Journal of Petroleum Science and Engineering 208 (2022) 109378

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

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

Long-term effect of desorption-induced matrix shrinkage on the evolution of coal permeability during coalbed methane production

Mingyao Wei [a,b], Chun Liu [a,*], Yingke Liu [c,**], Jishan Liu [d], Derek Elsworth [e], Osvaldo A.F. A. Tivane [c], Chao Li [b]

[a] National and Local Joint Engineering Laboratory of Internet Application Technology on Mine, IoT Perception Mine Research Center, China University of Mining and Technology, Xuzhou, Jiangsu, 221116, China
[b] State Key Laboratory of Coal and CBM Co-Mining, Jincheng, Shanxi, 048012, China
[c] Faculty of Safety Engineering, China University of Mining and Technology, Xuzhou, Jiangsu, 221116, China
[d] School of Engineering, The University of Western Australia, 35 Stirling Highway, Perth, WA, 6009, Australia
[e] Department of Energy and Mineral Engineering, G3 Center and Energy Institute, The Pennsylvania State University, University Park, PA16802, USA

ARTICLE INFO

Keywords:
Adsorption swelling
Coal permeability
Long-term effect
CBM production
Two-phase flow

ABSTRACT

In a coal reservoir, matrix shrinkage caused by gas desorption is regarded as a significant factor that can influence natural fracture permeability. It is considered to be a constant and lasting effect throughout coalbed methane (CBM) production based on previous investigations. However, experimental measurements of long-term permeability change have demonstrated that adsorption-induced strain has a time-dependent effect on permeability evolution. This study presents long-term investigations on permeability evolution of coal reservoir during CBM production. A fully coupled two-phase flow model for gas-water is specially proposed. Furthermore, the independent impacts of the matrix swelling during gas adsorption are characterized by a strain-rate-based permeability model. The competing effect between pressure depletion and desorption shrinkage on the permeability change is evaluated during the process of long-term production. The calculations of the proposed model are respectively consistent with experimental and field data and the findings show that matrix shrinkage is the most important factor in permeability evolution towards the wellbore. The effect of matrix shrinkage on permeability enhancement is significant in the primary stage and vanishes with uniform depressurization in the matrix. As a result, matrix shrinkage dominates permeability first, followed by effective stress. A sensitivity analysis of mechanical properties and flow properties on permeability evolution was performed and has demonstrated that the larger the matrix shrinkage-induced strain is, the higher the permeability enhancement is, which can be also enhanced with greater initial permeability and a lower diffusion coefficient of the matrix and the impact of the negative strain induced by decreasing pore pressure is solely related to the bulk modulus. The range of permeability variation is narrowed when porosity is high, which implies that the influence of matrix shrinkage and effective stress on permeability is suppressed. This research will advance the understanding of the permeability change during long-term CBM production.

1. Introduction

Coalbed methane is an essential unconventional natural gas with major deposits across the globe. It is a significant resource globally, especially for China, Canada, Australia and India with an increasing energy demand. However, coalbed methane production is difficult to predict due to the complex geological conditions. The production performance of coalbed methane reserves cannot be projected using conventional analytical and numerical techniques. This is due to the complicated interaction of single-phase gas diffusion through the micropore (matrix) system and two-phase gas and water flow through the macropore (fracture) system, which is connected through the desorption process (Thakur et al., 2014).

The production of gas from CBM reservoirs is a typical multiphysics process that involves coupling of fluid flow and solid deformation during the gas desorption process. The gas-water flow behavior in coal deposit

* Corresponding author. China University of Mining & Technology, Xuzhou, 221000, China.
** Corresponding author.
E-mail address: lccumt@163.com (C. Liu).

https://doi.org/10.1016/j.petrol.2021.109378
Received 1 February 2021; Received in revised form 2 July 2021; Accepted 13 August 2021
Available online 14 August 2021
0920-4105/

is regulated by several characteristics and processes. However, the permeability is a crucial characteristic for the production of gas, in another word the geomechanical reaction of the coal and neighbouring geology is linked to the change in permeability generated by the adsorption-induced swelling strain associated with gas production or increased gas content (Connell and Detournay, 2009). The coal reservoir is affected by effective stress simultaneous changes, coal matrix swelling/shrinkage, and pore pressure in the fracture throughout the coalbed methane process. The permeability in coal may be exponentially higher to the respect to influence of the coupling effect. The number of permeability models has been expanded to take into consideration the dominant factors in the last few decades (Somerton et al., 1975; Schwerer et al., 1984; Seidle et al., 1992; Palmer, 2009; Gilman and Beckie, 2000; Bertrand et al., 2017, 2019; Liu et al., 2021). These models have comprehensively described the change of coal permeability related to combined influence of coal matrix shrinkage and effective stress. Because the fracture aperture is sensitive to confining pressure, coal permeability has an excellent relationship to effective stress (Seidle et al., 1992; Pan and Connel, 2012). Some novel approaches have been adopted to built permeability model, such as fractal dimension, nuclear magnetic resonance (NMR) and geomechanical parameters (Golsanami et al., 2020; Zhang et al., 2018; Liu et al., 2020; Wang et al., 2021b). Adorption-induced swelling also has a significant impact on the change of permeability (Espinoza, 2014). It has been observed that permeability increases by over two orders of magnitude due to the opposing effects of desorption-induced shrinkage and fracture opening (Palmer and Mansoori, 1998; Scott et al., 2012).

Adsorption-induced swelling has recently been studied with a more precise approach. Based on the change theory in adsorption surface-energy induced, Liu and Harpalani (2013) proposed a new theoretical model illustrating the volumetric changes in the matrix. For more complicated conditions, the adsorption-induced swelling effect on permeability is widely measured experimentally. Among them, Chen et al. (2011) conducted a series of experiments to determine the effect of adsorption strain on the change in permeability for adsorbing gas flows. Hol and Spiers (2012) measured the volumetric response of adsorption-induced swelling and elastic compression components independently. Previous research confirmed that coal swelling deformation was a heterogeneous process that was dependent on the distribution of coal voids such as fractures. When the coal matrix inflated during CO2 adsorption, the cracks were crushed. (Zhou et al., 2020).

The shrinkage strain as a result of gas adsorption within coal has been found to be responsible for the permeability increase during gas pressure depletion (Harpalani and Mitra, 2010). Various models have been developed to illustrate the permeability of coal. Wei and Zhang (2010) have elaborated a geomechanical and fully coupled fluid-flow model to describe the effective stress and micro-pore swelling/shrinkage coupling influence. In the model, the fluid flow process is simulated with a triple porosity/dual. With a combined fluid flow, geomechanics, and gas adsorption/desorption model, the coupling effects of effective stress and matrix swelling/shrinkage approach are simulated. Yet, Qu et al. (2014) expanded the notion of matrix swelling alternation from local to global swelling subject to complex circumstances where numerous processes including heat transfer, transportation of gas and deformation of coal, that are taken into account. While, Chen et al. (2015) reviewed the controlling mechanisms of permeability evolution of coal deposits, by taking into consideration the effective stress, gas slippage and coal matrix shrinkage in three mathematical permeability change models. Wang et al. (2021a) developed an experimental approach to separating the adsorption-induced swelling strain of coal matrices and hydrostatic compression.

It has been observed that the coal matrix swelling caused by adsorption leads to both internal fracture compression and bulk swelling (Karacan, 2003; Pone et al., 2009). Because the coal bridge connects the coal matrix, the total coal matrix swelling induced by adsorption can be divided into two distinct parts, one regulates swelling and the other part plays a role in the coal block swelling (Liu and Rutqvist, 2010; Zang et al., 2015). Liu et al. (2011.) firstly defined this part of strain as "internal swelling strain" that causes the interactions between matrix swelling and fracture deformation. It is commonly assumed that the strain contributed to permeability variation is proportional to the overall adsorption-induced strain of the matrix (Zang et al., 2015). In all previous models, it is deduced a constant strain splitting factor to define the ratio of the matrix adsorption strain affecting the facture permeability (Jiang et al., 2020; Qu et al., 2014; Chen et al., 2011; Wang et al., 2014; Liu et al., 2017b; Li et al., 2020). However, Shi et al. (2020) directly measured the evolution of strain of a prismatic coal core throughout gas injection. It confirms that the deformations of the coal core is nonuniform in space-time during the non-equilibrium condition. Wei et al. (2019) conducted a long-term test to measure the influence of adsorption strain on the permeability. Experimental results suggest that the adsorption strain has a strong effect on the permeability change at first, then this impact vanishes with the swelling of whole coal bulk. In order to evaluate the ratio of strain acting on fractures, Jiang et al. (2020) proposed the notion of differential swelling index (DSI) outlining the relation within coal bulk fracture and matrix strain induced by adsorption at the equilibrium state. It is found that DSI changes as a equilibrium pressure function. Previous studies have suggested a model based on the strain gradient to characterize non-uniform deformation induced by gas adsorption. All these studies focus on laboratory tests and modeling.

During the primary production of coalbed methane, *in-situ* coal permeability can change significantly as a result to decrease in gas pressure and matrix shrinkage-induced by desorption (Gray, 1987). These effects have a significant effect on gas and water production. Many researchers have analyzed the geo-mechanical impact on two-phase flow during coalbed methane (CBM) production (Zhao et al., 2014; Ma et al., 2017). Through changes in cracks produced by effective stress fluctuations and desorption-driven shrinkage, the model analyzes changes in two-phase fluid flow characteristics, such as coal porosity, permeability, water retention, and relative permeability curves. However, it is commonly supposed that the gas desorption-induced shrinkage leads to permeability increasing continuously. It could result in an overestimation of the gas production rate without considering mechanical compression. This paper presents a simulation study to investigate the change of gas permeability for the each period of CBM production. The strain-gradient-based model is incorporated into the mass balance equation for two-phase flow. The influence of matrix shrinkage on permeability is evaluated in the whole process of gas production. The competing effect between mechanical compression and desorption shrinkage on the permeability change is evaluated. It can give new insights into the long-term evolution of permeability of the *in-situ* coal seam during CBM production.

2. Theoretical model of gas and water flow in coal reservoirs

CBM production from coal seam deposits is characterized by the complexity of interactions between gas flow and solid deformation. The schematics of diffusion of the desorbed gas within the matrix and gas-water flow along the fracture are shown in Fig. 1 (Aminian and Ameri, 2009; Pan and Connell, 2012). The single-phase gas is mainly accumulated within the matrix system as an adsorbed phase. The primary gas production involves a reservoir pressure drop resulting in the desorption of gas. The free gas migrates from the matrix to the fracture afterwards. Fractures can provide seepage pathways for desorbed gas and water.

CBM migration characteristics are sensitive to change of both pore pressure and adsorption strain. According to the assumptions of multilayer moisture adsorption, only the first layer of adsorbed particles was able to modify the surface energy, as Pan and Connell (2012) developed a model to explain the coal swelling strain based on the loss of moisture content. Gas production causes pore pressure depletion in fractures at

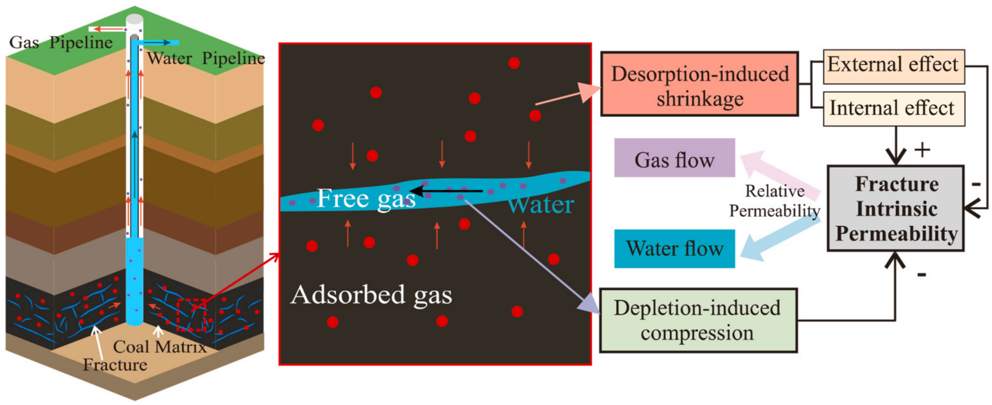


Fig. 1. Illustration of a coupled two-phase flow during CBM production.

first. It results in a reduction of fracture aperture due to the effective stress increase. Thus, the permeability of coal is initially reduced with the decrease in pore pressure. Simultaneously, reservoir depletion causes the desorption of gas and coal matrix shrinkage. Based on previous studies, desorption-induced shrinkage strain can be divided into two parts (Liu et al., 2011). One part of internal shrinkage strain leads to the increase of fracture space and permeability. Coal permeability is expected to decrease gradually when the entire coal bulk starts to shrink. The external effect and internal effect have the opposite affecting on fracture permeability. The gas desorption-induced coal shrinkage is both gas-pressure- and time-dependent. It means that these two controlling factors change with the spreading of pore pressure. The opposing effects of effective stress and coal matrix shrinkage during gas production demonstrate that variation in coal reservoir permeability is non-monotonic.

2.1. Water-phase flow model

The mass balance equation is the fundamental equation for the description of the movement of fluids. It simply states that total mass in any system is always conserved. For liquid water that migrates through the coal fracture, the mass balance equation can be written as (Ma et al., 2017):

$$\varphi\frac{\partial S_w}{\partial t}+\nabla\cdot\left[-\frac{k_{int}k_{r,w}}{\mu_w}\nabla(p_w)\right]=Q \tag{1}$$

where φ is the total porosity, S_w is the effective water saturation; t is time; k_{int} is the intrinsic permeability; and $k_{r,w}$ is the relative permeability of water. Here van Genuchten retention model is used to determine the hydraulic properties; μ_w is fluid's dynamic viscosity; p_w is water pressure; and Q is the flow source or sink.

2.2. Gas-phase flow model

The free gas is presumed to flow within the fracture, and the adsorbed gas is stored within the matrix (Wu et al., 2010). For the free gas in coal fractures, the total mass flow equation is:

$$\varphi\frac{\partial(1-S_w)}{\partial t}+\nabla\cdot\left[-\frac{k_{int}k_{r,g}}{\mu_g}\nabla(p_g)\right]=-Q_d \tag{2}$$

where $k_{r,g}$ is the relative gas permeability; $\mu_g$is the dynamic viscosity of gas; p_g is the pressure of gas within the fractures; and Q_d is the source from desorbed gas.

The Langmuir adsorption theory is used to calculate the amount of adsorbed gas in coal matrix. Theoretically, it is applicable to systems where adsorbed molecules form no more than a monolayer on the surface, each site for adsorption is equivalent in terms of adsorption energy and there are no interactions between adjacent adsorbed molecules. If the gas flow is a slow process, its flow rate can be calculated by a diffusion law. Advection is neglected because of the extremely low permeability of the ultratight matrix (Liu and Emami-Meybodi, 2021). The total mass flux is conceived as the sum of free phase diffusive and sorbed phase diffusive flux (Aljaberi et al., 2021). And the diffusion supplies methane to the fracture system (Wang et al., 2012). The gas mass balance equation in the matrix can be defined as:

$$\frac{\partial}{\partial t}\left((1-\varphi)\rho_s\rho_{\text{ka}}\frac{L_a p_m}{p_m+L_b}\right)+\left(-D_{\text{m}}\frac{M}{RT}\nabla p_m\right)=Q_d \tag{3}$$

where ρ_s is the density of coal; ρ_{ka} is the density of gas at atmospheric pressure; L_a represents the Langmuir volume constant; L_b represents the Langmuir pressure; D_m is the diffusion coefficient; and p_m is the pressure of gas in the matrix. The contribution of diffusive flux is domain in the total flux at low pressure (Aljaberi et al., 2021). The total diffusive flux is a direct function of total porosity. The contribution of adsorped phas diffusive flux is high when total porosity is low (Liu and Emami-Meybodi, 2021). The adsorbed gas flow from the matrix to fractures can be considered as one form of diffusion of gas along the nanopores between two systems (Pan and Connell, 2015):

$$Q_d=aD_m(\rho_f-\rho_m) \tag{4}$$

where a is a shape factor, ρ_m is the density of gas in the matrix, and ρ_f is the density of gas in the fracture.

2.3. Geo-mechanical model

During the process of CBM production, the decline of reservoir pressure leads to a continuous interaction between interstitial fluid flow and fracture deformation. The inertial force is neglected for a pseudo-static deformation process (Wang et al., 2012). It is generally supposed that the fracture deformation is a response to the change of effective stress, confining stress and desorption shrinkage. Coal seam is treated as a linear elastic, continuous, homogeneous and isotropic porous media. The deformation of coal seam and natural gas flow process within both cleats and coal matrix are all pseudo-static. The constitutive equations and equilibrium equation combination can yield the Navier-type equation for the isotropic, homogeneous, and elastic medium based on the effective stress concept (Wu et al., 2010) and which can be written as:

$$\mathrm{G}u_{\mathrm{i,kk}}+\frac{\mathrm{G}}{1-2\mathrm{v}}u_{\mathrm{k,ik}}-\delta p_{\mathrm{m,i}}-\beta p_{\mathrm{g,i}}-K\varepsilon_L\frac{L_b}{(p_m+L_b)^2}p_{m,\mathrm{i}}+f_{\mathrm{i}}=0 \tag{5}$$

where u_i is the displacement component in the i-direction; G is the shear modulus; ν is the Possion's ratio; δ and β are the Biot coefficients; K is the bulk modulus; ε_L is a constant defining the volumetric strain at infinite pore pressure; and f_i is the component of body force in the *i*-direction.

2.4. A strain-rate-based permeability model

Previous studies on permeability have either been short-term studies or have not covered enough impact factors. This paper adopts a strain-gradient-based model considering the complex influence of desorption-induced shrinkage on long-term permeability evolution instead of understanding the long-term development of coal permeability under the influence of various processes caused by gas adsorption and which is critical for CO_2 sequestration efficiency (Wei, 2019b). The pore pressure gradient in the coal matrix changes with time from initial equilibrium state to final equilibrium state during gas production. The non-uniform strain gradient results in that local shrinking widens the fracture aperture. This impact on fracture permeability vanishes once the coal matrix swelling achieves uniformity. The time-dependent model is written as (Wei, 2019b):

$$\frac{k_{int}}{k_0} = \left(1 + \frac{\alpha}{\varphi}\left(\Delta\left(\varepsilon_f + \gamma\frac{\partial}{\partial t}\left(-\frac{\Delta p_m}{K_m} + \Delta\varepsilon_s\right)\right) - \frac{p_g}{K_s}\right)\right)^3 \quad (6)$$

where k_0 is the initial permeability; α is the Biot coefficient; ε_f is the strain component of the fracture induced by the confining stress; γ is a characteristic time factor; K_m is the matrix bulk modulus; $\Delta\varepsilon_s$ is the gas adsorption-induced volumetrical matrix strain increment and K_s is the fracture bulk modulus.

The new model can incorporate the variational effect of adsorption strain on permeability. The changes in strain associated with adsorption happen continually over time. It has the maximum impact on permeability when the matrix deformation is non-uniform. It vanishes at the pressure equilibrium state. In order to validate the permeability model, the experimental data is compared to the model prediction, as shown in Fig. 2. The experimental data are from a long-term coal permeability measurement throughout gas injection (Wei et al., 2019). Both injection pressure and confining stress are kept constant for nearly 90 days. The permeability is measured based on the pulse decay technique periodically. It is clear that calculation of the strain-gradient-based permeability model is consistent with experimental data, which ensures the viability of the new proposed model. The permeability increases rapidly in response to the gas injection at first. This shows that effective stress within the fracture is a critical element in limiting permeability at the start. Then permeability decreases slowly as a result of the matrix nonuniform deformation. It could be explained by the strain gradient near the fracture wall induced by adsorption swelling, which narrows the fracture space at this stage. The matrix swelling strain becomes homogeneous as the gas spreads over the area. The internal permeability effect fades with time. Finally, because to the coal bulk swelling, the permeability improves. At this point, the external influence increases permeability. It is evident the adsorption strain has opposite effects on permeability at different stages. The comparison confirms that the new model can characterize the long-term effect of adsorption strain on permeability evolution precisely.

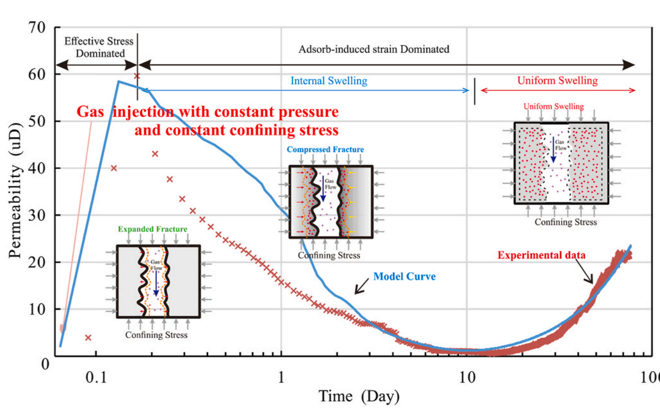


Fig. 2. Comparison between experimental data and model prediction (Wei, 2019a; Wei, 2019b).

The gas was injected into coal sample in Fig. 3 that is an opposite process of gas production. However, the influence mechanism of fracture deformation on permeability is same. The strain-rate-based permeability model can capture the effect of adsorption strain on permeability. Therefore, this model can used to explain the permeability evolution in process of gas production.

3. Model verification versus field data

In this section, field data in region PZ and region SZ are used for historical matching. CBM production data, including the gas and water production ratio, are collected from two vertical wells. These two regions are in the south of Shanxi Province, and this is a vital area for CBM exploitation and development in China. The basin contains approximately 15 % of China's entire CBM reservoirs. Region PZ and SZ are situated in the south of Qinshui Basin, which strikes NNE-SSW and is characterized as a complex syncline basin. The bearing stratum in the area include Permian Taiyuan and Shanxi Formations in the lower Pennsylvanian. It is composed of coal, shale, fine-grained sandstone, and several carbonates with approximately 150m of thickness. The form of coal is anthracite, which is described as is hard and brittle with high fixed-carbon content.

3.1. Historical matching with field data in region PZ

Considering geometry symmetry, a quarter of the reservoir is chosen for analysis. The 2D plain reservoir geometry model has dimensions of 1000 m × 1000 m. The production wellbore is on the lower left corner. The pressure in wellbore is set as the actual value of bottomhole pressure. The constant confining stress condition is applied to the boundaries for simulating the CBM reservoir condition. The no-flow assumption is also used at the boundaries. The isotropic initial stress and initial pore pressure of the reservoir are set according to the actual values of the reservoir, respectively. The flow and mechanics parameters adopted for the simulation are shown in Table 1.

The mass balance equation (Eqs. (1)–(3)) and constitutive equation (Eq. (5)) are combined in the solution procedure to couple the gas flow and coal deformation in the model. The values of permeability vary with pressure depletion according to the model (Eq. (6)) used in the calculation. The variation of permeability is affected by both effective stress and matrix shrinkage strain. For the conventional models, fully-coupled relation is not considered. One typical permeability model is pore-pressure-based. The increase in effective stress decreases the pore pressure, therefore decreasing the fracture permeability. Under this circumstance, Eq. (6) can be expressed as:

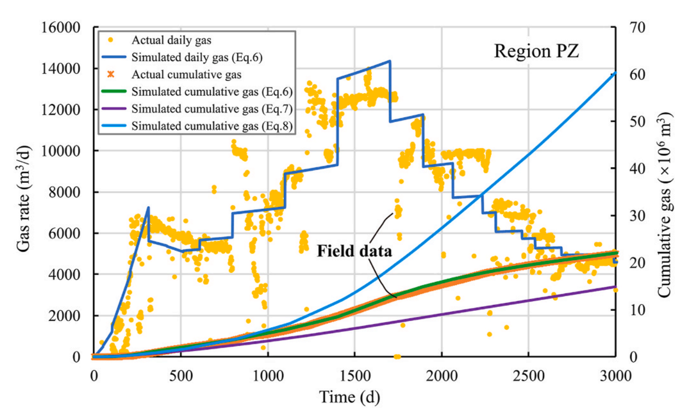


Fig. 3. Historical matching for region PZ.

Table 1
Parameters used in the model for two cases.

Parameters	Value (Region PZ)	Value (Region SZ)	Notes
Bulk modulus, K	15 GPa	12 GPa	Measured
Bulk modulus of matrix, K_m	20 GPa	17 GPa	Measured
Bulk modulus of fracture, K_s	1 GPa	0.7 GPa	Fitting
Shear modulus, G	4 GPa	3 GPa	Measured
Langmuir volume, L_a	0.0418 m^3/kg	0.0318 m^3/kg	Fitting
Langmuir pressure, L_b	2.48 MPa	3.8 MPa	Fitting
Langmuir volumetric strain, ε_L	0.0218	0.0188	Measured
Porosity of coal bulk, φ	0.04	0.04	Measured
Initial permeability of the fracture, k_0	2×10^{-15} m^2	1.4×10^{-16} m^2	Measured
Diffusion coefficient, D_m	1×10^{-9} m^2/s	1×10^{-9} m^2/s	Measured
Characteristic time factor, γ	1×10^6 s	1×10^6 s	[Wei et al., 2019b]
Coal density, ρ_s	1350 kg/m^3	1350 kg/m^3	Measured
Initial water saturation	0.5	0.8	Fitting
Coal seam thickness	3.4 m	6 m	Reservoir condition
Initial reservoir pressure	4 MPa	3.41 MPa	Reservoir condition
Confining stress	6 MPa	6 MPa	Reservoir condition

$$\frac{k_{int}}{k_0} = \left(1 + \frac{\alpha}{\varphi}\left(\Delta\varepsilon_f - \frac{p_g}{K_s}\right)\right)^3 \tag{7}$$

The matrix adsorption-induced strain impact on permeability is considered in another model. It is assumed that matrix shrinkage strain continuously increases the permeability. The model can be written as:

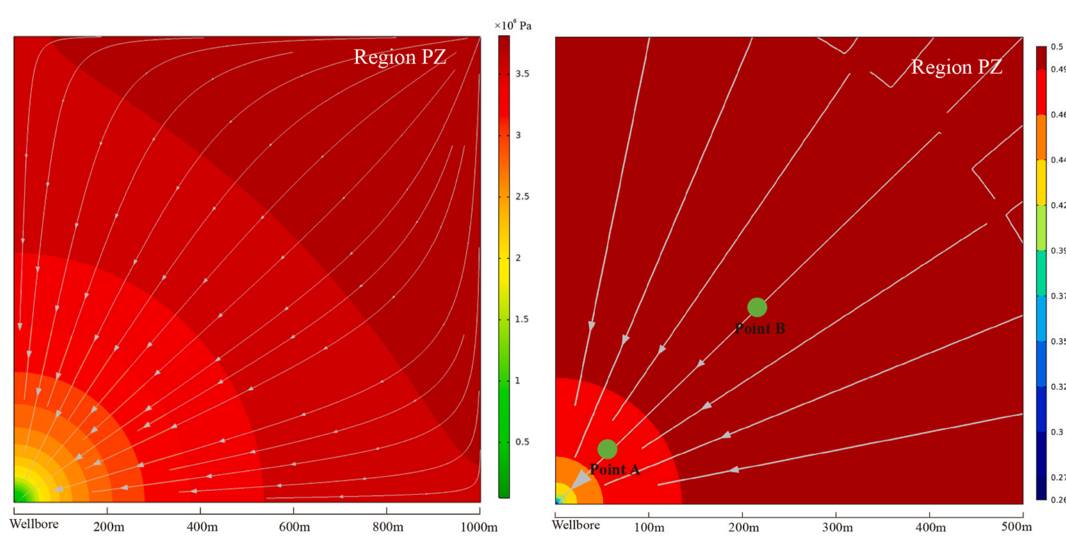
$$\frac{k_{int}}{k_0} = \left(1 + \frac{\alpha}{\varphi}\left(\Delta\left(\varepsilon_f + \left(-\frac{\Delta p_m}{K_m} + \Delta\varepsilon_s\right)\right) - \frac{p_g}{K_s}\right)\right)^3 \tag{8}$$

Fig. 3 shows the historical matching using each of the conventional models (Eqs. (6)–(8)). The gas rate and cumulative gas obtained by Eq. (6) are consistent of field data. Daily gas production increases for the first four years, and then it continuously drops. The average gas rate is at a very high level of 7000 m^3/d. It indicates that this block is significant with high gas content and a beneficial development condition for achieving high production. Comparing with predicted cumulative gas from conventional models, there is a large deviation from actual data. For the pore pressure-based model, the prediction value is lower. It could be due to the neglect of the effect of matrix shrinkage. The predicted cumulative gas with Eq. (8) shows a trend of linear growth. At last, the model result is three times higher than the actual value. This high-production can attribute to the high permeability induced by matrix shrinkage.

The pore pressure spatial distributions and saturation of water are plotted in Fig. 4. It can be observed that the gas production results in the largest decrease of pore pressure closed to the wellbore. It also leads to a decrease in water saturation during water production. For region PZ, the initial water saturation of the coal reservoir is low. Therefore, the descending zone of water saturation is relatively small.

Reservoir pressure generally decreases with gas and water production. It increases the effective stress and causes coal matrix shrinkage. To investigate the effective stress and matrix shrinkage-induced strain impact on the change of coal permeability, three tests were carried out as displayed in Fig. 10. The solid lines represent the combined effective stress and coal matrix shrinkage influences on coal permeability as defined in Eq. (6). The dashed lines present the variation of the pore pressure-induced permeability change as defined in Eq. (7). It shows that the changes of effective stress caused by pore pressure result in the decrease of permeability near-wellbore area. However, the initial permeability is lower than that of the permeability incorporated with the matrix shrinkage influence. It indicates that matrix shrinkage-induced strain has an opposite consequence for the permeability change. It also confirms that the matrix shrinkage have an effect in the permeability evolution near the wellbore.

It shows the permeability ratio generally tends to rise in the first 2000 days in Fig. 4. Then it falls slightly for the last 1000 days. The variation of permeability is shown in Fig. 6 for two monitor points. Point A and point B are respectively located 70.7 m and 282.8 m diagonal distance away from the wellbore as shown in Fig. 4(b). It is shown that the permeability changes with time. The matrix shrinkage-induced permeability change is presented in brown and yellow lines. It can also be expressed by Eq. (6) with constant pore pressure. It is simplified into a permeability model ignoring the deformation due to the change of pore pressure. At first, the matrix shrinkage occurs at the internal fracture walls of the coal. The fracture volume rises inducing the enhancement of permeability. When the permeability reaches a turning point, it drops for the following days. It is because the fracture is compressed by external confining stress when matrix shrinkage is uniform. It indicates that compaction between coal matrixs become the dominant factor in reducing coal permeability. At last, it returns to the initial value, which



(a) Pore pressure (b) Water saturation

Fig. 4. Spatial distributions of the pore pressure and water saturation after 3000 days of production.

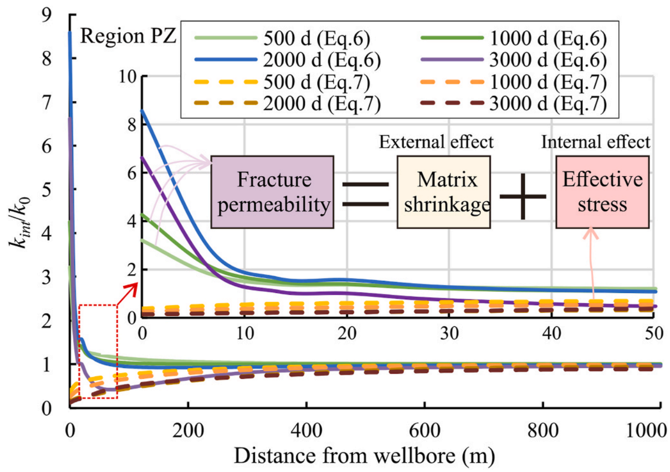


Fig. 5. Permeability evolution during gas production for two permeability models.

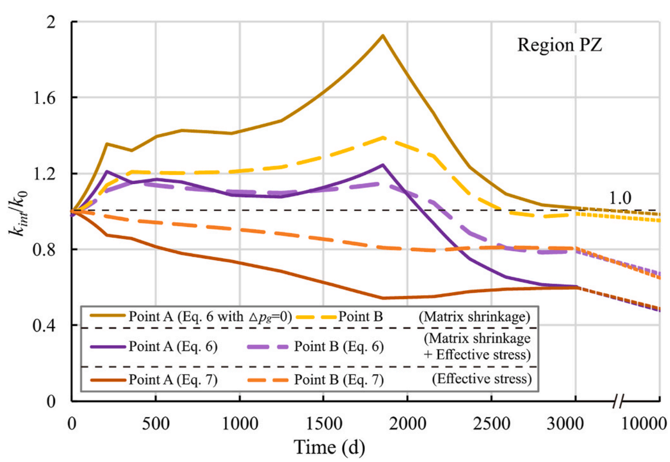


Fig. 6. Impacts of matrix shrinkage and effective stress on permeability evolution for region PZ.

implies the disappearance of the matrix strain-gradient. The changes in permeability caused by pore pressure variation are presented in scarlet and red lines for the two points, respectively. On the contrary, permeability drops proportionally with the pore pressure drawndown. The purple lines represent the combined effective stress and coal matrix shrinkage influences. It is observed the permeability maintains above the baseline for a long term after a fast rise at first. Then it declines and moves close to the scarlet and red lines. For the last 7000 days, the permeability is nearly unchanged. It exhibits two stages where the permeability is controlled by the coal matrix shrinkage firstly and effective stress lastly. It is evident that the variation range for point A is wider due to the decline of pore pressure is faster and severer near the wellbore.

3.2. *Historical matching with field data in region SZ*

The production data of region SZ are matched with the proposed model's results as shown in Fig. 7. Simulated curves of cumulative water and gas are in accordance with the *in-situ* data. The pressure of the bottom hole is one of the important factors that control gas production. Reducing the bottom hole pressure can lead to a fast increase in gas production. It should be noted that water production is relatively high. And the cumulative gas is only 1/60 of region PZ. The coal reservoir is rich in water, which causes a high water production and an extremely low gas rate.

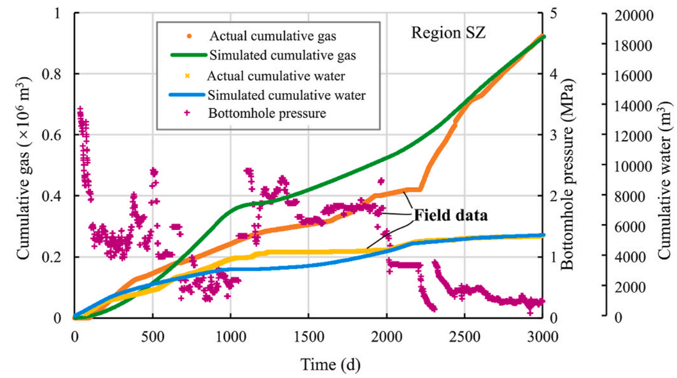


Fig. 7. Historical matching for region SZ.

As noted above, the depletion of pore pressure is low due to low gas production. In this case, it would induce the change of permeability over a long term. Fig. 8 shows the permeability evolution for monitor point A during a long period of gas production. The matrix shrinkage causes a fast increase in permeability for the first 4000 days. Then, it drops slightly for the last 6000 days. However, it is still three times greater than the initial value at last. Hence, the combined effects lead to a higher permeability ratio persistently. It will take an extremely long time to reach the final state. This indicates that both effective stress and coal matrix shrinkage control the variation of permeability throughout the full production cycle of the well for this case.

4. Discussion

Coal is an example of a dual porosity/permeability system, with a porous matrix surrounded by fractures. Because of its critical importance in the effective extraction of coal seam gas, coal permeability has received a great deal of attention. It is generally believed the permeability of coal can be described as a relation of elastic matrix strain, effective stress, and adsorption strain within the fracture system (Liu et al., 2011). The change of effective stress is correlated to the pore pressure variation or external confining pressure. The directional fracture strain induced by effective-stress is governed by the generalized Hooke constitutive model (Wu et al., 2010). For the condition of a constant stress-controlled boundary, the effective stress can be directly obtained according to the Terzaghi's principle. The matrix strain is produced by a pore pressure change in the matrix block. Adorption-induced matrix deformation plays a major role in the whole deformation. The fracture strain induced by coal matrix shrinkage and

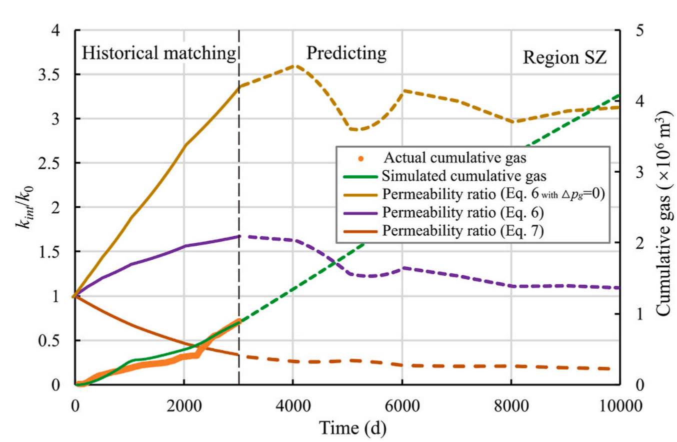


Fig. 8. Impacts of matrix shrinkage and effective stress on permeability evolution for region SZ.

effective stress is plotted in the yellow bar and orange bar, respectively, as shown in Fig. 9. It reveals the fracture strain and permeability ratio variation during the CBM depletion. The decrease of pore pressure induces the negative strain that results in closure of the fracture. Note that the negative value stands for compression strain. On the contrary, matrix shrinkage widens the fracture aperture. Due to the decrease in pore pressure, the positive strain rises firstly, and then drops to zero. It confirms that the coal matrix shrinkage impact on permeability is time-dependent. The variation of matrix shrinkage-induced fracture strain is not included in conventional permeability models. We believe it is the reason for the failure of gas production prediction by previous models.

As discussed above, fracture permeability is under a combined influence, which is controlled by the physical parameters of the proposed model. A sensitivity analysis was performed to study the influence of mechanical properties and flow properties on the evolution of coal permeability. Distinct values of parameters were assigned in the simulation model, respectively. The variation ranges of permeability during the full production process for different cases are shown in Fig. 10. The variation of permeability is displayed by a candlestick chart. It indicates the initial, high, low, and final values of permeability for each case. The dominant factors for the shape of permeability curves are discussed below.

The sensitivity analysis shows that Langmuir volumetric strain is the most influential parameter. The lowest and highest values of permeability are both higher with a larger Langmuir strain constant. The permeability could reach two orders of magnitude greater than the initial value when Langmuir volumetric strain is ten times greater. The entire range of permeability is enhanced by a greater matrix shrinkage strain. The permeability is also enhanced when the initial permeability is greater. In this case, the fast pressure depletion leads to rapid desorption of methane in the matrix. Thus, a substantial desorption strain is caused by the strongest influences of shrinkage on the fracture aperture change, which results in a considerable permeability increase. This section of the matrix strain leads to the change of fracture permeability only before the uniform shrinkage of the matrix block. If gas desorption from the matrix to fractures is faster, the shrinkage occurs in whole the matrix in a short time. It would weaken the matrix shrinkage influence on the enhancement of permeability. Therefore, the bottom of the permeability value is much lower with a higher diffusion coefficient.

The reciprocal bulk modulus can also be called compressibility, which is the capacity of resistance to compression. The bulk modulus of fractures can have a significant impact on fracture strain under external compression. The fracture compressibility reduces as a result of the increase in the modulus. The higher the bulk modulus is, the less the strain of fractures induced by effective stress will be. Thus, the impact of negative strain caused by decreasing pore pressure on permeability is smaller. The fracture permeability is higher with a greater bulk modulus. The effect of porosity on permeability is also evaluated. The

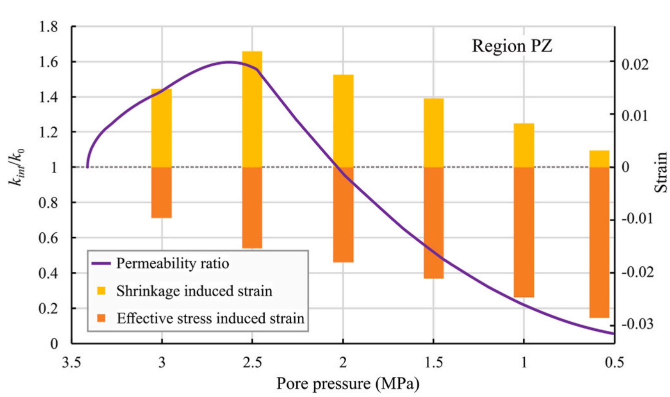


Fig. 9. Change of the fracture strain and permeability ratio with pore pressure.

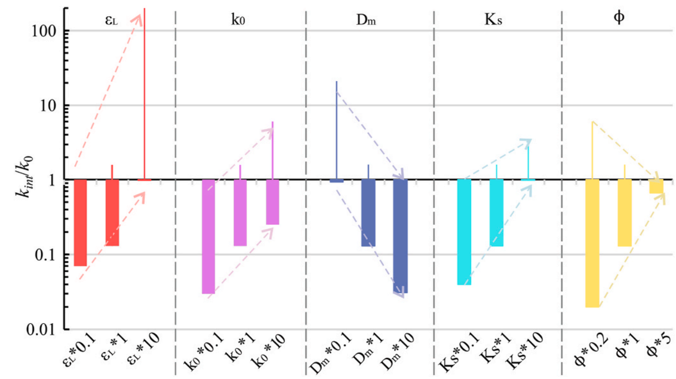


Fig. 10. Effects of reservoir properties on the permeability variation.

porosity can be described as the ratio of the volume of void space to total coal block volume. It is assumed that only connected pores are included in the permeability model. Therefore, fracture volume is closely related to porosity. It can be seen that the range of permeability variation is narrowed when porosity is higher, which implies that both impacts of effective stress and matrix shrinkage are sensitive to porosity. The proportion of external deformation from effective stress and matrix shrinkage in fracture space is comparatively small when the porosity is great. Thus, larger porosity suppresses the impact of effective stress and matrix shrinkage on coal permeability.

5. Conclusions

In this study, a model of fully-coupled two-phase flow is proposed. The influence of coal matrix deformation on fracture permeability is incorporated in a model of strain-rate-based. The effect of the variation of adsorption/desorption-induced matrix swelling/shrinkage on fractures is defined as a time-dependent strain in this model. The model-predicated permeability evolution is consistent with long-term experimental data, which ensures the viability of the new proposed model.

The proposed model is also verified with field data from two CBM exploitation regions. Comparison of conventional permeability models' prediction with real field data illustrates the failure of prediction without considering the effect of matrix shrinkage variation. The competing effect between pressure depletion and desorption shrinkage on the permeability change is evaluated during CBM depletion. The changes in effective stress induced by pore pressure cause a decrease of permeability during CBM depletion. However, the permeability is much higher than the initial permeability if it is incorporated with the effect of matrix shrinkage. The matrix shrinkage influence on coal permeability vanishes when depressurization in the matrix is uniform. It demonstrates that matrix shrinkage contributes to the evolution of permeability near the wellbore. It can also be determined the coal permeability is controlled by matrix shrinkage firstly and effective stress lastly.

A sensitivity analysis of mechanical properties and flow properties on permeability evolution was performed. Among the parameters, the Langmuir volumetric strain constant is the most influential parameter. The entire range of permeability is enhanced by a greater matrix shrinkage-induced strain. The permeability can also be enhanced if the coal has greater initial permeability and lower matrix diffusion coefficient. The higher the bulk modulus, the lesser will be the impact of negative strain induced by pore pressure depletion on permeability. The high bulk modulus increases the matrix shrinkage impact on the permeability. The porosity of coal determines the sensitivity of fracture permeability to the external strain. Thus, the greater porosity could suppress the impact of effective stress and matrix shrinkage on permeability. Overall, this study demonstrates the matrix shrinkage influence on CBM production. This research will advance the understanding of the permeability change during long-term CBM production.

Credit author statement

Mingyao Wei conducted the simulation study and drafted the manuscript. Chun Liu formulation research goals and aims. Yingke Liu helped to analyze the results. Jishan Liu contributed to the conception of the study. Derek Elsworth approved the final version. Osvaldo A. F. A. Tivane polished the manuscript. Chao Li helped revise the manuscript and provided suggestions.

Declaration of competing interest

The authors declare that they have no conflict of interest.

Acknowledgments

This work is a partial result of funding by the China Postdoctoral Science Foundation (2019M661997), National Natural Science Foundation of China (52074283; 51774277), the Fundamental Research Funds for the Central Universities (2017QNB15), the Australian Research Council under Grant (DP200101293), the Science and Technology Major Project of Shanxi Province, China (20201102001) and the Open Fund of State Key Laboratory of Coal and CBM Co-Mining (2018KF09). These sources of support are gratefully acknowledged.

References

Aminian, K., Ameri, S., 2009. Predicting production performance of CBM reservoirs. J. Nat. Gas Sci. Eng. 1 (Issues 1–2), 25–30.

Bertrand, F., Cerfontaine, B., Collin, F., 2017. A fully coupled hydro-mechanical model for the modeling of coalbed methane recovery. J. Nat. Gas Sci. Eng. 46, 307–325.

Bertrand, François, Olivier, Buzzi, Frédéric, Collin, 2019. Cleat-scale modelling of the coal permeability evolution due to sorption-induced strain. Int. J. Coal Geol. 216, 103320.

Chen, Z., Pan, Z., Liu, J., et al., 2011. Effect of the effective stress coefficient and sorption-induced strain on the evolution of coal permeability: experimental observations. International Journal of Greenhouse Gas Control 5 (5), 1284–1293.

Chen, Yaxi, Liu, Dameng, Yao, Yanbin, Cai, Yidong, Chen, Longwei, 2015. Dynamic permeability change during coalbed methane production and its controlling factors. J. Nat. Gas Sci. Eng. 25, 335–346.

Connell, L.D., Detournay, C., 2009. Coupled flow and geomechanical processes during enhanced coal seam methane recovery through CO2 sequestration. Int. J. Coal Geol. 77, 222–233.

Espinoza, D.N., Vandamme, Matthieu, Pereira, Jean-Michel, Dangla, Patrick, Vidal-Gilbert, Sandrine, 2014. Measurement and modeling of adsorptive-poromechanical properties of bituminous coal cores exposed to CO2: adsorption, swelling strains, swelling stresses and impact on fracture permeability. Int. J. Coal Geol. 134 https://doi.org/10.1016/j.coal.2014.09.010.

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

Golsanami, N., Bakhshi, E., Yan, W.C., Dong, H.M., Barzgar, E., Zhang, G.C., Mahbaz, S. B., 2020. Relationships between the geomechanical parameters and Archie's coefficients of fractured carbonate reservoirs: a new insight. Energy Sources, Part A Recovery, Util. Environ. Eff. https://doi.org/10.1080/15567036.2020.1849463.

Gray, I., 1987. Reservoir engineering in coal seams: part 1 -The physical process of gas storage and process of gasstorage and movement in coal seams. Geological So-ciety Special Publication (2), 28–34.

Harpalani, S., Mitra, A., 2010. Impact of CO2 injection on flow behavior of coalbed methane reservoirs. Transport Porous Media 82, 141–156.

Hol, S., Spiers, C.J., 2012. Competition between adsorption-induced swelling and elastic compression of coal at CO2 pressures up to 100 MPa. J. Mech. Phys. Solid. 60 (11), 1862–1882.

Jaber, Aljaberi, Saad, Alafnan, Guenther, Glatz, Sultan Abdullah, S., Clement, Afagwu, 2021. The impact of kerogen tortuosity on shale permeability. SPE J. 26, 765–779.

Jiang, Chuanzhong, Zhao, Zhenfeng, Zhang, Xiwei, Liu, Jishan, Cui, Guanglei, 2020. Controlling effects of differential swelling index on evolution of coal permeability. Journal of Rock Mechanics and Geotechnical Engineering 12 (3), 461–472.

Karacan, C.Ö., 2003. Heterogeneous sorption and swelling in a confined and stressed coal during CO2 injection. Energy Fuels 17 (6), 1595–1608.

Li, Wai, Liu, Jishan, Zeng, Jie, Yee-Kwong, Leong, Derek, Elsworth, Tian, Jianwei, Lin, Li, 2020. A fully coupled multidomain and multiphysics model for evaluation of shale gas extraction. Fuel 278. No.118214.

Liu, Zizhong, Emami-Meybodi, Hamid, 2021. Diffusion-based modeling of gas transport in organic-rich ultratight reservoirs. SPE J. 26, 857–882.

Liu, S., Harpalani, S., 2013. A new theoretical approach to model sorption-induced coal shrinkage or swelling. AAPG Bull. 97 (7), 1033–1049.

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

Liu, J., Wang, J., Chen, Z., Wang, S., Elsworth, D., Jiang, Y., 2011. Impact of transition from local swelling to macro swelling on the evolution of coal permeability. Int. J. Coal Geol. 88 (1), 31–40.

Liu, T., Lin, B., Yang, W., 2017. Impact of matrix-fracture interactions on coal permeability:model development and analysis. Fuel 207, 522–532.

Liu, G.N., Yu, B.M., Gao, F., Ye, D.Y., Yue, F.T., 2020. Analysis of permeability evolution characteristics based on dual fractal coupling model for coal seam. Fractals 28, 2050133.

Liu, Ang, Liu, Shimin, Liu, Peng, Satya, Harpalani, 2021. The role of sorption-induced coal matrix shrinkage on permeability and stress evolutions under replicated *in situ* condition for CBM reservoirs. Fuel 294, 120530.

Ma, Tianran, Jonny, Rutqvist, Oldenburg Curtis, M., Liu, Weiqun, Chen, Junguo, 2017. Fully coupled two-phase flow and poromechanics modeling of coalbed methane recovery: impact of geomechanics on production rate. J. Nat. Gas Sci. Eng. 45, 474–486.

Palmer, I., 2009. Permeability changes in coal: analytical modeling. Int. J. Coal Geol. 77, 119–126.

Palmer, I., Mansoori, J., 1998. How permeability depends on stress and pore pressure in coalbeds: a new model. Evaluation 539–544.

Pan, Z., Connell, L.D., 2012. Modelling permeability for coal reservoirs: a review of analytical models and testing data. Int. J. Coal Geol. 92 (1), 1–44.

Pan, Zhejun, Connell, Luke, 2015. Reservoir simulation of free and adsorbed gas production from shale. J. Nat. Gas Sci. Eng. 22, 359–370.

Pone, J.D.N., Hile, M., Halleck, P.M., Mathews, J.P., 2009. Three-dimensional carbon dioxide induced strain distribution within a confined bituminous coal. Int. J. Coal Geol. 77 (1e2), 103e8.

Qu, H., Liu, J., Pan, Z., et al., 2014. Impact of matrix swelling area propagation on the evolution of coal permeability under coupled multiple processes. J. Nat. Gas Sci. Eng. 18, 451–466.

Schwerer, F., Pavone, A., et al., 1984. Effect of pressure-dependent permeability on welltest analyses and long-term production of methane from coal seams. In: SPE Unconventional Gas Recovery Symposium. Society of Petroleum Engineers.

Scott, M., Mazumder, S., Jiang, J., 2012. Permeability increase in Bowen Basin coal as a result of matrix shrinkage during primary depletion. SPE International SPE 158152.

Seidle, J., Jeansonne, M., Erickson, D., et al., 1992. Application of matchstick geometry to stress dependent permeability in coals. In: SPE Rocky Mountain Regional Meeting. Society of Petroleum Engineers.

Shi, R., Liu, J., Wang, X., et al., 2020. Experimental observations of heterogeneous strains inside a dual porosity sample under the influence of gas-sorption: a case study of fractured coal. Int. J. Coal Geol. 223, 103450.

Somerton, W.H., Soylemezoglu, I., Dudley, R., 1975. Effect of stress on permeability of coal. Int. J. Rock Mech. Min. Sci. Geomech. Abstr. 12, 129–145.

Thakur, Pramod, Schatzel Steve, Kashy, Aminian, 2014. Coal bed methane. In: - Evaluation of Coalbed Methane Reservoirs. Elsevier, pp. 63–91.

Wang, J.G., Kabir, A., Liu, J., et al., 2012. Effects of non-Darcy flow on the performance of coal seam gas wells. Int. J. Coal Geol. 93, 62–74.

Wang, K., Zang, J., Wang, G., Zhou, A., 2014. Anisotropic permeability evolution of coal with effective stress variation and gas sorption: model development and analysis. Int. J. Coal Geol. 130, 53–65.

Wang, Chunguang, Zhang, Jidong, Chen, Junguo, Zhong, Ruizhi, Cui, Guanglei, Jiang, Yujing, Liu, Weitao, Chen, Zhongwei, 2021a. Understanding competing effect between sorption swelling and mechanical compression on coal matrix deformation and its permeability. Int. J. Rock Mech. Min. Sci. 138, 104639.

Wang, Bin, Li, Bobo, Li, Jianhua, Gao, Zheng, Jiang, Xu, Ren, Chonghong, Zhang, Yao, 2021b. Measurement and modeling of coal adsorption-permeability based on the fractal method. J. Nat. Gas Sci. Eng. 88, 103824.

Wei, Z., Zhang, D., 2010. Coupled fluid-flow and geomechanics for triple-porosity/dual-permeability modeling of coalbed methane recovery. Int. J. Rock Mech. Min. Sci. 47 (8), 1242–1253.

Wei, M., Liu, J., Shi, R., Elsworth, D., Liu, Z., 2019. Long-term evolution of coal permeability under effective stresses gap between matrix and fracture during CO2 injection. Transport Porous Media 130 (3), 969–983.

Wu, Yu, Liu, Jishan, Derek, Elsworth, Miao, Xiexing, Mao, Xianbiao, 2010. Development of anisotropic permeability during coalbed methane production. J. Nat. Gas Sci. Eng. 2 (4), 197–210.

Zang, J., Wang, K., Zhao, Y.X., 2015. Evaluation of gas sorption-induced internal swelling in coal. Fuel 143, 165–172.

Zhang, D., Chu, Y., Li, S., Yang, Y., Bai, X., Ye, C., Wen, D., 2018. Petrophysical characterization of high-rank coal by nuclear magnetic resonance: a case study of the Baijiao coal reservoir, SW China. R Soc Open Sci 5 (12), 181411. https://doi.org/10.1098/rsos.181411. PMID: 30662747; PMCID: PMC6304127.

Zhao, Junlong, Tang, Dazhen, Xu, Hao, Meng, Yanjun, Lv, Yumin, Shu, Tao, 2014. A dynamic prediction model for gas-water effective permeability in unsaturated coalbed methane reservoirs based on production data. J. Nat. Gas Sci. Eng. 21, 496–506.

Zhou, D., Liu, Z., Feng, Z., Shen, Y., Wu, Y., 2020. The study of the local area density homogenization effect of meso-structures in coal during methane adsorption. J. Petrol. Sci. Eng. 191, 107141.