free shrinkage.

Direct observations of the influence of coal swelling on permeability change were made by Robertson (2005). In this study, four different gasses (helium, N_2, CH_4 and CO_2) were injected into coal samples. Similar experiments have been conducted by others (Kiyama et al., 2011; Pini et al., 2009; Siriwardane et al., 2009; Wang et al., 2010). These observations demonstrate that even under controlled stress conditions the injection of adsorptive gasses reduces the coal permeability at a lower gas pressure and the coal permeability might rebound at a higher gas pressure. This observed switch in behavior is presumably due to the dependence of coal swelling on the gas pressure: coal swelling diminishes at high pressures.

Similar to the gas desorption cases, because all of the mentioned experimental observations were made under controlled stress conditions, they should be equal to or close to the theoretical solution under the free swelling condition. As shown in Fig. 5, this has not been the case: the observations are close to the constant volumetric case even though they are made under the free swelling conditions.

4.2. Field observations

In-situ measured data show that the absolute permeability of coal gas reservoirs increases significantly with continued gas production (Cherian et al., 2010; Clarkson et al., 2008; Sparks et al., 1995; Young et al., 1991). This phenomenon caused gas-production rates to be many times greater than expected. The phenomenon also caused producing bottom hole pressures to increase when gas rates were constant, opposite from that expected from conventional applications of Darcy's law.

However, the opposite observation was made when CO_2 was injected to enhance CBM production. One example is the Allison Unit CO_2 enhanced coalbed methane recovery pilot project, located in the northern New Mexico portion of the San Juan Basin. Reeves et al. (2003) reported the evidence of significant coal permeability reduction with CO_2 injection. Another example is the CO_2-ECBM pilot project in Qinshui Basin, China. It has been reported that the CO_2 injectivity decreased during injection but permeability rebounded after an extended production period of 1 month (Wong et al., 2007). Similar observations were also made in other ECBM pilot projects (Fujioka et al., 2010; George et al., 2009; Mavor and Vaughn, 1998; Mavor et al., 2004; Palmer, 2009; van Bergen et al., 2009).

Assuming all of coal gas reservoirs are under conditions of controlled stress and the ground stresses are maintained as constant during the gas extraction/injection, the influences of these constant ground stresses on the coal permeability change could be eliminated. Under the hydrostatic stress condition, 0% of coal shrinking/swelling would contribute to the coal permeability enhancement/reduction. This represents the free swelling case. Alternately, assuming coal gas reservoirs are under conditions of complete deformational constraint then the bulk volume of a coal gas reservoir would not change during the gas extraction/injection. Under this assumption, 100% of coal shrinking/swelling would contribute to the enhancement/reduction of coal permeability. This represents the constant volumetric case. Comparison of field observations with both the free shrinkage model and constant volumetric model is presented in Fig. 6. Because all of the in-situ observations were made under unknown conditions of in-situ stress they should lie within the bracketing behaviors. As shown in Fig. 6, in-situ observations demonstrate that coal gas reservoirs behave more closely to the constant volume case.

4.3. Evaluation of coal permeability models

Laboratory observations are made under conditions of controlled stress. Under these conditions, coal samples are free to swell/shrink and no swelling/shrinkage strain contributes to the coal permeability change. However, these theoretical conclusions are not consistent with experimental observations. These observations indicate that although the experiments were conducted under controlled stress conditions the experimental measurements are more closely related to those expected under constant volume conditions. These discrepancies illustrate the obvious drawbacks of the current coal permeability models. If a coal gas reservoir is treated as a whole, with full lateral restraint and invariant overburden stress, its behavior should represent components of the free swelling/shrinkage and the constant volume models. This could explain why current coal permeability models representing conditions of uniaxial strain condition can successfully match some field data.

All of the coal permeability models are derived based on the theory of poroelasticity. These models honor their various assumptions, but have failed to fully replicate laboratory observations, and achieved only limited success in matching field data. The most recent viewpoints (Izadi et al., 2011; Liu and Rutqvist, 2010) have demonstrated that the main reason for the failure is that the impact of coal matrix–fracture compartment interactions on the evolution of coal permeability has not been incorporated appropriately. Current experimental studies have been focusing on the overall behaviors of coal samples and only a few of them focus on the impact of fractures (Siriwardane et al., 2009; Wang et al., 2011). However, no direct observations are currently available.

5. Interaction of multiple processes

Gas flow within coal seams differs significantly from that of conventional reservoirs. Detailed studies have examined the storage and transport mechanisms of gas in coal seams. In situ and laboratory data indicate that the storage and flow of gas in coal seams are associated with the matrix structure of coal and the absorption or desorption of gas. Coal is a naturally fractured dual-porosity reservoir, consisting of micro-porous matrix and cleats. Most of the gas is initially stored within micro-pores in the absorbed state. When gas recovery begins, the gas desorbs and diffuses from the matrix to the cleats due to the concentration gradient. The rate of gas flow through the cleats is considered to be controlled by the permeability of the coal seam. Gas flow within coal seams is a complex physical and chemical process coupling solid deformation, gas desorption and gas movement, as shown in Fig. 1. The complexities of process interactions exert a strong control on ultimate behavior—these include linear physical interactions, but also the development of material nonlinearities that irreversibly alter the affected media.

According to Minkoff et al. (2003), there are three basic algorithms for the simulation of coupled processes: one-way coupling, loose coupling, and full coupling. For one-way coupling, separate sets of equations are solved independently over the same total time interval. Periodically, output from one simulator is passed as input to the other; however, information is passed in only one direction. A loose coupling resides somewhere between full and one-way coupling. In loose coupling, different sets of equations are solved independently (as in one-way coupling), but information is passed at designated time intervals in both directions between the simulators. For a full coupling, a single set of equations (generally a large system of nonlinear coupled partial differential equations) incorporating all of the relevant physics must be solved simultaneously.

5.1. One-way coupling

As concluded in the discussion of fundamental principles (Section 2), coal porosity and permeability models have a variety of forms when specific conditions are imposed. When the change in total stress is equal to zero, $\Delta\sigma = 0$, both coal porosity and permeability are independent of the total stress. Similarly, when the coal sample is under the uniaxial strain condition and the overburden load remains unchanged, they are also independent of the total stress. In this review, studies under these assumptions are considered as one-way coupling.

Balla (1989) developed a mathematical modeling to simulate methane flow in a borehole coal mining system, which considered both the sorption phenomenon of methane and, as a consequence of this, a change in the permeability of the coal. Young (1998) used the nonequilibrium and pseudosteady state formulations to simulate coalbed methane production performance, in which the diffusion coefficient is considered to be dependent on the geometry of the matrix elements and time. The stress-induced changes in cleat porosity and permeability were included, and the matrix shrinkage due to release of adsorbed gas are also considered. Similarly, Gilman and Beckie (2000) proposed a simplified mathematical model of methane movement in a coal seam taking into account the following features: a relatively regular cleat system, adsorptive methane storage, an extremely slow mechanism of methane release from the coal matrix into cleats and a significant change of permeability due to desorption.

Considering coal to be a triple-porosity system, the implementation of a bidisperse pore-diffusion model in a coalbed reservoir simulator was discussed by Shi and Durucan (2005), in which the gas adsorption is assumed to take place only in the micropores with macropores providing storage for free gas, as well as tortuous paths for gas transport between the micropores and cleats. Recently, Ross et al. (2009) presented a 3D stochastic reservoir model to address gas buoyancy and leakage associated with CO_2 injection in coalbeds by using geostatistical techniques and history-matching. More recently, a mathematical model was developed by Ozdemir (2009) to predict coal bed methane (CBM) production and carbon dioxide (CO_2) sequestration in a coal seam accounting for the coal seam properties. It was assumed that the flow in a coal seam is a two-phase flow including a water phase and a gas phase governed by Darcy's law while the flow in the coal matrix is a diffusional flow governed by Fick's Law, but constant absolute permeability was used in this study.

These prior studies did not accommodate geomechanical influences related to the role of changes in total stress on performance. Zhao and Valliappan (1995) derived the governing equations of methane gas migration in coal seams, which considered the effect of deformation of the medium, two-phase flow and mass/gas transfer on methane transport processes in porous media. The permeability magnitudes for both gas and water flow were considered to be same and constant. This work was extended by Valliappan and Wohua (1996), who presented the development of a mathematical model for methane gas migration in coal seams, mainly focusing on the coupling between the gas flow and deformation of solid coal. Anisotropic flow and the effect of diffusion of adsorbed methane have been considered in this study, but assumed that the porosity of the coal seam does not change when the gas pressure varies and is constant within an individual element.

5.2. Loose coupling

When coal is under variable stress conditions and the impact of coal fractures and gas compositions is considered, coal porosity and permeability models are defined as a function of effective stress, coal matrix–fracture interactions, and gas compositions. Under these conditions, important non-linear responses due to the effective stress effects must be recovered. This can be achieved through loose coupling. In loose coupling, different sets of equations are solved independently (as in one-way coupling), but information is passed at designated time intervals in both directions between the simulators.

The theory describing fluid–solid coupling was first presented by Biot (1941) for a linear solid where deformation occurred but where no updating was applied to changes in permeabilities due to infinitesimal changes in porosity. The original Biot theory is for a single-fluid/single-solid model consistent with single porosity behavior. Naturally fractured reservoirs are often modeled by the dual-porosity (overlapping continua) type of concept developed by Barenblatt et al. (1960). Models incorporating both Biot poroelasticity and Barenblatt dual-porosity concepts have been studied by many authors (Chen and Teufel, 1997; Duguid and Lee, 1977; Valliappan and Khalili-Naghadeh, 1990). A mathematical model of coupled solid–gas for gas flow in coal seams was presented by Zhao et al. (1994), but the permeability was considered to be constant and the sorption-induced strain was not coupled in this study. In 2004, Zhao et al. (2004) extended their work by considering permeability is a function of volumetric stress and pore pressure to emphasize the coupled interaction laws between solid deformations and gas seepage within the coal matrix and fractures, but the influence of sorption-induced strain on permeability change was still not considered. Gu and Chalaturnyk (2005, 2006) utilized the dynamic change of permeability for geomechanical and reservoir explicit-sequential coupling simulations, where the geomechanical simulation is implemented for generalized deformation and stress change predictions, while multiphase flow is simulated with an appropriate reservoir simulator. Recently, Gu and Chalaturnyk (2010) established new porosity and permeability models used for reservoir and geomechanical coupled simulation, which considered a discontinuous coal mass (containing cleats and matrix) as an equivalent continuum elastic medium and the anisotropic permeability of coalbeds. Matrix shrinkage/swelling due to gas desorption/adsorption, thermal expansion due to temperature change and mechanical parameters, are included in their work. Similar work has also been conducted by Wang et al. (2010). Connell (2009) conducted a coupled numerical model and used it to investigate the applicability of these geomechanical assumptions for gas drainage from coal seams. The modeling approach

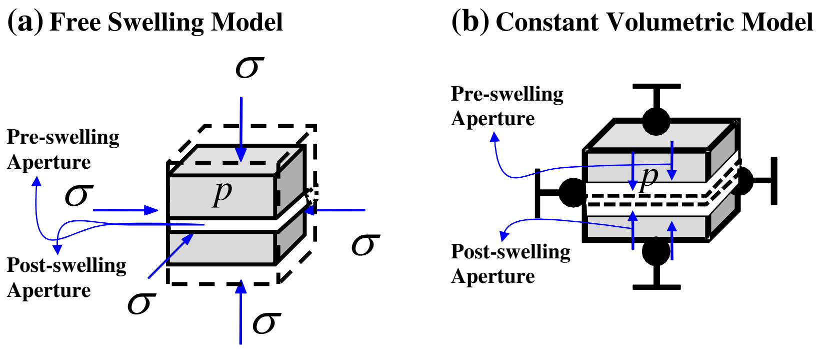

Fig. 2. Schematic diagram of two extreme cases: (a) Free swelling model, where constant stress conditions are applied throughout the whole process; (b) Constant volumetric model, where constant volume conditions are maintained throughout the whole process. These two cases represent the lower and upper bounds for permeability and porosity response.

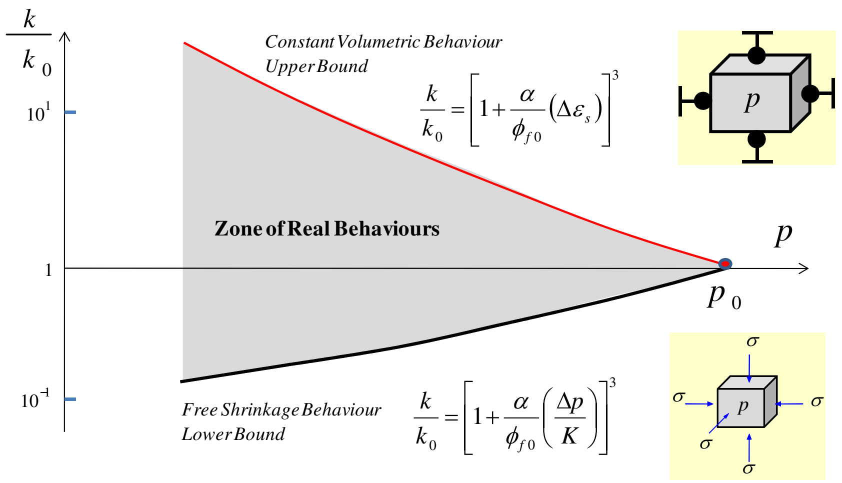

Fig. 3. Illustration of two theoretical models: free shrinkage model and constant volumetric model. Actual coal permeability is bounded by these two behaviors.

involved coupling the existing coal seam gas reservoir simulator, SIMED II, with the geomechanical simulator, FLAC3D. While SIMED II was used to simulate gas migration in a hypothetical coal seam and a series of production scenarios, FLAC3D simulated the geomechanical response of the coal and the adjacent non-coal geological formations to fluid pressure and gas content changes imported from SIMED II. Recently, this work was extended to CO_2-ECBM (Connell and Detournay, 2009). Similarly, Zuo-Tang et al. (2009) proposed a deformation-flow coupled model to address CO_2-geosequestration enhanced coal bed methane recovery. Permeability was considered to be a function of effective stress, but the influence of the sorption-induced strain on permeability was not coupled. The interaction between mechanical deformation and fluid flow in fault zones was addressed by Cappa and Rutqvist (2010), and the TOUGH-FLAC simulator was applied to supercritical CO_2 injection, geomechanics, and ground surface deformations. Liu et al. (2010c) performed a coupled reactive flow and transport modeling to simulate large scale CO_2 injection. The governing mathematical equation was employed in TOUGHREACT to describe geochemical processes involving fluid–rock interactions. More recently, considering the Klinkenberg effect, Wei and Zhang (2010) developed a two-dimensional, two-phase, triple-porosity/dual-permeability, coupled fluid-flow and geomechanics CBM simulator for modeling gas and water production, and the coupling effects of effective stress and micro-pore swelling/shrinkage were modeled with the coupled fluid-flow and geomechanical deformation approach.

5.3. Full coupling

In order to recover important non-linear responses due to the effective stress effects, mechanical influences must be rigorously coupled with the gas transport system. This can be achieved through the full coupling approach. For full coupling, a single set of equations (generally a large system of non-linear coupled partial differential equations) incorporating all of the relevant physics will be solved simultaneously.

A coupled mathematical model for solid deformation and gas flow was proposed and implemented by Zhu et al. (2007). The finite element method was used to solve the coupled processes together with Klinkenberg effect. The empirical permeability expression obtained by Harpalani and Schraufnagel (1990) was used. Similarly, Zhang et al. (2008) conducted another study on coupled gas flow and coal deformation processes incorporating the newly developed permeability

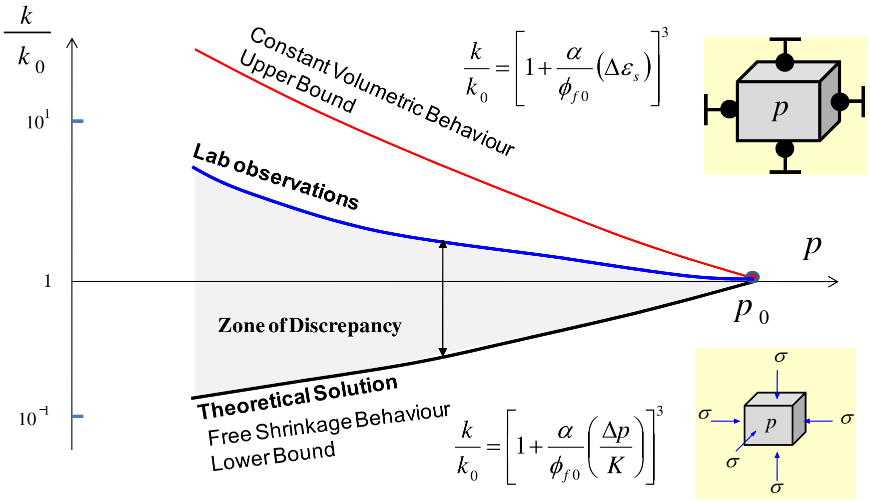

Fig. 4. Comparison between the observed typical changes in coal permeability due to gas desorption in the laboratory and the theoretical solutions for free shrinkage and constant volumetric models.

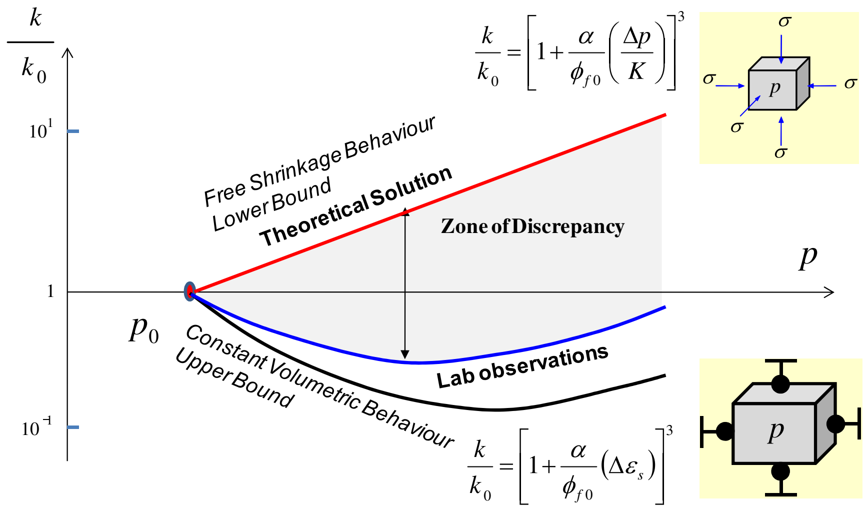

Fig. 5. Comparison between the observed typical coal permeability change due to gas adsorption in the lab and the theoretical solution both of which are bounded by free shrinkage and constant volumetric models.

model, which considers the controlling factors of the volume occupied by the free-phase gas, the volume occupied by the adsorbed phase gas, the coal mechanical deformation induced pore volume change, and the sorption induced coal pore volume change. Based on Zhang et al.'s work, equivalent poroelastic models (Liu et al., 2010a and Liu et al., 2010b) were developed to simulate the interactions of multiple processes triggered by the injection or production of single gas. Chen et al. (2009, 2010a) extended these single poroelastic models to include the flow and transport of gas mixtures (binary gasses: CO_2 and CH_4). Wu et al. (2010b, 2011) extended these models further to a dual poroelastic model (dual solid media — coal matrix and fracture) for both single gas and binary gas systems. Based on the variable saturation model, Liu and Smirnov (2008) solved a set of related variables regarding CO_2 sequestration in coalbeds, including capillary pressure, relative permeability, porosity, coupled adsorption model, concentration and temperature equations. With the same assumptions, the above work was extended to address the importance of structural deformation effects on carbon sequestration modeling, which affects the fluid flow and leads to a faster drop of the resulting capillary pressure and relative permeability of the gas phase (Liu and Smirnov, 2009).

5.4. Concluding remarks

To define a fully coupled computer simulator for the full mechanics of coal–gas interactions, a single set of equations (generally a large system of non-linear coupled partial differential equations) incorporating all of the relevant physics must be derived. Full coupling is often the preferred method for simulating multiple types of physics simultaneously since it should theoretically produce the most realistic results. This is the only approach to represent important non-linear responses due to the effective stress effects when mechanical influences are rigorously coupled with the gas transport system.

6. Key knowledge gaps

Laboratory observations indicate that although experiments are typically conducted under conditions of free shrinkage/swelling, measurements are more like those anticipated under conditions of constant volume. Similarly, in situ observations demonstrate that coal gas reservoirs behave more closely to the constant volume case although all of the in-situ observations are made under unknown in-

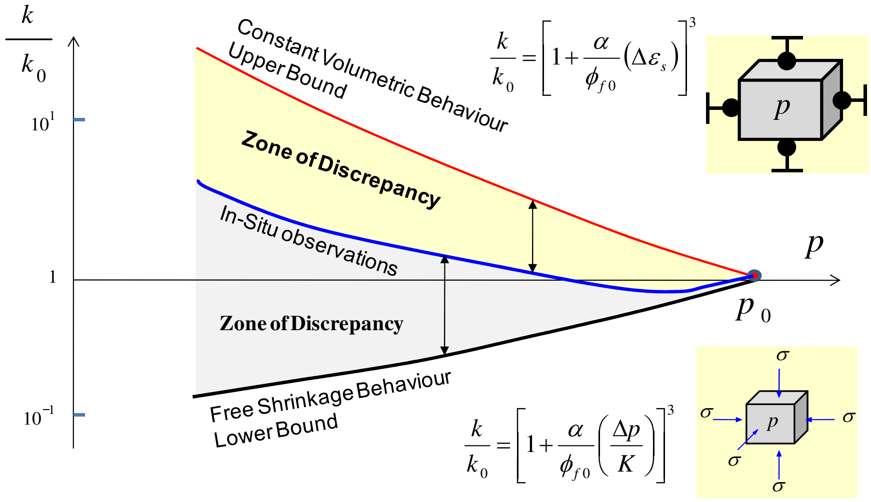

Fig. 6. Comparison between the observed typical coal permeability change due to gas desorption in coal gas reservoirs and the theoretical solution both of which are bounded by the free shrinkage and the constant volumetric models.

situ stress conditions. These comparisons demonstrate that current models have so far failed to explain the results from stress-controlled shrinking/swelling laboratory tests, and only achieved some limited successes in explaining and matching in-situ data. The most recent views of this contradiction (Izadi et al., 2011; Liu and Rutqvist, 2010; Liu et al., 2010a, 2010b; Siriwardane et al., 2009; Wang et al., 2010) have demonstrated that coal matrix–fracture compartment interactions are responsible for the discrepancies between observations and theoretical characterizations. Thus key questions remain that relate to needs for (1) direct observations of coal matrix–fracture compartment interactions through novel free shrinking/swelling experiments; (2) incorporation of these direct observations into coal permeability models through equivalent porous medium theory or dual porosity and permeability representations; and (3) implementation of these new permeability models into a fully coupled simulation framework accommodating all important feedbacks.

Nomenclature

a	the width of the coal matrix block
a'	material constant
b'	material constant
B	Langmuir pressure constant (Pa^{-1}).
b	fracture aperture
Δb	fracture aperture change
b_0	the initial aperture
b_m	the mechanical aperture of a fracture
c_f	coal cleat compressibility
C_m	shrinkage compressibility
d_e	the effective diameter of grains
E	Young's modulus of coal
E_f	Young's modulus for the fracture
E_s	Young's modulus of the solid phase
E_m	Young's modulus for matrix system
E_0	Young's modulus without swelling influence
f	a fraction between 0 and 1
G	the shear modulus of coal
l	the crack length
k	coal permeability
k_{i0}	initial permeability in i direction
k_i	current permeability in i direction
K	the bulk modulus of coal
K_s	the bulk modulus of coal grains
K_p	the bulk modulus of coal pore system
L	Langmuir sorption constant (mol/kg)
p	the gas pressure within the pores
p_L	Langmuir pressure constant
Δp_s	equivalent sorption pressure.
R	the gas constant ($8.314\ \mathrm{J\ mol^{-1}\ K^{-1}}$)
R_m	elastic modulus reduction ratio
s	cleat spacing
ΔS	the change of the adsorbate mass
T	reservoir temperature
u_s	shear displacement of fracture
u_s^p	peak shear displacement of fracture
ν	Poisson's ratio of coal
ν_s	Poisson's ratio for solid phase
ρ_s	Density for solid phase.
δ_{ij}	the Kronecker delta (1 for $i=j$and 0 for $i\neq j$)
ϕ	coal porosity
ϕ_f	the cleat porosity
ε_i	current principal strains
ε_L	the maximum volumetric strain
$\Delta\varepsilon_L^t$	the total change of linear strain of a composite unit
ε_s	the sorption-induced volumetric strain
ε_v	the volumetric strain of coal
ε_e	the total effective volumetric strain
$d\varepsilon_p$	the incremental pore volume strain
$d\varepsilon_r$	the incremental rock bulk volume strain
$d\varepsilon_g$	the incremental grain volume strain
$\Delta\varepsilon_f$	the change of normal strain of fracture (cleat)
$\Delta\varepsilon_{li}$	the directional effective strain
$\Delta\varepsilon_{lEi}$	the mechanical deformation due to stress change
$\Delta\varepsilon_{lPi}$	the mechanical deformation due to pressure change
$\Delta\varepsilon_{lDi}$	matrix shrinkage/swelling due to desorption/sorption
$\Delta\varepsilon_{lTi}$	thermal contract/expansion due to temperature changes.
α	the Biot's coefficient
α_T	the coefficient of volumetric thermal expansion.
α_c	change rate in fracture compressibility
σ_h	the horizontal stress
σ_{h0}	the initial horizontal stress
$\Delta\sigma_{in}$	the internal swelling stress
γ	the volumetric welling/shrinkage coefficient
γ'	grain compressibility
$\Delta\gamma_f$	change of shear strain of a fracture
ψ^m	the mobilized dilation angle

Acknowledgements

The views expressed in this review have developed as a result of support from the Australian Research Council (ARC), CSIRO, the US National Institute for Safety and Health (NIOSH) and from ConocoPhillips. The views expressed in this review are those of the authors alone.

References

Al-Yousef, H.Y., 2005. Permeability anisotropy measurement on whole cores — analytical solution and application. SPE Middle East Oil and Gas Show and Conference. Society of Petroleum Engineers, Kingdom of Bahrain.

Bai, M., Elsworth, D., Roegiers, J.-C., 1993. Multiporosity/multipermeability approach to the simulation of naturally fractured reservoirs. Water Resources Research 29 (6), 1621–1633.

Bai, M., Roegiers, J.-C., Elsworth, D., 1995. Poromechanical response of fractured-porous rock masses. Journal of Petroleum Science and Engineering 13 (3–4), 155–168.

Bai, M., Elsworth, D., Inyang, H.I., Roegiers, J.C., 1997. Modeling contaminant migration with linear sorption in strongly heterogeneous media. Journal of Environmental Engineering 123 (11), 1116–1125.

Balla, L., 1989. Mathematical modeling of methane flow in a borehole coal mining system. Transport in Porous Media 4 (2), 199–212.

Barenblatt, G.I., Zheltov, I.P., Kochina, I.N., 1960. Basic concepts in the theory of seepage of homogeneous liquids in fissured rocks. Journal of Applied Mathematics and Mechanics 24, 1286–1303.

Bear, J., Corapcioglu, M.Y., 1981. A mathematical model for consolidation in a thermoelastic aquifer due to hot water injection or pumping. Water Resources Research 17 (3), 723–736.

Biot, M.A., 1941. General theory of three-dimensional consolidation. Journal of Applied Physics 12 (2), 155–164.

Boyer, C.M., 1994. International Coalbed Methane—Where's the Production? North American Coalbed Methane Forum, Morgantown, WV.

Cappa, F., Rutqvist, J., 2010. Modelling of coupled deformation and permeability evolution during fault reactivation induced by deep underground injection of CO_2. International Journal of Greenhouse Gas Control. doi:10.1016/j.ijggc.2010.08.005.

Chen, H.-Y., Teufel, L.W., 1997. Coupling fluid-flow and geomechanics in dual-porosity modeling of naturally fractured reservoirs. SPE Annual Technical Conference and Exhibition. Society of Petroleum Engineers, Inc, San Antonio, Texas.

Chen, Z., Liu, J., Connell, L., Pan, Z., Zhou, L., 2008. Impact of Effective Stress and CH_4–CO_2 Counter-Diffusion on CO_2 Enhanced Coalbed Methane Recovery. SPE Asia Pacific Oil and Gas Conference and Exhibition, Perth, Australia.

Chen, Z., Liu, J., Elsworth, D., Connell, L., Pan, Z., 2009. Investigation of CO_2 injection induced coal–gas interactions, 43rd U.S. Rock Mechanics Symposium & 4th U.S.–Canada Rock Mechanics Symposium. American Rock Mechanics Association, Asheville, North Carolina.

Chen, Z., Liu, J., Elsworth, D., Connell, L.D., Pan, Z., 2010a. Impact of CO_2 injection and differential deformation on CO_2 injectivity under in-situ stress conditions. International Journal of Coal Geology 81 (2), 97–108.

Chen, Z., Liu, J., Pan, Z., Connell, L., Elsworth, D., 2010b. Relations between coal permeability and directional strains and their application to San Juan Basin. 44th U.S. Rock Mechanics Symposium and 5th U.S.–Canada Rock Mechanics Symposium. American Rock Mechanics Association, Salt Lake City, Utah.

Cherian, B.V., et al., 2010. An Integrated Single-Well Approach to Evaluating Completion Effectiveness and Reservoir Properties in the Wind Dancer Field, Tight Gas Completions Conference. Society of Petroleum Engineers, San Antonio, Texas, USA.

Chilingar, G.V., 1964. Relationship between porosity, permeability, and grain-size distribution of sands and sandstones. In: Straaten, L.M.J.U.v. (Ed.), Developments in Sedimentology. Elsevier, pp. 71–75.

Clarkson, C.R., Pan, Z., Palmer, I.D., Harpalani, S., 2008. Predicting Sorption-Induced Strain and Permeability Increase With Depletion for CBM Reservoirs, SPE Annual Technical Conference and Exhibition. Denver, Colorado, USA.

Connell, L.D., 2009. Coupled flow and geomechanical processes during gas production from coal seams. International Journal of Coal Geology 79 (1–2), 18–28.

Connell, L.D., Detournay, C., 2009. Coupled flow and geomechanical processes during enhanced coal seam methane recovery through CO_2 sequestration. International Journal of Coal Geology 77 (1–2), 222–233.

Connell, L.D., Lu, M., Pan, Z., 2010. An analytical coal permeability model for tri-axial strain and stress conditions. International Journal of Coal Geology 84 (2), 103–114.

Cui, X., Bustin, R.M., 2005. Volumetric strain associated with methane desorption and its impact on coalbed gas production from deep coal seams. AAPG Bulletin 89 (9), 1181–1202.

Dabbous, M.K., Reznik, A.A., Taber, J.J., Fulton, P.F., 1974. The Permeability of Coal to Gas and Water 14 (6), 563–572.

Detournay, E., Cheng, A.H.-D., 1993. Fundamentals of poroelasticity. In: Fairhurst, C. (Ed.), Chapter 5 in Comprehensive Rock Engineering: Principles, Practice and Projects. Analysis and Design Method, vol. II. Pergamon Press, pp. 113–171.

Douglas Jr., J., Hensley, J.L., Arbogast, T., 1991. A dual-porosity model for waterflooding in naturally fractured reservoirs. Computer Methods in Applied Mechanics and Engineering 87 (2–3), 157–174.

Duguid, J.O., Lee, P.C.Y., 1977. Flow in fractured porous media. Water Resources Research 13 (3), 558–566.

Durucan, S., Edwards, J.S., 1986. The effects of stress and fracturing on permeability of coal. Mining Science and Technology 3 (3), 205–216.

Elsworth, D., Bai, M., 1992. Flow-deformation response of dual-porosity media. Journal of Geotechnical Engineering 118 (1), 107–124.

Fujioka, M., Yamaguchi, S., Nako, M., 2010. CO_2-ECBM field tests in the Ishikari Coal Basin of Japan. International Journal of Coal Geology 82 (3–4), 287–298.

Gash, B.W., Richard, F.V., Potter, G., Corgan, J.M., 1992. The Effects of Cleat Orientation and Confining Pressure on Cleat Porosity, Permeability and Relative Permeability in Coal. SPWLA/SCA Symposium, Oklahoma City.

George Jr., J.K., et al., 2009. CO_2-ECBM/storage activities at the San Juan Basin's pump canyon test site. SPE Annual Technical Conference and Exhibition. Society of Petroleum Engineers, New Orleans, Louisiana.

Gilman, A., Beckie, R., 2000. Flow of coal-bed methane to a gallery. Transport in Porous Media 41 (1), 1–16.

Gray, I., 1987. Reservoir engineering in coal seams: part 1—the physical process of gas storage and movement in coal seams. SPE Reservoir Engineering 2 (1), 28–34.

Gu, F. and Chalaturnyk, J.J., 2005. Analysis of coalbed methane production by reservoir and geomechanical coupling simulation. 44(10).

Gu, F., Chalaturnyk, R.J., 2006. Numerical simulation of stress and strain due to gas sorption/desorption and their effects on in situ permeability of coalbeds. Journal of Canadian Petroleum Technology 45 (10), 52–62.

Gu, F., Chalaturnyk, R., 2010. Permeability and porosity models considering anisotropy and discontinuity of coalbeds and application in coupled simulation. Journal of Petroleum Science and Engineering 74 (3–4), 113–131.

Harpalani, S., Chen, G., 1997. Influence of gas production induced volumetric strain on permeability of coal. Geotechnical and Geological Engineering 15 (4), 303–325.

Harpalani, S., Schraufnagel, R.A., 1990. Shrinkage of coal matrix with release of gas and its impact on permeability of coal. Fuel 69 (5), 551–556.

Hudson, J.A., Fairhurst, C., et al., 1993. Comprehensive rock engineering: principles, practice, and projects. Analysis and Design Method, vol. II. Pergamon, Oxford.

Izadi, G., Wang, S., Elsworth, D., Liu, J., Wu, Y., Pone, D., 2011. Permeability evolution of fluid-infiltrated coal containing discrete fractures. International Journal of Coal Geology 8, 202–211.

Kiyama, T., Nishimoto, S., Fujioka, M., Xue, Z., Ishijima, Y., Pan, Z., Connell, L.D., 2011. Coal swelling strain and permeability change with injecting liquid/supercritical CO_2 and N_2 at stress-constrained conditions. International Journal of Coal Geology 85, 56–64.

Koenig, R.A., Stubbs, P.B., 1986. Interference testing of a coalbed methane reservoir. SPE Unconventional Gas Technology Symposium. Society of Petroleum Engineers, Inc, Louisville, Kentucky.

Kuuskraa, V.A., Boyer, C.M., Kelafant, J.A., 1992. Hunt for quality basins goes abroad. Oil & Gas Journal 5, 72–77.

Liu, J., Elsworth, D., 1997. Three-dimensional effects of hydraulic conductivity enhancement and desaturation around mined panels. International Journal of Rock Mechanics and Mining Sciences 34 (8), 1139–1152.

Liu, H.-H., Rutqvist, J., 2010. A new coal-permeability model: internal swelling stress and fracture–matrix interaction. Transport in Porous Media 82 (1), 157–171.

Liu, G., Smirnov, A.V., 2008. Modeling of carbon sequestration in coal-beds: a variable saturated simulation. Energy Conversion and Management 49 (10), 2849–2858.

Liu, G., Smirnov, A.V., 2009. Carbon sequestration in coal-beds with structural deformation effects. Energy Conversion and Management 50 (6), 1586–1594.

Liu, F., Lu, P., Zhu, C., Xiao, Y., 2010a. Coupled reactive flow and transport modeling of CO2 sequestration in the Mt. Simon sandstone formation, Midwest U.S.A. International Journal of Greenhouse Gas Control. doi:10.1016/j.ijggc.2010.08.008.

Liu, J., Chen, Z., Elsworth, D., Miao, X., Mao, X., 2010b. Evaluation of stress-controlled coal swelling processes. International Journal of Coal Geology 83 (4), 446–455.

Liu, J., Chen, Z., Elsworth, D., Miao, X., Mao, X., 2010c. Linking gas-sorption induced changes in coal permeability to directional strains through a modulus reduction ratio. International Journal of Coal Geology 83 (1), 21–30.

Liu, J., Chen, Z., Qu, H., 2010d. Multiphysics of coal–gas interactions: the scientific foundation for CBM extraction. SPE Asia Pacific Oil and Gas Conference and Exhibition, Brisbane, Queensland, Australia.

Liu, J., Chen, Z., Elsworth, D., Miao, X., Mao, X., 2011. Evolution of coal permeability from stress-controlled to displacement-controlled swelling conditions. Fuel. doi:10.1016/j.fuel.2011.04.032.

Lu, M., Connell, L.D., 2007. A model for the flow of gas mixtures in adsorption dominated dual porosity reservoirs incorporating multi-component matrix diffusion: part I. Theoretical development. Journal of Petroleum Science and Engineering 59 (1–2), 17–26.

Ma, Q., Harpalani, S., Liu, S., 2011. A simplified permeability model for coalbed methane reservoirs based on matchstick strain and constant volume theory. International Journal of Coal Geology 85 (1), 43–48.

Massarotto, P., Golding, S.D., Rudolph, V., 2009. Constant Volume CBM Reservoirs: An Important Principle. International Coalbed Methane Symposium, Tuscaloosa, Alabama.

Mavor, M.J., Vaughn, J.E., 1998. Increasing coal absolute permeability in the San Juan Basin fruitland formation. SPE Reservoir Evaluation and Engineering 1 (3), 201–206.

Mavor, M.J., Gunter, W.D., Robinson, J.R., 2004. Alberta multiwell micro-pilot testing for CBM properties, enhanced methane recovery and CO_2 storage potential. SPE Annual Technical Conference and Exhibition, Houston, Texas.

McKee, C.R., Bumb, A.C., Koenig, R.A., 1988. Stress-dependent permeability and porosity of coal and other geologic formations. SPE Formation Evaluation 3 (1), 81–91.

Minkoff, S.E., Stone, C.M., Bryant, S., Peszynska, M., Wheeler, M.F., 2003. Coupled fluid flow and geomechanical deformation modeling. Journal of Petroleum Science and Engineering 38 (1–2), 37–56.

Murray, D.K., 1996. Coalbed methane in the USA: analogues for worldwide development. Geological Society, London, Special Publications 109 (1), 1–12.

Nowacki, W., 1995. Dynamic Problems of Thermoelasticity. Noordhoff, Leiden, The Netherlands.

Ouyang, Z., Elsworth, D., 1993. Evaluation of groundwater flow into mined panels. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts 30 (2), 71–79.

Ozdemir, E., 2009. Modeling of coal bed methane (CBM) production and CO2 sequestration in coal seams. International Journal of Coal Geology 77 (1–2), 145–152.

Palmer, I., 2008. Coalbed methane wells are cheap, but permeability can be expensive! Energy Tribune 10–13.

Palmer, I., 2009. Permeability changes in coal: analytical modeling. International Journal of Coal Geology 77 (1–2), 119–126.

Palmer, I., Mansoori, J., 1996. How permeability depends on stress and pore pressure in coalbeds: a new model. SPE Annual Technical Conference and Exhibition. Society of Petroleum Engineers, Inc, Denver, Colorado.

Palmer, I.D., Mavor, M., Gunter, B., 2007. Permeability changes in coal seams during production and injection. International Coalbed Methane Symposium. University of Alabama, Tuscaloosa, Alabama. Paper 0713.

Pan, Z., Connell, L.D., 2007. A theoretical model for gas adsorption-induced coal swelling. International Journal of Coal Geology 69 (4), 243–252.

Pan, Z., Connell, L.D., 2011. Modelling of anisotropic coal swelling and its impact on permeability behaviour for primary and enhanced coalbed methane recovery. International Journal of Coal Geology 85 (3–4), 257–267.

Pan, Z., Connell, L.D., Camilleri, M., 2010. Laboratory characterisation of coal reservoir permeability for primary and enhanced coalbed methane recovery. International Journal of Coal Geology 82 (3–4), 252–261.

Patching, T.H., 1965. Variations in permeability of coal. Proc. 3rd Rock Mech. Symp. Univ. of Toronto, U.K, pp. 185–199.

Patching, T.H., 1970. Retention and release of gas in coal — a review. Canadian Mining and Metallurgical Bulletin 63 (703), 1302–1308.

Pekot, L.J., Reeves, S.R., 2002. Modeling the Effects of Matrix Shrinkage and Differential Swelling on Coalbed Methane Recovery and Carbon Sequestration. U.S. Department of Energy. DE-FC26-00NT40924.

Pini, R., Ottiger, S., Burlini, L., Storti, G., Mazzotti, M., 2009. Role of adsorption and swelling on the dynamics of gas injection in coal. Journal of Geophysical Research 114 (B4), B04203.

Pomeroy, C.D., Robinson, D.J., 1967. The effect of applied stresses on the permeability of a middle rank coal to water. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts 4 (3), 329–343.

Reeves, S., Taillefert, A., Pekot, L., Clarkson, C., 2003. The Allison unit CO_2-ECBM pilot: a reservoir modelling study. U.S. Department of Energy. Topical Report DE-FC26-0NT40924., February.

Reiss, L.H., 1980. The Reservoir Engineering Aspects of Fractured Formations. Gulf Publishing Co., Houston.

Robertson, E.P., 2005. Modeling permeability in coal using sorption-induced strain data. SPE Annual Technical Conference and Exhibition. Society of Petroleum Engineers, Dallas, Texas.

Robertson, E.P., Christiansen, R.L., 2006. A permeability model for coal and other fractured, sorptive-elastic media. SPE Eastern Regional Meeting. Society of Petroleum Engineers, Canton, Ohio, USA.

Rose, R.E., Foh, S.E., 1984. Liquid permeability of coal as a function of net stress. SPE Unconventional Gas Recovery Symposium. Society of Petroleum Engineers of AIME, Pittsburgh, Pennsylvania.

Ross, H.E., Hagin, P., Zoback, M.D., 2009. CO_2 storage and enhanced coalbed methane recovery: reservoir characterization and fluid flow simulations of the Big George coal, Powder River Basin, Wyoming, USA. International Journal of Greenhouse Gas Control 3 (6), 773–786.

Seidle, J.R., Huitt, L.G., 1995. Experimental measurement of coal matrix shrinkage due to gas desorption and implications for cleat permeability increases. International Meeting on Petroleum Engineering. Society of Petroleum Engineers, Inc, Beijing, China.

Seidle, J.P., Jeansonne, M.W., Erickson, D.J., 1992. Application of matchstick geometry to stress dependent permeability in coals. SPE Rocky Mountain Regional Meeting, Casper, Wyoming.

Shi, J.Q., Durucan, S., 2004. Drawdown induced changes in permeability of coalbeds: a new interpretation of the reservoir response to primary recovery. Transport in Porous Media 56 (1), 1–16.

Shi, J.-Q., Durucan, S., 2005. Gas storage and flow in coalbed reservoirs: implementation of a bidisperse pore model for gas diffusion in coal matrix. SPE Reservoir Evaluation and Engineering 8 (2), 169–175.

Siriwardane, H., et al., 2009. Influence of carbon dioxide on coal permeability determined by pressure transient methods. International Journal of Coal Geology 77 (1–2), 109–118.

Somerton, W.H., Söylemezoglu, I.M., Dudley, R.C., 1975. Effect of stress on permeability of coal. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts 12 (5–6), 129–145.

Sparks, D.P., McLendon, T.H., Saulsberry, J.L., Lambert, S.W., 1995. The effects of stress on coalbed reservoir performance, Black Warrior Basin, U.S.A. SPE Annual Technical Conference and Exhibition. Society of Petroleum Engineers, Inc, Dallas, Texas.

Valliappan, S., Khalili-Naghadeh, N., 1990. Flow through fissured porous media with deformable matrix. International Journal for Numerical Methods in Engineering 29 (5), 1079–1094.

Valliappan, S., Wohua, Z., 1996. Numerical modelling of methane gas migration in dry coal seams. International Journal for Numerical and Analytical Methods in Geomechanics 20 (8), 571–593.

van Bergen, F., Spiers, C., Floor, G., Bots, P., 2009. Strain development in unconfined coals exposed to CO2, CH4 and Ar: effect of moisture. International Journal of Coal Geology 77 (1–2), 43–53.

Wang, G.X., Massarotto, P., Rudolph, V., 2009. An improved permeability model of coal for coalbed methane recovery and CO_2 geosequestration. International Journal of Coal Geology 77 (1–2), 127–136.

Wang, G.X., Wei, X.R., Wang, K., Massarotto, P., Rudolph, V., 2010. Sorption-induced swelling/shrinkage and permeability of coal under stressed adsorption/desorption conditions. International Journal of Coal Geology 83 (1), 46–54.

Wang, S., Elsworth, D., Liu, J., 2011. Permeability evolution in fractured coal: the roles of fracture geometry and water-content. International Journal of Coal Geology. doi:10.1016/j.coal.2011.04.009.

Warren, J.E., Root, P.J., 1963. The Behavior of Naturally Fractured Reservoirs 3 (3), 245–255.

Wei, Z., Zhang, D., 2010. Coupled fluid-flow and geomechanics for triple-porosity/dual-permeability modeling of coalbed methane recovery. International Journal of Rock Mechanics and Mining Sciences 47 (8), 1242–1253.

White, C.M., et al., 2005. Sequestration of carbon dioxide in coal with enhanced coalbed methane recovery—a review†. Energy & Fuels 19 (3), 659–724.

Wong, R.C., 2003. A model for strain-induced permeability anisotropy in deformable granular media. Canadian Geotechnical Journal 40, 95–106.

Wong, S., et al., 2007. Enhanced coalbed methane and CO2 storage in anthracitic coals—micro-pilot test at South Qinshui, Shanxi, China. International Journal of Greenhouse Gas Control 1 (2), 215–222.

Wu, Y., et al., 2010a. Dual poroelastic response of a coal seam to CO_2 injection. International Journal of Greenhouse Gas Control 4 (4), 668–678.

Wu, Y., Liu, J., Elsworth, D., Miao, X., Mao, X., 2010b. Development of anisotropic permeability during coalbed methane production. Journal of Natural Gas Science and Engineering 2 (4), 197–210.

Young, G.B.C., 1998. Computer modeling and simulation of coalbed methane resources. International Journal of Coal Geology 35 (1–4), 369–379.

Young, G.B.C., McElhiney, J.E., Paul, G.W., McBane, R.A., 1991. An analysis of fruitland coalbed methane production, Cedar Hill Field, Northern San Juan Basin. SPE Annual Technical Conference and Exhibition. Society of Petroleum Engineers, Inc, Dallas, Texas.

Zhang, H., Liu, J., Elsworth, D., 2008. How sorption-induced matrix deformation affects gas flow in coal seams: a new FE model. International Journal of Rock Mechanics and Mining Sciences 45 (8), 1226–1236.

Zhao, C., Valliappan, S., 1995. Finite element modelling of methane gas migration in coal seams. Computers and Structures 55 (4), 625–629.

Zhao, Y., Jin, Z., Sun, J., 1994. Mathematical model for coupled solid deformation and methane flow in coal seams. Applied Mathematical Modelling 18 (6), 328–333.

Zhao, Y., Hu, Y., Zhao, B., Yang, D., 2004. Nonlinear coupled mathematical model for solid deformation and gas seepage in fractured media. Transport in Porous Media 55 (2), 119–136.

Zhu, W.C., Liu, J., Sheng, J.C., Elsworth, D., 2007. Analysis of coupled gas flow and deformation process with desorption and Klinkenberg effects in coal seams. International Journal of Rock Mechanics and Mining Sciences 44 (7), 971–980.

Zuo-tang, W., et al., 2009. Simulation of CO_2-geosequestration enhanced coal bed methane recovery with a deformation-flow coupled model. Procedia Earth and Planetary Science 1 (1), 81–89.