Fuel 143 (2015) 165–172

Contents lists available at ScienceDirect

Fuel

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

# Evaluation of gas sorption-induced internal swelling in coal

Jie Zang [a,*], Kai Wang [a,*], Yixin Zhao [b]

[a] Faculty of Resources & Safety Engineering, China University of Mining & Technology (Beijing), Beijing 100083, China
[b] State Key Laboratory of Coal Resources and Safe Mining, China University of Mining & Technology (Beijing), Beijing 100083, China

## HIGHLIGHTS

- The gas sorption-induced internal swelling was evaluated.
- The internal swelling varied with many influencing factors.
- The internal swelling ratio can be assumed to be constant during CBM recovery.
- The confining stress can affect permeability by influencing gas sorption.

## ARTICLE INFO

*Article history:*
Received 12 August 2014
Received in revised form 25 October 2014
Accepted 3 November 2014
Available online 15 November 2014

*Keywords:*
Internal swelling
Internal swelling ratio
Sorption strain
Coal permeability
Coalbed methane

## ABSTRACT

Gas sorption plays an important role in permeability evolution and gas flow in coal. Many efforts have been made to evaluate the effect of gas sorption on permeability. For example, the total gas sorption matrix swelling is divided in to two pars, one acts on cleat (internal swelling) and the other contributes to coal block deformation. Nevertheless, this effect has not been fully identified yet. This paper proposed a method that regressed the internal swelling by using a proposed permeability model. The internal swelling values under different boundary conditions were calculated by using the well-measured permeability from two published papers. The results indicated that the internal swelling was positively proportional to pore pressure and negatively proportional to confining stress for gaseous and supercritical methane and gaseous carbon dioxide. For supercritical carbon dioxide, the internal swelling increased with increasing pore pressure but was almost independent of confining stress. The internal swelling may be affected by sorbate type, coal structure and coal lithotypes in addition to pore pressure and confining stress. The internal swelling ratio that is defined as the ratio of the internal swelling to the gas sorption-induced swelling of coal matrix or coal block was also calculated. The internal swelling ratio may roughly keep constant during coalbed methane recovery when the *in situ* stress was greater than 5 MPa. This assumption was practically useful for engineering application as it linked the effect of gas sorption on *in situ* permeability to the easy-measured sorption strain. Although the constant value cannot capture the full nature of the *in situ* internal swelling ratio, it was still capable of improving the accuracy of permeability prediction to some extent.



## 1. Introduction

Gas sorption-induced coal deformation has been observed both in laboratory [1–4] and in field [5]. As pore pressure decreases during coalbed methane (CBM) recovery, methane ($CH_4$) gas desorbs from coal and the coal matrix shrinks. When injecting a gas, such as carbon dioxide ($CO_2$), into coal, the sorption (*i.e.*, adsorption and absorption) causes coal to swell. The gas sorption-induced coal deformation has strong impacts on coal permeability, which is an important property that determines gas flow behaviors in cleats. To figure out the effect of gas sorption on coal permeability, many efforts have been made in laboratory to measure the gas sorption-induced permeability change [6–11]. The results of these works indicate that the gas sorption-induced matrix swelling reduces permeability, and the permeability reduction increases with increasing sorption-induced matrix swelling [6,9]. Harpalani and Chen [12] reported that as pore pressure decreased from 6.2 MPa to 0.7 MPa, the permeability of coal sample increased by 17 times, of which 70.6% was due to the sorption strain.

A variety of permeability models has also incorporated the gas sorption-induced deformation term. Gray [13] applied a linear

* Corresponding authors at: D11 Xueyuan Road, Haidian District, Beijing, China. Tel./fax: +86 10 62339036.

*E-mail addresses:* jzangcumtb@gmail.com (J. Zang), wkcumtb@gmail.com (K. Wang).

http://dx.doi.org/10.1016/j.fuel.2014.11.007
0016-2361/

equation to represent the relationship between sorption strain and pore pressure in his permeability model. Sawyer et al. [14] and Seidle and Huitt [15] used a linear relationship with gas content to describe the impact of sorption strain on coal permeability. Levine [1] found that the correlation between sorption strain and gas pressure conformed to the Langmuir equation. Since then many permeability models have used the Langmuir equation to represent the gas sorption-caused permeability change [16–19]. In addition, Pan and Connell [20] developed a theoretical model to describe the gas sorption-induced coal swelling by assuming that the surface energy change due to gas sorption was equal to the elastic energy change of coal. This model was implemented into an existing permeability model to evaluate the effect of anisotropic swelling on permeability variation [21]. Recently, Liu and Harpalani [22] proposed a model to describe the volumetric change in coal matrix due to gas sorption. Their model was based on that the surface energy variation was a result of gas sorption. This model was implemented into various permeability models to fit two series of field permeability data [23].

The permeability models presented above all assume that the total sorption strain of the unconfined coal matrix contributes to permeability variation. This may overestimate the effect of gas sorption on permeability, especially under laboratory conditions where the coal sample can expand outward [11]. Connell et al. [6] proposed two analytical permeability model representations, in which the sorption strains of matrix and cleat are functions of that of coal block. Liu and Rutqvist [24] assumed that matrix blocks were connected by matrix bridges rather than completely separated by cleats. A result of this assumption is that only part of the gas sorption-induced matrix swelling contributed to permeability change and the remaining caused coal block deformation [24]. Liu and Rutqvist [24] also assumed that the ratio of the sorption-induced matrix swelling on permeability to the total gas sorption-induced swelling of the unconfined coal matrix was constant. Liu and co-workers also made many efforts to interpret the contribution of sorption strain to permeability [25–27]. The permeability models in this paragraph, except [25], all assume that only partial gas sorption-induced matrix swelling contributes to permeability. They also assume that the ratio of this portion to the total sorption-induced swelling of the unconfined coal matrix is constant. Recently, Shi et al. [28] extended their previously proposed permeability model by isolating the effect of sorption strain on permeability to a swelling strain term. They used an empirical equation in Langmuir form to link this term to the sorption-induced matrix swelling.

Normally, these permeability models agree well with some measured permeability data [26–28]. These models nevertheless have not captured the full nature of the effect of gas sorption on permeability yet as the effect of confining stress on gas sorption has not been fully accommodated. The sorption strain that is incorporated in permeability models is normally the strain of the unconfined coal matrix. This strain can be measured by using a small coal sample that is absent of cleats under unconfined conditions [4,10,29]. Coals under *in situ* or laboratory conditions however are normally confined. Under confined boundary conditions, the confining stress affects sorption capacity and the sorption-induced matrix swelling [30–32].

Our previous work [33] proposed a permeability model to represent the anisotropic permeability evolution with effective stress change and gas sorption. The concepts 'internal swelling' and 'internal swelling ratio' were introduced to evaluate the contribution of gas sorption to permeability. The internal swelling is defined as the proportion of the gas sorption-induced matrix swelling that influences permeability. The internal swelling ratio is defined as the ratio of the internal swelling to the gas sorption-induced swelling of an unconfined coal matrix, an unconfined coal block or a confined coal block. That work indicates that the internal swelling ratio may be a constant under constant confining stress conditions. Under varying confining stress conditions, on the other hand, the internal swelling ratio is a variant. These results are preliminary and incomplete as some important issues are not covered. These issues include how confining stress affects the internal swelling, what the relationship between the internal swelling and pore pressure is under different confined boundary conditions, whether the internal swelling is sorbate-dependent, etc. In order to answer these questions, this paper will calculate the internal swelling by using published permeability data obtained under different confined boundary conditions. Combining with literature and the results obtained in this work, the correlations between the internal swelling and its influencing factors will be discussed. The implications of the internal swelling ratio for permeability evolution under *in situ* conditions are also interpreted.

## 2. Methods

On a microscopic scale, coal is heterogeneous, so is the internal swelling [34]. On the macroscopic scale, the internal swelling may have a statistical average value but this value is hardly measured directly. This section thus will present a method for calculating the internal swelling by using a proposed permeability model.

The anisotropic coal permeability variation due to effective stress change and gas sorption can be calculate by [33]

$$k_i = k_{i0}\left\{1+\frac{1}{\phi_{i0}}\left[\begin{array}{l}\frac{\Delta\sigma_{ej}-v^b_{jk}\Delta\sigma_{ek}-v^b_{ij}\Delta\sigma_{ei}}{E^b_j}-\frac{\Delta\sigma_{ej}-v^m_{jk}\Delta\sigma_{ek}-v^m_{ij}\Delta\sigma_{ei}}{E^m_j}\\ +\frac{\Delta\sigma_{ek}-v^b_{ki}\Delta\sigma_{ei}-v^b_{jk}\Delta\sigma_{ej}}{E^b_k}-\frac{\Delta\sigma_{ek}-v^m_{ki}\Delta\sigma_{ei}-v^m_{jk}\Delta\sigma_{ej}}{E^m_k}\\ -\varepsilon_{Lj}\left(\frac{F_{Ij}p}{p_{Lj}+p}-\frac{F_{Ij0}p_0}{p_{Lj}+p_0}\right)-\varepsilon_{Lk}\left(\frac{F_{Ik}p}{p_{Lk}+p}-\frac{F_{Ik0}p_0}{p_{Lk}+p_0}\right)\end{array}\right]\right\}^3 \quad (i\neq j\neq k) \tag{1}$$

where $i$, $j$ and $k$ represent direction $x$, $y$ or $z$ and are mutually orthogonal. $k_i$ denotes the directional permeability in $i$ direction and $k_{i0}$ is its corresponding initial value. $\Delta\sigma_{ej}$ denotes the increment of directional effective stress in $j$ direction. $E^b_j$ denotes Young's modulus of coal block in $j$ direction and $E^m_j$ is that of coal matrix. $v^b_{jk}$ represents Poisson's ratio of coal block between $j$ and $k$ directions and $v^m_{jk}$ is that of coal matrix. $\varepsilon_{Lj}$ denotes linear Langmuir strain constant in $j$ direction, and $p_{Lj}$ represents Langmuir pressure constant in $j$ direction. $F_{Ij}$ denotes the directional internal swelling ratio in $j$ direction and $F_{Ij0}$ is its corresponding initial value. $p$ denotes pore pressure and $p_0$ is its corresponding initial value. $\phi_{i0}$ represents the areal porosity of cleat in $i$ direction and its physical meaning is explained in detail in [33].

Eq. (1) is independent of any boundary conditions and can be expanded according to specific boundary conditions [33]. Assuming that the coal matrix behaves as an elastic material and is rigid compared with coal block, $E^m_i \gg E^b_i$, Eq. (1) regresses to

$$k_i = k_{i0}\left\{1+\frac{1}{\phi_{i0}}\left[\begin{array}{c}\frac{\Delta\sigma_{ej}-v^b_{jk}\Delta\sigma_{ek}-v^b_{ij}\Delta\sigma_{ei}}{E^b_j}+\frac{\Delta\sigma_{ek}-v^b_{ki}\Delta\sigma_{ei}-v^b_{jk}\Delta\sigma_{ej}}{E^b_k}\\ -\varepsilon_{Lj}\left(\frac{F_{Ij}p}{p_{Lj}+p}-\frac{F_{Ij0}p_0}{p_{Lj}+p_0}\right)-\varepsilon_{Lk}\left(\frac{F_{Ik}p}{p_{Lk}+p}-\frac{F_{Ik0}p_0}{p_{Lk}+p_0}\right)\end{array}\right]\right\}^3 \quad (i\neq j\neq k) \tag{2}$$

With isotropic assumption Eq. (2) can be rewritten as

$$\begin{aligned} k &= k_0\left\{1+\frac{3}{2\phi_0}\left[\frac{2(\Delta\sigma_e - v^b\Delta\sigma_e - v^b\Delta\sigma_e)}{E^b} - 2\varepsilon_L\left(\frac{F_I p}{p_L+p}-\frac{F_{I0}p_0}{p_L+p_0}\right)\right]\right\}^3 \\ &= k_0\left[1+\frac{1}{\phi_0}\left(\frac{\Delta\sigma_e}{K}-\Delta\varepsilon_{sI}\right)\right]^3 \end{aligned} \tag{3}$$

where $\phi_0$ denotes the volumetric porosity of cleat and is 1.5 times of $\phi_{i0}$. $K = E^b/3(1-2v^b)$ denotes the bulk modulus of coal block. $\Delta\varepsilon_{sI} = \varepsilon_{sI} - \varepsilon_{sI0} = F_I\varepsilon_s - F_{I0}\varepsilon_{s0} = 3[F_I\varepsilon_L p/(p_L+p) - F_{I0}\varepsilon_L p_0/(p_L+p_0)]$