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Full Length Article

Effect of non-uniform swelling on coal multiphysics during gas injection: The triangle approach

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ABSTRACT

In current dual porosity/permeability models, there exists a fundamental assumption that the adsorption-induced swelling is distributed uniformly within the representative elementary volume (REV), irrespective of its internal structures and transient processes. However, both internal structures and transient processes can lead to the non-uniform swelling. In this study, we hypothesize that the non-uniform swelling is responsible for why coal permeability in experimental measurements is not only controlled by the effective stress but also is affected by the adsorption-induced swelling. We propose a concept of the swelling triangle composed of swelling paths to characterize the evolution of the non-uniform swelling and serve as a core link in coupled multiphysics. A swelling path is determined by a dimensionless volumetric ratio and a dimensionless swelling ratio. Different swelling paths have the same start and end point, and each swelling path represents a unique swelling case. The swelling path as the diagonal of the triangle represents the case of the uniform swelling while that as the two perpendicular boundaries represents the case of the localized swelling. The paths of all intermediate cases populate inside the triangle. The corresponding relations between the swelling path and the response of coal multiphysics are established by a non-uniform swelling coefficient. We define this method as the triangle approach and corresponding models as swelling path-based ones. The proposed concept and models are verified against a long-term experimental measurement of permeability and strains under constant effective stress. Our results demonstrate that during gas injection, coal multiphysics responses have a close dependence on the swelling path, and that in both future experiments and field predictions, this dependence must be considered.

1. Introduction

Coalbed methane (CBM) is an essential unconventional natural gas with major deposits worldwide. As the residential area for CBM, coal is composed of fractures and matrix solid skeleton, involving discontinuous, heterogeneous, and anisotropic structures, which provides particular challenges for modelling coal behaviors (such as deformation and permeability evolution) (Fan and Ettehadtavakkol., 2017; Martyushev et al., 2023). In order to fully understand how coal responses to gas injection/extraction, it is necessary to introduce certain assumptions to develop appropriate models (Berre et al., 2019). Currently, continuum models (such as single porosity or dual permeability models) are widely used due to their simplicity and high computational efficiency (Wei et al., 2021).

Under continuum framework, coal is characterized by the representative elementary volume (REV), and the established REV can accurately reflect the actual coal structure and state (Berre et al., 2019; Jackson et al., 2020). In previous continuum models, the REV with matrix and fractures is incorporated into a mathematical construct (called simulation cell), and physical-mechanics properties (such as bulk modulus, porosity, and Langmuir's adsorption capacity) and variables (such as pressure and effective stress) at the simulation cell are represented by only one value. This means that these parameters are assumed to be distributed uniformly in matrix and fracture, and the REV consists of two uniform systems (Liu et al., 2020; Huang et al., 2022). Conventional

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continuum models are derived and established based on the uniform REV. The results of these models suggest that under stress-controlled boundary conditions, coal permeability is only related to the effective stress (determined by the difference between confining pressure and pore pressure) and is independent of the adsorption-induced swelling (Palmer and Mansoori, 1996; Cui and Bustin, 2005; Shi and Durucan, 2005; Zhang et al., 2008; Wu et al., 2010). In this case, with gas injection, permeability should monotonically increase with the decrease of the effective stress under constant confining pressure (CCP). However, current experimental observations demonstrate that the adsorption-induced swelling also plays a non-negligible role, and permeability shows a scattering trend with pressure under CCP (possible increasing, decreasing, or fluctuating) (Shi et al., 2018; Wei et al., 2019a; Li et al., 2020; Zhao et al., 2021; Gao et al., 2022). In order to address the discrepancy between experimental results and theoretical solutions, the concept of the internal swelling strain was firstly proposed to determine the influence of the adsorption-induced matrix swelling on the fracture aperture and corresponding coal permeability (i.e. matrix-fracture mechanical interactions) (Liu and Rutqvist, 2010; Guo et al., 2014; Liu et al., 2017; Jiang et al., 2020). In these publications, a splitting coefficient was generally introduced to define the proportion of the matrix swelling acting on fractures. However, the physical meaning of the proposed coefficient is not clear, and the magnitudes of the coefficient are generally obtained by fitting experimental observations (Liu et al., 2020; Huang et al., 2022). The actual mechanisms responsible for the matrix-fracture mechanical interactions are still not fully understood and considered in these models.

In our recent work, we proposed that due to the high contrast in permeability between matrix and fractures, gas transport in the two systems lasts for distinct times (Wei et al., 2019b, 2021; Huang et al., 2022). Typically, gas fills fractures instantaneously, while gas diffusion in matrix potentially takes months to years (Peng et al., 2014). This means that after gas injection/extraction, coal would be in a non-equilibrium state for a long time (Liu et al., 2011a, 2011b). During this period, pressure and the associated adsorption-induced swelling are distributed non-uniformly throughout whole matrix, and change with time and space (Shi et al., 2020). Previous models fail to consider this transient process and the resulting non-uniform matrix swelling. The underlying uniform REV only reflects the distribution of pressure and swelling at initial equilibrium (prior to gas injection) and ultimate equilibrium (after gas fully invasion) (Wei et al., 2021). Therefore, the calculated results only refer to the coal behaviors in equilibrium (Liu et al., 2023). However, most experiments to date are not conducted long enough to allow samples to equilibrate, and thus, the data are generally collected in non-equilibrium stages (Liu et al., 2011b; Shi et al., 2018). Therefore, there is a mismatch between the uniform swelling assumption within the REV in conventional continuum models and coal actual states in the experiments.

In addition to the transient process, the heterogeneity of the Langmuir's adsorption constant also leads to the matrix non-uniform swelling. Due to the combination of geological factors (such as sediment sources, diagenesis, and tectonic settings), a high degree of the spatial structural heterogeneity is present. Coal matrix is composed of various components with different structures, densities, and properties (Li and Benson, 2015; Mathews et al., 2017). To date, a majority of studies pay close attention to the structural heterogeneity at the global scale, that is, when establishing physical or geological models, physical properties are generally set to various values in different regions to reflect the structural heterogeneity (Flett et al., 2007; Deng et al., 2012; Chen et al., 2013; Tan et al., 2018; Martyushev and Yurikov, 2021; Makarian et al., 2023). However, the heterogeneities within the REV are rarely considered. In fact, compositional heterogeneities of matrix are present in all geological scales, and the results of the advanced high-resolution imaging techniques show that even at the local scale, matrix still exhibits strong heterogeneity (Yao et al., 2009; Al-Raoush and Papadopoulos, 2010; Wu et al., 2019; Jackson et al., 2020; Galkin et al., 2022; Tian et al., 2022a, 2022b). The uniform REV fails to characterize the complicated matrix components and associated heterogeneity of physical properties. However, it is critical to predict the macroscopic constitutive response on the basis of underlying microstructure (Kouznetsova et al., 2002; Ye et al., 2021). Therefore, when establishing the REV, it is necessary to consider structural heterogeneity and the distribution of physical properties. In this study, we focus on the matrix adsorption-induced swelling. The swelling can be defined by a Langmuir-type equation and be controlled by the Langmuir' adsorption constant. Consequently, among numerous physical properties, we only consider the heterogeneity of the Langmuir's adsorption constant in matrix within the REV.

As reviewed above, in conventional continuum models, there is a basic assumption of the uniform swelling in the underlying REV. However, the assumption would be invalid, due to the combination effect of long-term gas diffusion and heterogeneity of the Langmuir's adsorption constant, leading to a non-uniform distribution of the matrix swelling. We hypothesize that the variations in matrix swelling behaviors would result in a series of local mechanisms affecting the coal behaviors (such as matrix-fracture mechanical interactions). Conventional continuum models based on the uniform REV fail to consider this non-uniformity and to incorporate resulting important mechanisms, which would prevent them from fully explaining experimental observations. In this study, we derive novel coal permeability and multiphysics models based on the REV with non-uniform matrix to resolve the long-term enigmatic issue why laboratory measurements of coal permeability scatter with pressure.

2. Concept of swelling path

The dual porosity/permeability approach under continuum framework is widely used in simulating the fluid flow in coal reservoirs. In this approach, coal is idealized by two overlapping continuum media (one represents matrix and the other represents fractures), and the REV with matrix and fractures is incorporated into a mathematical construct (called simulation cell), as shown in Fig. 1a. The simulation cell has no spatial information, at which, each parameter is represented by only one value. This means that structures and transient processes in the REV are ignored. Therefore, no distribution of pressure and the Langmuir's adsorption constant is considered, and these parameters are regarded to be uniform in matrix within the REV, as plotted in Fig. 1b. Conventional dual porosity/permeability models are derived based on the REV with uniform matrix. However, this uniform REV cannot accurately reflect the actual coal structure and state. As mentioned above, due to long-term gas diffusion and various components in matrix, pressure and the Langmuir's adsorption constant would be distributed non-uniformly. In order to resolve these knowledge deficiencies, we establish the REV with non-uniform matrix, as shown in Fig. 1c, and subsequently the influence of the matrix non-uniform swelling is explored.

At first, according to a pressure mapping method (Huang et al., 2022), the REV with non-uniform matrix is connected to the simulation cell, that is, matrix pressure at the simulation cell calculated by the dual porosity/permeability approach is treated as average pressure of the matrix block in the non-uniform REV. The pressure distribution within the matrix block during gas diffusion is characterized by the one-dimensional diffusion equation (Bear,

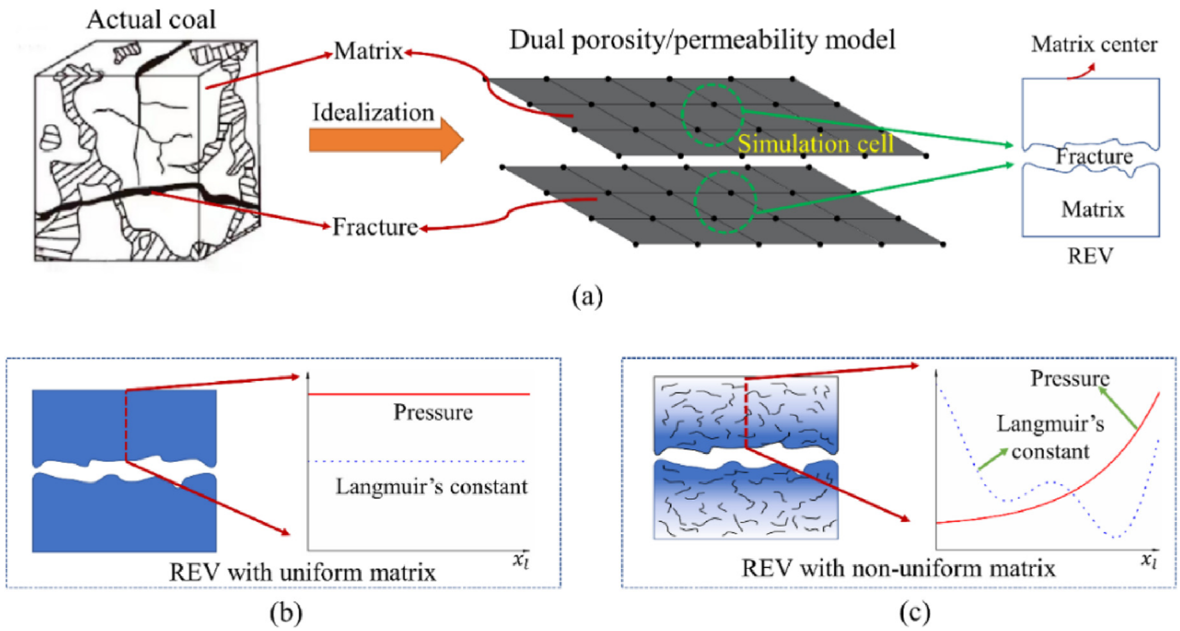

Fig. 1. Schematic of REV (a) Dual porosity/permeability model; (b) REV with uniform matrix; and (c) REV with non-uniform matrix.

1988; Patzek et al., 2013, 2014). Through this method, the non-uniform REV is embedded into the overall multiphysics (dual porosity/permeability approach). It is worth noting that after embedment, there would exist two systems, one is the local embedded non-uniform REV and the other is the overall multiphysics of the dual porosity/permeability framework. The overall results would affect the distribution of pressure and corresponding swelling in the local embedded REV, while the variations in the pressure and swelling distribution would also in turn influence the results of the overall multiphysics. In order to have an explicit closed-form expression for the solution to the diffusion equation, it is necessary to introduce some assumptions: (1) gas is ideal; (2) viscosity, permeability and porosity keep unchanged; and (3) the influence of adsorption on gas diffusion is neglected. Under these assumptions, when accounting for the pressure distribution in matrix, the effect of the non-uniform matrix swelling is ignored. Therefore, the average pressure and pressure distribution within the matrix block in the local REV can be expressed as

$$\overline{p_l}(t_l) = \sum_{n=0}^{\infty} \frac{8\left(p_i - p_{gf}\right)}{\left[(2n+1)\pi\right]^2} e^{-\left[\left(\frac{(2n+1)\pi}{2L}\right)^2 \frac{k_{m_0}}{\varphi_{m_0}\mu c_t}\right] t_l} + p_{gf} \tag{1}$$

$$p_l(x_l, t_l) = \sum_{n=0}^{\infty} \frac{4\left(p_i - p_{gf}\right)}{(2n+1)\pi} e^{-\left[\left(\frac{(2n+1)\pi}{2L}\right)^2 \frac{k_{m_0}}{\varphi_{m_0}\mu c_t}\right] t_l} \sin\frac{(2n+1)\pi x_l}{2L} + p_{gf} \tag{2}$$

where the subscripts g and l are employed to mark the parameters and equations in the overall multiphysics and local embedded REV for distinction; $\overline{p_l}$ is the average pressure of the matrix block in the local system; p_l is the pressure in the matrix block; p_i is the initial pressure; p_{gf} is the fracture pressure in the global system; t_l is the characteristic time; L refers to half the length of the matrix block (i.e. the distance between the fracture wall and the matrix centre), whose magnitude determines the mass transfer shape factor in the overall multiphysics; x_l is the coordinate in the local system; k_{m_0} is the initial matrix permeability; φ_{m_0} is the initial matrix porosity; μ is the gas viscosity; and c_t is the gas compressibility. It is evident that after inputting the results of pressure calculated from the overall multiphysics into Eq. (1), t_l can be obtained, and once t_l is substituted into Eq. (2), the pressure distribution within the matrix block in the local embedded REV can be obtained.

The previous literature has indicated that the Weibull statistical distribution is able to precisely describe the experimental data on the distribution of microstructures within rocks (Weibull, 1951; Hudson and Fairhurst, 1969; Liu et al., 2004). As a result, the Weibull statistical distribution has become a common method for characterizing the heterogeneous distribution of physical properties within coal over the past few decades (Tang et al., 2000; Zhu and Tang, 2004). Therefore, in this study, the Langmuir's adsorption constant within the matrix block is assumed to follow the Weibull statistical distribution, which can be expressed as (Zhu et al., 2013; Kong et al., 2019):

$$f(\varepsilon_{lL}) = \frac{\tau}{\varepsilon_{lL}}\left(\frac{\varepsilon_{lL}}{u_0}\right)^{\tau-1} \exp\left[-\left(\frac{\varepsilon_{lL}}{u_0}\right)^{\tau}\right] \tag{3}$$

where ε_{lL} is the Langmuir's adsorption constant within the matrix block in the local REV; u_0 is a scale parameter related to the average Langmuir's adsorption constant; and τ is the shape parameter.

Based on the Langmuir adsorption isotherm and combination of Eqs. (2) and (3), the non-uniform distribution of the matrix swelling in the local embed REV is obtained (Zhang et al., 2008):

$$\varepsilon_{ls}(x_l, t_l) = \frac{\varepsilon_{lL}(x_l)p_l(x_l, t_l)}{p_l(x_l, t_l) + p_L} \tag{4}$$

where p_L is the Langmuir's pressure constant.

After establishing the REV with non-uniform matrix, we introduce the concept of the swelling path and a novel non-uniform swelling coefficient to quantify the degree of the non-uniform swelling. At first, we categorize the swelling behaviors in matrix into three cases. We define the case where the swelling strain is equal everywhere as the uniform case (Case 1), and the case where the swelling only occurs on the fracture wall (corresponding to gas just invades from fracture into matrix) is defined as the localized case (Case 2). In general, the actual swelling distribution is somewhere between these two extreme cases, as shown in Case 3. After that, the matrix swelling is integrated with a variable upper limit that is the distance from the matrix center ($\int_0^x \varepsilon_{ls} dx_l$). With the dimensionless volumetric ratio (x/L) as the X axis and the dimensionless swelling ratio ($\int_0^x \varepsilon_{ls} dx_l / \int_0^L \varepsilon_{ls} dx_l$) as the Y axis, the swelling paths for three cases are generated, as shown in Fig. 2. The swelling path for the uniform case is shown by the black line (i.e. with the increase in the volumetric ratio, the dimensionless swelling is linearly increasing with a slope of 1), and that for the localized case is shown by the red line (i.e. the dimensionless swelling is always zero at first and abruptly increases almost vertically to 100 at the end). The swelling paths for the two extreme cases would delineate a swelling triangle, and the paths of all intermediate cases would populate inside the triangle (like the blue line). Any swelling path has the same start and end point, but different paths between the two ends reflect the various swelling behaviours in the REV. Hereafter, we define the area between the black and blue lines as A and that between the blue and red lines as B, and the non-uniform swelling coefficient, β, is expressed as

$$\beta = \frac{B}{A + B} \tag{5}$$

It is apparent that when the adsorption constant is homogeneous and an equilibrium state is reached (i.e. the distribution of the adsorption-induced swelling is uniform), the blue line coincides with the black line. In this case, $\beta = 1$. When the swelling is all concentrated at one point (fracture wall), the blue line and red line are overlapping, implying that $\beta = 0$. For any other intermediate path inside the triangle, $0 < \beta < 1$.

3. Model development

In the last section, the non-uniform swelling in the REV induced by the gas diffusion process and the heterogeneity of the Langmuir's adsorption constant is considered, and this non-uniformity is quantified by the swelling path and the non-uniform swelling coefficient. In this part, based on this coefficient, the influence of the non-uniform matrix swelling is incorporated into the overall governing equations, and generic swelling path-based coal permeability and multiphysics model are proposed.

3.1. Governing equations for coal deformation

According to the poroelastic theory as well as an analogy between thermodynamics and the adsorption-induced swelling, the coal deformation is mainly induced by changes in confining pressure, fracture pressure, and matrix swelling. Previous publications, based on the uniform REV, have suggested how these three items affect the coal deformation and derived the constitutive relations for the coal deformation at the uniform swelling case (Zhang et al., 2008, 2018; Peng et al., 2014):

$$\varepsilon_{gij} = \frac{1}{2G}\sigma_{gij} - \left(\frac{1}{6G} - \frac{1}{9K}\right)\sigma_{gkk}\delta_{ij} + \frac{a_f p_{gf}}{3K}\delta_{ij} + \frac{\varepsilon_{gms}}{3}\delta_{ij} \tag{6}$$

where the subscripts m and f refer to matrix and fractures, respectively; σ_{gij} is the component of the total stress tensor; ε_{gij} is the component of the total strain tensor; σ_{gkk} is the total normal stress; G is the shear modulus of coal; K is the bulk modulus of coal; $G = E/2(1 + \nu)$, $K = E/3(1 - 2\nu)$, in which E is the Young's modulus of coal; ν is the Poisson's ratio; a_f is the Biot's coefficient; δ_{ij} is the Kronecker delta; and ε_{gms} is the adsorption-induced swelling for matrix.

As shown in Eq. (6), once the swelling distribution is uniform, the matrix swelling would fully contribute to the coal bulk, that is, the adsorption-induced swelling for coal (ε_{gcs}) is consistent with that for matrix (ε_{gms}). However, it has been proposed in recent studies that the two are not equal, and in general, the former one is much smaller than the latter one (Jiang et al., 2020; Shi et al., 2020). This is because, except for the coal bulk, the matrix swelling also contributes to fractures (i.e. matrix-fracture mechanical interactions), and the fundamental reason for this phenomenon is the non-uniform distribution of the adsorption swelling in matrix (Liu et al., 2011a, 2011b; Peng et al., 2014). Under this condition, the coal swelling for the non-uniform case is smaller than that for the uniform case. In order to accurately capture the coal deformation with the influence of the non-uniform swelling, we propose the concept of the fictitious stress to modify the governing equations of deformation. We assume that when the swelling distribution is non-uniform, the coal deformation would be affected by the fictitious stress, in addition to the changes in confining pressure, fracture pressure, and matrix swelling, as shown in Fig. 3. Under the effect of this stress, coal would be pushed back from the uniform swelling case, and the magnitude of this stress is defined by the

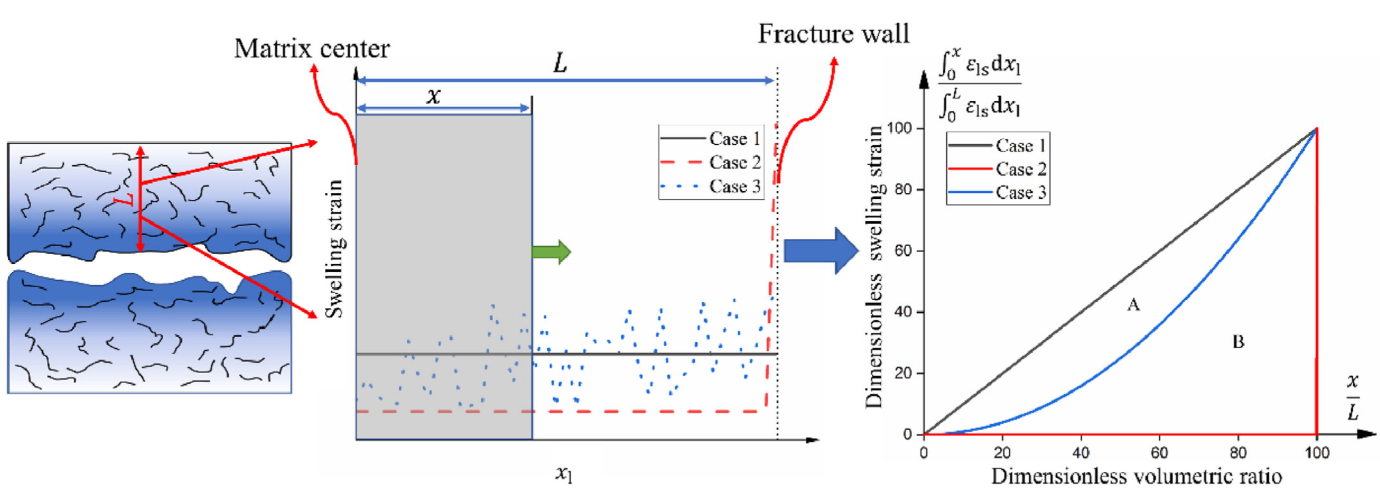

Fig. 2. Illustration of swelling path and swelling triangle.

difference between ε_{gcs} and ε_{gms}. Under this condition, the total applied tension for the coal deformation becomes two parts:

$$\sigma_g = \sigma_{con} + \sigma_{fic} \tag{7}$$

where σ_{con} is confining pressure, and σ_{fic} is the fictitious stress, which can be defined as

$$\sigma_{fic} = K(\varepsilon_{gcs} - \varepsilon_{gms}) \tag{8}$$

As mentioned above, the coal swelling is influenced by the matrix swelling and its distribution. Therefore, based on the proposed non-uniform swelling coefficient, the adsorption-induced swelling for coal is derived as

$$\varepsilon_{gcs} = \beta\varepsilon_{gms} = \frac{\beta\varepsilon_{gL}p_{gm}}{p_L + p_{gm}} \tag{9}$$

After substituting Eqs. (7)–(9) into Eq. (6), the volumetric strain of coal with the inclusion of the non-uniform swelling is obtained:

$$\varepsilon_{gv} = -\frac{\sigma_{con} - \alpha_f p_{gf}}{K} + \frac{\beta\varepsilon_{gL}p_{gm}}{p_L + p_{gm}} \tag{10}$$

where ε_{gv} is the coal strain; ε_{gL} is the Langmuir's adsorption constant in the global system; and p_{gm} is the matrix pressure.

3.2. Governing equations of gas flow in matrix and fractures

Gas flow in matrix and fractures follows Mass Conservation Law and Darcy's law, and can be respectively described as (Zhang et al., 2008; Huang et al., 2022):

$$\frac{\partial}{\partial t_g}\left(\varphi_{gf}\rho_{gf} + \rho_s\rho_c\frac{V_L p_{gf}}{p_{gf}+p_L}\right) + \nabla\bullet\left(-\rho_{gf}\frac{k_{gf}}{\mu}\nabla p_{gf}\right) = -\frac{k_{gm}\rho_{gm}}{\mu}\gamma\left(p_{gf}-p_{gm}\right) \tag{11}$$

$$\frac{\partial}{\partial t_g}\left(\varphi_{gm}\rho_{gm} + \rho_s\rho_c\frac{V_L p_{gm}}{p_{gm}+p_L}\right) + \nabla\bullet\left(-\rho_{gm}\frac{k_{gm}}{\mu}\nabla p_{gm}\right) = \frac{k_{gm}\rho_{gm}}{\mu}\gamma\left(p_{gf}-p_{gm}\right) \tag{12}$$

where ρ_g is the gas density; ρ_s is the gas density at standard conditions; ρ_c is the coal density; V_L is the Langmuir's volume constant; k_g is the permeability; φ_g is the porosity; and γ is called the mass transfer shape factor and is related to the matrix length (L) in the local embedded REV.

According to previous publications, coal permeability generally depends on the fracture system, and the typical relationship between permeability and porosity yields the cubic law (Liu et al., 2011c; Pan and Connell, 2012), which can be expressed as

$$\frac{k_{gf}}{k_{gf_0}} = \left(\frac{\varphi_{gf}}{\varphi_{gf0}}\right)^3 \tag{13}$$

where k_{gf} is the fracture permeability; φ_{gf} is the fracture porosity; and the subscript 0 denotes the initial value.

Further, the porosity ratio is the funciton of the effective strain (Liu et al., 2011c):

$$\frac{\varphi_{gf}}{\varphi_{gf0}} = 1 + \frac{\alpha_f}{\varphi_{gf0}}\Delta\varepsilon_{ge} \tag{14}$$

The effective strain increment is calculated by the difference between the applied tension and pore pressure (Liu et al., 2011a, 2011c):

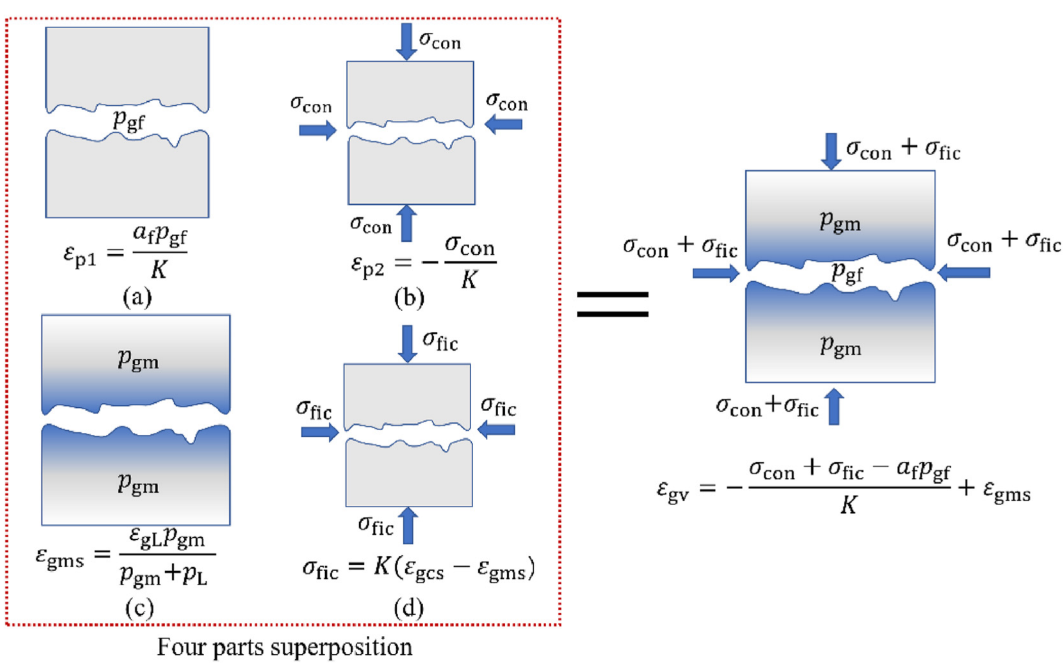

Fig. 3. Illustration of coal deformation at non-uniform swelling: (a) Fracture pressure; (b) Confining pressure; (c) Matrix swelling; and (d) Fictitious stress.

$$\Delta\varepsilon_{\rm ge} = -\frac{\Delta\sigma_{\rm g} - \Delta p_{\rm gf}}{K} \tag{15}$$

As we discussed in the governing equations for the coal deformation, for the case where the matrix swelling is non-uniform, the applied tension consists of the fictitious stress in addition to the confining pressure. Therefore, after combining Eq. (7), Eq. (8), and Eqs. 13–15, coal permeability can be defined as

$$\frac{k_{\rm gf}}{k_{\rm gf_0}}=\left\{1+\frac{\alpha_{\rm f}}{\varphi_{\rm gf0}}\left\{-\frac{\Delta\sigma_{\rm con}-\Delta p_{\rm gf}}{K}+\left[(\beta-1)\varepsilon_{\rm gms}-(\beta_0-1)\varepsilon_{\rm gms_0}\right]\right\}\right\}^3 \tag{16}$$

where β_0 refers to the non-uniform swelling coefficient at the initial state.

From Eq. (16), it can be seen that permeability is no longer only related to the effective stress, but is also controlled by the swelling path. When the swelling path is different, the effect of the gas adsorption on permeability is various. Once the swelling distribution within matrix is uniform, the non-uniform swelling coefficient would be equal to 1, and the adsorption effect would be vanished. Under this condition, Eq. (16) degenerates to the exact solution of conventional continuum models (Zhang et al., 2008; Wu et al., 2010). Once the swelling path deviates from the diagonal, the matrix swelling would affect the fracture volume, inducing matrix-fracture mechanical interactions. Different swelling behaviors would result in various proportions of the matrix swelling acting on fracture. Therefore, Eq. (16) also can be degenerated to the models based on the internal swelling strain (Liu and Rutqvist, 2010; Guo et al., 2014; Liu et al., 2017), and the splitting coefficient is related to the swelling behaviors in matrix.

4. Model verification

Currently, most experimental measurements are performed shortly after injection pressure reaches the predetermined value, and data are collected only once rather than continuously. This is because they believe that coal samples reach equilibrium within a short period, and the data would no longer change (Shi et al., 2018). However, in fact, due to the slow process of gas diffusion, the measurements in previous experiments were conducted in non-equilibrium states, and the obtained results only refer to the small portion of the coal behaviors from initial to ultimate equilibrium. In order to obtain complete experimental data, a long-term laboratory test was conducted. In this experiment, a cylindrical coal sample with a length of 10.06 cm and a diameter of 5.02 cm was subjected to a confining pressure of 6 MPa and continuously injected with CO_2 at 3 MPa for 90 d, and the coal permeability, bulk strain, and fracture strain during this process were continuously collected. The permeability data were measured by the transient method. Specifically, the pressure of the upstream and downstream of the coal sample was changed periodically to create a pressure difference, and permeability was determined by evaluating the pressure decay and increase rates in the upstream and downstream reservoir. The coal bulk strain was measured by two strain gauges which were tightly attached to the sample surface in directions perpendicular and parallel to the axial direction of the sample respectively. Since the fracture deformation cannot be measured directly, a gas expansion method was proposed to capture the fracture strain indirectly. The matrix strain was calculated based on the volumetric relationship among matrix, fracture, and coal bulk. The specific measurement principle mentioned can refer to previously published research (Zhao et al., 2021, 2023). In this section, we verify the proposed permeability and multiphysics models by comparing the simulation results with the long-term experimental observations. The calculations of a conventional continuum model (Zhang et al., 2008) are plotted, to illustrate the effect of the non-uniform swelling. In addition, the results of another permeability model that considers the non-uniform swelling are also compared (Zhang et al., 2018). According to the experimental information, a case of the physical model is established, as shown in Fig. 4. Part of the mechanical parameters (i.e. Young's modulus and Poisson's ratio) are given in the experiment, while other parameters are collected from related studies or determined by matching with experimental data (Zhang et al., 2008; Wu et al., 2010). All parameters used in the simulation are listed in Table 1.

Based on Eqs. (4), (10) and (16), the matrix strain, bulk strain, and permeability are obtained, and according to the volumetric relation among matrix, fracture and coal bulk, the fracture strain can be calculated. The comparison between simulation results and experimental ones is plotted in Fig. 5. It is evident that coal permeability, bulk strain, fracture strain and matrix strain calculated by the proposed model follow a similar pattern to the experimental observations, while there is a significant deviation in the results of the other two models. The conventional permeability model suggests that the evolution of permeability is only related to injection pressure, and as injection pressure reaches the preset value (almost instantaneously), permeability would remain unchanged. However, the experimental observations suggest that the permeability evolution is a long-term process, and except for initial increase, it also exhibits decline and rebound before reaching a plateau. This is because permeability is influenced by swelling behaviors that change with the gas diffusion process. Although another model can also predict the multi-stage evolution of permeability, the calculated results are much higher than the experimental observations. This is because this model does not consider the actual distribution of the swelling in matrix during gas diffusion, and the changes in matrix swelling behaviors are characterized by the pressure difference in matrix and fractures. In this case, the true nature of the non-uniform swelling has not been fully taken into account. In addition, the effect of matrix heterogeneity is

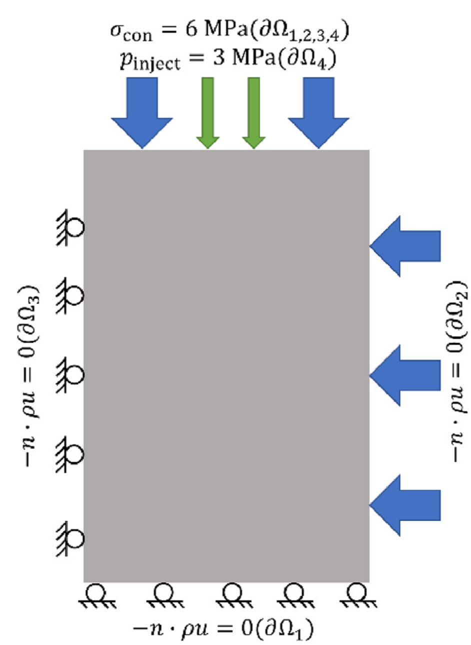

Fig. 4. Simulation physical model.

Table 1
Parameters of the simulation model.

Parameters	Value
Initial matrix porosity	0.02
Initial fracture porosity	0.005
Coal Young's modulus (GPa)	2.433
Possion's ratio	0.2184
Gas viscosity (Pa s)	1.89×10^{-5}
Biot's coefficient	0.8
Initial matrix permeability (m^2)	5×10^{-20}
Initial fracture permeability (m^2)	1×10^{-17}
Coal density (kg/m^3)	1200
Langmuir's adsorption constant	0.01
Langmuir's volume constant (m^3/kg)	0.015
Langmuir's pressure constant (MPa)	6
Shape factor (m^{-2})	986
Gas density (kg/m^3)	0.717
Initial pressure (MPa)	0.1
Matrix length (m)	0.05
Gas compressibility (Pa^{-1})	3.42^{-8}

not incorporated in this model, and the Langmuir's adsorption constant in matrix is still assumed to be distributed uniformly.

In order to further illustrate the influence of the variations in swelling behaviors in matrix, the swelling paths at different times are plotted, as shown in Fig. 6. After being injected, gas fills fractures in a short time followed by slow diffusion in matrix. During this period, the whole evolution process for the coal response can be divided into four stages according to changes in swelling behaviors. In this first stage, gas only flows in fractures and has not yet invaded matrix. In this case, the distribution of the swelling in matrix does not change, and permeability variations are only attributed to the effective stress. Therefore, permeability increases dramatically with gas injection during this period. Once gas diffuses into matrix, the coal response enters the second stage. With gas diffusion, the swelling behaviors in matrix change, which leads to different swelling paths. Initially, the swelling path is close to two perpendicular lines of the triangle (localized case). The coal deformation would be constricted by the fictitious stress and basically remain unchanged. The adsorption effect plays a major role in the permeability evolution, which counterweights the effect of the drop in the effective stress in the first stage. Consequently, permeability in this stage shows a decline trend. As gas further diffuses into matrix, the swelling path gradually approaches the uniform case. This means that the matrix swelling would gradually become uniform. The effect of the non-uniformity weakens, and consequently permeability rebounds. However, due to the heterogeneity of the Langmuir's adsorption constant, even with gas fully invasion, the distribution of the matrix swelling is still non-uniform, that is, the swelling path does not coincide with the diagonal of the triangle. Under this condition, the adsorption effect would not fully vanish, and permeability does not fully rebound to the results of the conventional model. Therefore, at equilibrium state, the distance between permeability results of the proposed model and those of the conventional model would reflect the compositional characteristics of matrix. Based on the simulation results, it can be concluded that under the influence of the matrix non-uniform swelling, the coal response shows a totally different trend, and coal behaviors are closely related to the swelling path.

5. Results and discussion

Through Eqs. (10) and (16), the influence of the matrix non-uniform swelling is incorporated into the overall formulations,

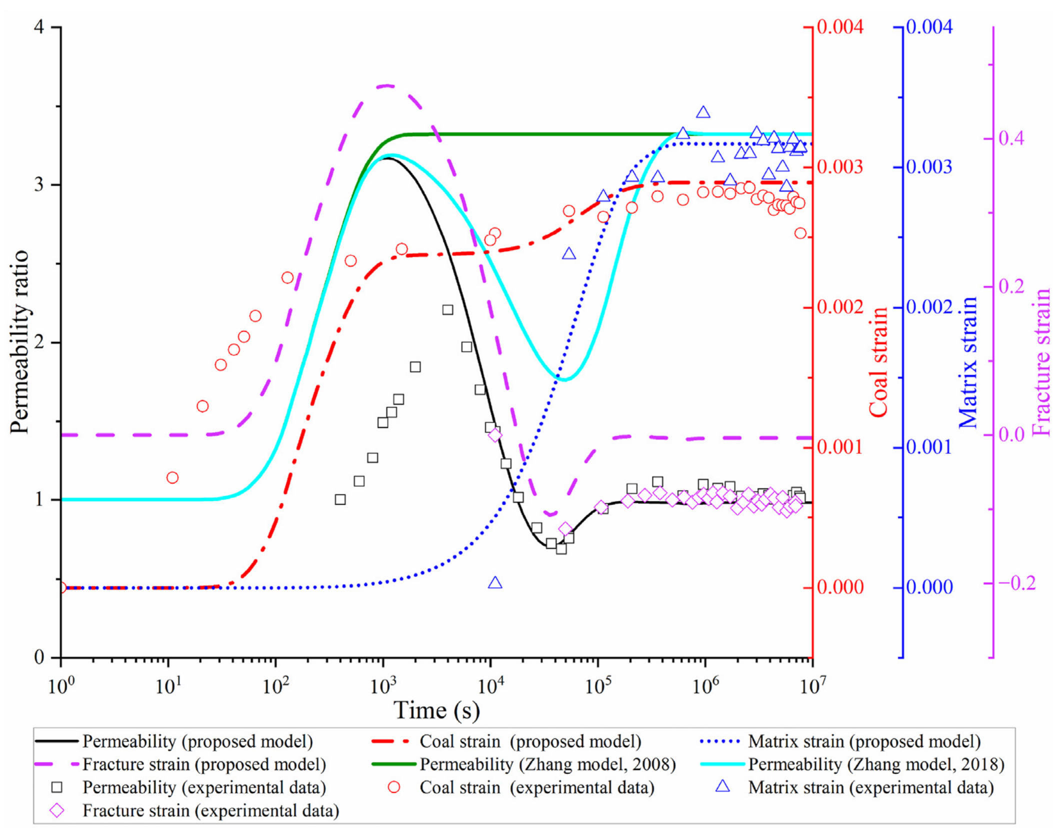

Fig. 5. Comparison between simulation results and experimental data for permeability and strains during CO_2 injection.

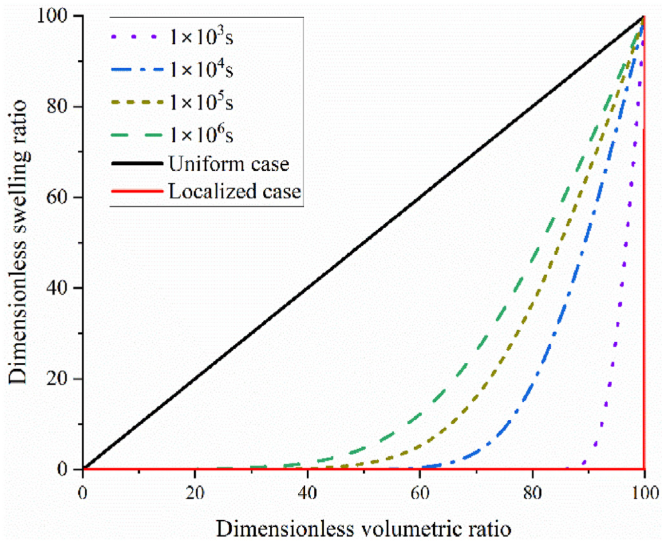

Fig. 6. Swelling paths for four moments during gas diffusion.

and swelling path-based coal permeability and multiphysics models are established. Moreover, in the last section, we have demonstrated that the variations of swelling behaviors in matrix play an important role in the coal response. The non-uniform distribution of the matrix swelling is attributed to two reasons, one is the gas diffusion process, and the other is the heterogeneity of the Langmuir's adsorption constant. Therefore, here, we conduct a series of sensitivity analyses to explore how the two factors affect the distribution of the swelling and permeability evolution.

5.1. Influence of gas diffusion

The gas diffusion process is primarily affected by two factors: matrix permeability, which regulates the speed of diffusion, and matrix size, which determines the distance of diffusion. In order to explore the effect of the matrix property changes and geometrical differences on the transient process and overall response of coal, the proposed models are applied to three scenarios with different matrix permeability and three scenarios with various matrix sizes. It is worth noting that in this part, we focus solely on the role of gas diffusion, and the influence of the heterogeneity of the Langmuir's adsorption constant is ignored. Therefore, the adsorption constant is homogeneous in matrix in the local embedded REV for all cases. The evolutions of the non-uniform swelling coefficient and permeability for the mentioned cases are plotted in Figs. 7 and 8, respectively. It is evident that for the cases with different matrix sizes and matrix permeability, the non-uniform swelling coefficient and permeability would take distinct times to evolve from initial to ultimate stability. Typically, with the increase in matrix length and the decrease in matrix permeability, the non-uniform swelling induced by gas diffusion would have a pronounced long-term effect on permeability. In addition, it is noteworthy that when the matrix size is larger or matrix permeability is lower, the time for the non-uniform coefficient to decrease becomes later, and correspondingly, permeability is affected by the gas adsorption effect later. This is due to the fact that a decrease in matrix permeability or an increase in the matrix size would reduce the proportion of the gas invasion area to whole matrix in the same time interval. Although the evolution process presents a diversified trend, for all cases, their permeability has the same magnitude at the beginning and the end, and the non-uniform swelling coefficient at the two ends is equal to unity. This means that once gas diffusion is over, matrix would swell uniformly, and permeability is only controlled by the effective stress, independent of the gas adsorption effect. Therefore, based on the calculated results, we can conclude that the non-uniform swelling induced by gas diffusion controls how coal permeability evolves from the beginning to the end. When the duration of gas diffusion is short, that is, the matrix length is small or permeability is large, it is acceptable to ignore the transient processes and their influences.

5.2. Influence of heterogeneity of Langmuir's adsorption constant

In order to explore the effect of the heterogeneity of the Langmuir's adsorption constant on the permeability evolution, we establish four cases, in which, the distributions of the adsorption constant in matrix are different but the average value for the

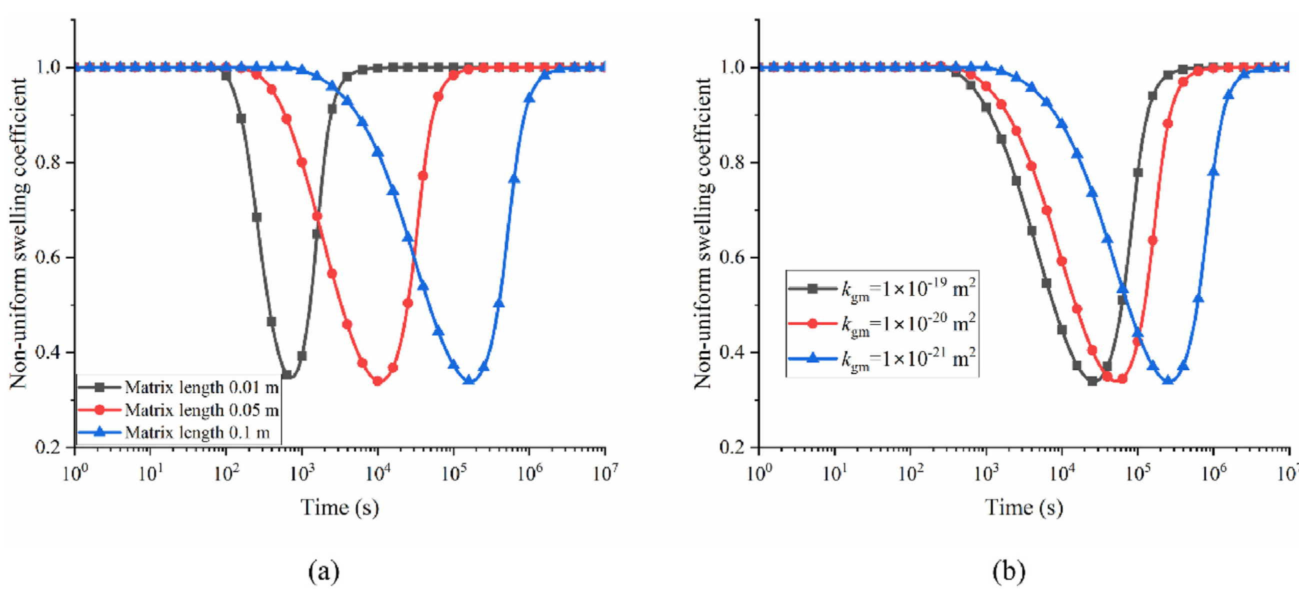

Fig. 7. Effect of matrix size and matrix permeability on evolution of non-uniform swelling coefficient: (a) Different matrix size; and (b) Different matrix permeability.

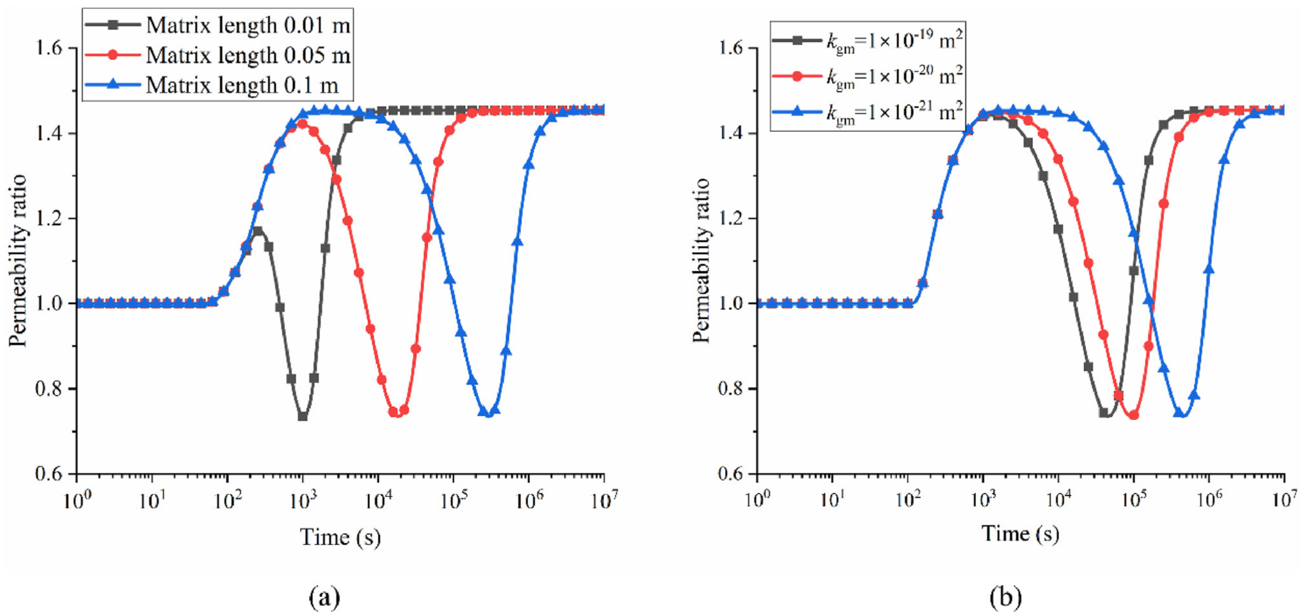

Fig. 8. Effect of matrix size and matrix permeability on evolution of coal permeability: (a) Different matrix size; and (b) Different matrix permeability.

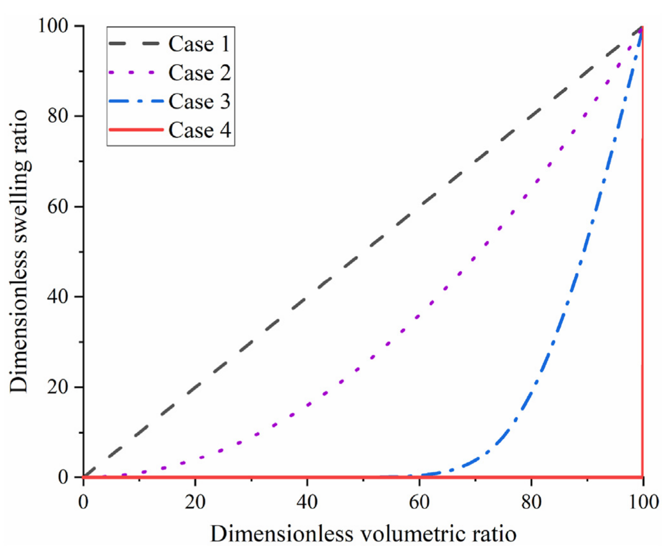

Fig. 9. Swelling paths for four cases with different distributions of Langmuir's adsorption constant in matrix.

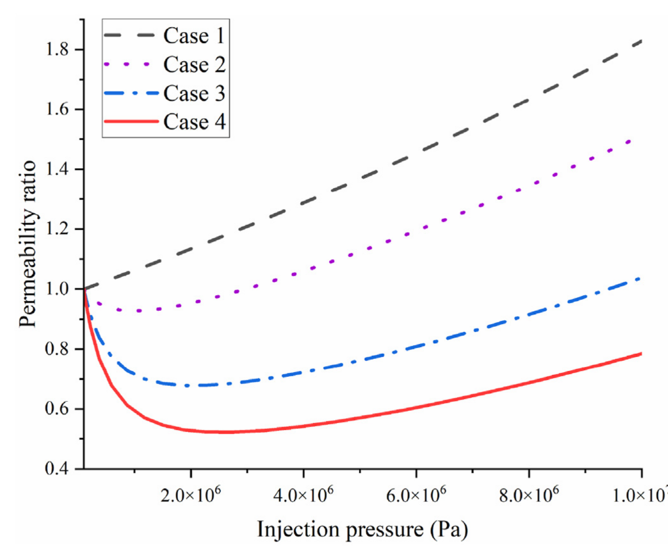

Fig. 10. Permeability evolution for four cases with different distributions of Langmuir's adsorption constant in matrix.

constant is the same in all these cases. In Case 1, the Langmuir's adsorption constant is distributed uniformly, while in Case 4, the Langmuir's adsorption constant is zero everywhere in matrix, except for the vicinity of fracture walls. The adsorption constant for Case 3 and Case 4 exhibits a distribution that lies between the uniform and localized distribution. Fig. 9 presents the swelling paths for these four cases. In this section, we aim to solely find out the effect of the heterogeneity. Therefore, we only collect the permeability data at equilibrium under different injection pressure. The permeability evolutions with injection pressure for four cases are plotted in Fig. 10. It is apparent that permeability exhibits a scattering trend with increasing pressure, which is consistent with experimental observations reported in previous publications (Shi et al., 2020). For these four cases, even under the same pressure, the different distribution of the Langmuir's adsorption constant leads to distinct results of permeability. The distance in the permeability ratios under same injection pressure reflects the differences in structures and swelling behaviors in matrix. Therefore, permeability should be closely related to the swelling path rather than pressure only. In addition, different from gas diffusion, the influence induced by the heterogeneity of Langmuir's adsorption constant is always present, even at equilibrium. Consequently, it can be inferred that this structural heterogeneity determines the position of the permeability evolution at the start and end point.

6. Conclusions

In this study, the variations in the swelling behaviors in the REV are intuitively characterized by the swelling path and swelling triangle, and the consequent effects are incorporated into coal permeability and multiphysics models through a novel non-uniform swelling coefficient. Based on our results, the following conclusions can be drawn:

(1) The swelling paths are able to correspond quite well and characterize matrix swelling behaviors. All swelling paths delineate a swelling triangle. The diagonal path of the triangle corresponds to the case of the uniform swelling while two perpendicular lines represent the case of the localized swelling. The paths of all intermediate cases populate inside the triangle.
(2) Coal permeability evolution shows a close dependence on the swelling path. If the swelling path follows the diagonal line of the triangle, the adsorption-induced matrix swelling has no effect on permeability; if it follows the perpendicular lines, all the matrix swelling contributes to the permeability evolution. These two cases define the boundaries of coal permeability evolution. The dependence must be considered in both future experiments and field predictions.
(3) Two major factors control the evolution of the swelling path and associated permeability, one is the gas diffusion process and the other is the heterogeneity of Langmuir's adsorption constant. The former one defines how coal permeability evolves from initial to ultimate equilibrium while the latter one determines the magnitude of permeability at both ends.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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