

Full Length Article

Master role conversion between diffusion and seepage on coalbed methane production: Implications for adjusting suction pressure on extraction borehole

Zhengdong Liu^{a,b,c}, Yuanping Cheng^{a,b,c,*}, Jun Dong^{a,b,c}, Jingyu Jiang^{a,b,c}, Liang Wang^{a,b,c}, Wei Li^{a,b,c}

^a Key Laboratory of Gas and Fire Control for Coal Mines (China University of Mining and Technology), Ministry of Education, Xuzhou 221116, China

^b National Engineering Research Center for Coal and Gas Control, China University of Mining and Technology, Xuzhou, Jiangsu 221116, China

^c School of Safety Engineering, China University of Mining and Technology, Xuzhou, Jiangsu 221116, China

ARTICLE INFO

Keywords:

Dynamic diffusion coefficient
Coal permeability
Methane extraction
Suction pressure
Methane utilization

ABSTRACT

Diffusion and seepage control coalbed methane (CBM) production jointly, and their controlling roles differ significantly in different stages of extraction. Although many CBM models have well been established, but these models cannot better quantify the controlling degree of diffusion and seepage on CBM production at a certain moment and determine when the master role between them happens to convert. In this paper, the conversion between different forms of methane and the underlying controlling mechanisms were analyzed firstly. According to contributions of different forms of methane to total production, a theoretical master role conversion model between diffusion and seepage on CBM production was established. And the theoretical model can better distribute the contribution degree of in-situ adsorbed methane to the total CBM production. The model was employed to analyze the time nodes when master role conversion occurs with different initial permeabilities and diffusion coefficients. Results show that higher coal permeability/diffusion coefficient results in earlier the conversion time node. The same conclusion also applies to the time node when the diffusion effect almost completely controls the CBM production. Besides, the change curves of daily methane production indicate that the production is primarily controlled by seepage in early stage of extraction, while controlled by diffusion in later stage. Methane extraction efficiency and concentration are closely related to drainage pressure. For ensuring underground mining safety, constant low-pressure extraction strategy is employed frequently to insure the extraction efficiency, which, however, leads to low methane concentration and utilization rate. This paper proposes a new extraction pressure regulating method, namely, time-based pressure regulating method that selected time node in accordance with the master role conversion theory. The simulation results prove that the new method can not only ensure extraction efficiency, but also guarantee extraction concentration as well as utilization, thus reducing the natural emissions of methane and amount of greenhouse gas.

1. Introduction

Coalbed methane (CBM), an efficient clean energy, is produced during the continuous evolution of coal [1–3]. However, methane, which accounts for 14.3% of total amount of greenhouse gases, has become the second major global anthropogenic greenhouse gas emitted currently, ranking only second to CO₂ [4]. According to statistics, a total of 793 MtCO₂e of methane produced by mining will be emitted into the atmosphere by 2020, which is expected to account for 8.9%–12.8% of the entire anthropogenic methane emissions [5].

The development of CBM resources can not only cut the natural

emissions of greenhouse gases to ensure full utilization of energy, but also promote safe coal exploitation for reducing natural disasters, such as outburst and spontaneous combustion [6–10]. However, of the CBM resources, most can only be extracted by underground boreholes whereas merely a small part via surface wells owing to inherent geological characteristics (such as large burial depth and low permeability) of Chinese coal seams [11,12]. Therefore, the mechanism of methane migration during underground borehole extraction and the improvement of efficiency and concentration for underground CBM extraction have also become research hotspots for many scholars [13,14].

Two modes of methane migration: seepage and diffusion are mainly

* Corresponding author at: Key Laboratory of Gas and Fire Control for Coal Mines (China University of Mining and Technology), Ministry of Education, Xuzhou 221116, China.
E-mail address: ypcheng@cumt.edu.cn (Y. Cheng).

involved in the process of CBM extraction [15]. The methane within fractures basically exists in a free state whose migration law is widely believed to meet Darcy's law with permeability as an important parameter describing the difficulty degree of its flow. In recent years, models of coal permeability evolution have been established from different perspectives and applied to the study of variation of coal parameters during the extraction. For example, Perera et al. [16] developed a new permeability model based on gas-injecting pressure, gas adsorption and confining pressure. Pan and Connell [17] put forward a revised SD model that considered the effect of coal anisotropy. In consideration of the effect of matrix bridge, Liu and Rutqvist [18] developed a new matchstick model. Besides, the methane within the coal matrix is basically in an adsorbed state. It is generally believed that the methane flows from the matrix into the fracture due to concentration gradient in accordance with Fick's second law of diffusion. At present, major attention is paid on coal diffusion characteristics. According to the uni-pore diffusion theory and Fick's law, Pillalamarri et al. [14] estimated the diffusion coefficient based on modeling experimental data with results revealing a negative correlation between diffusion coefficient and gas pressure. Wang and Liu [19] proposed a new concept of diffusive permeability that could better describe the laws of methane migration. To investigate the effect of moisture on gas diffusion characteristics, Pan et al. [20] conducted an experimental study with some coal samples selected.

Different scholars hold varied views on the master role of diffusion and seepage on CBM production during CBM extraction. Reid et al. [21] argued that permeability was one of the most important factors affecting CBM production in addition to initial desorption pressure and drainage area, while parameters such as adsorption constant, adsorption time and extraction time have comparatively less important effects on CBM production. As the first to propose the relationship between measured in-situ stress value range and permeability, Sparks et al. [22] further studied the impact of in-situ stress on coal permeability and production, drawing a conclusion that for conventional reservoirs, gas-in-place and permeability are two factors of most importance controlling CBM production. Based on the comprehensive analyses of the existing classical permeability model and re-verified assumptions of them, Palmer [13] also deemed that permeability had a crucial influence on CBM production, which was verified by the comparison between the permeability value measured in the in-situ CBM extraction process and that generated by the model. Nevertheless, some scholars held opposite opinions. For example, Pillalamarri [14] experimentally studied the relationship between diffusion coefficient and methane gas pressure in the coal reservoir and estimated the long-term CBM production using the variable diffusion coefficient. The results manifested that for a high-permeability reservoir, the variable diffusion coefficient could function as the principle factor in CBM production, which was verified by the variation law of CBM production of San Juan Basin. Hence, he argued that the view of permeability-controlled CBM production should be re-evaluated. Besides, similar views were also presented in other scholars' studies [23,24]. Wang and Liu [19] established a pressure-dependent diffusive permeability model whose accuracy was validated through experimental data. They considered that diffusion acted as the dominant airflow during the extraction of mature CBM mature wells and its dominance strengthened with the decrease of reservoir pressure. Regarding CBM production as a complex process, Pan et al. [20] believed that the methane production rate was simultaneously controlled by both matrix diffusion and fracture seepage. Based on comprehensive analyses of the above viewpoints, the authors agree with the view that diffusion and seepage simultaneously control the methane production rate during the whole CBM extraction, yet their master roles on CBM-production differ in different extraction stages, which change constantly with the passage of extraction time. Currently, little research has been performed on the master roles of diffusion and seepage on CBM production in different extraction stages. Thus, it is of certain significance for methane production prediction to establish a quantitative

model of master roles of diffusion and seepage on CBM production by using the CBM flow theory. Meanwhile, this quantitative model can be applied to determine the time node of master role conversion of diffusion and seepage on CBM production.

As a crucial factor influencing methane extraction efficiency and concentration [25,26], theoretically speaking, the lower the borehole extraction pressure, the more the methane extracted from the fracture per unit time. However, in actual underground methane extraction project, the lower the pressure, the lower the concentration of methane extracted in the later stage, which results from the air entering the extraction borehole through primary fractures and secondary fractures formed in the drilling process during the extraction since greater amount of air will enter the borehole per unit time when the pressure is lower, causing the decrease in the concentration of methane extracted [27]. At present, for rapid extraction of a large amount of methane to ensure the safety and speed of coal mining, the extraction pressure is commonly set to a relatively small constant value, which contributes to the quick reduction of the methane concentration to an unserviceable concentration limit in the later extraction stage. Generally, the methane extraction system will stop working when methane concentration reaches this limit. Since then, CBM will be emitted directly into the atmosphere, causing serious environmental problems. Therefore, it is a subject worthy of study to put forward a reasonable extraction pressure regulating method which can guarantee both long-term high-concentration methane extraction and its efficiency.

In this study, the methane migration control equation was first proposed, covering the methane diffusion control equation of variable diffusion coefficient and the dynamic permeability evolution model, based on which the theoretical master role conversion model of diffusion and seepage on CBM production was established then and adopted to analyze the time nodes for the master role conversion in coals with different initial permeabilities as well as diffusion coefficients and for diffusion to almost completely master the CBM production. Finally, with the theoretical model taken as a reference, the time-based pressure regulating method was put forward to regulate borehole extraction pressure, ensuring both extraction efficiency and long-term high-concentration methane extraction.

2. Theory

Complex as the structure of natural coal, it is usually simplified as a dual poroelastic medium composed of fractures and matrixes in order to facilitate the study on the migration law of methane within natural coal [28]. During CBM extraction, the adsorbed methane from the matrix diffuses into the fracture at first before transforming into free methane and migrating into the borehole by means of seepage driven by the pressure difference between the fracture system and the extraction borehole. Therefore, all the methane entering the borehole (including both the in-situ free methane and in-situ adsorbed methane) is in a free state, as shown in Fig. 1. The methane migration characteristics are controlled by two key parameters, namely, permeability and diffusion coefficient, of which both change with reservoir methane pressure in the extraction process.

2.1. Assumptions of theory

The methane migration theory and master role conversion model are established on the basis of the following assumptions:

- (1) The coal seam is dry, i.e. The effect of water on methane migration is ignored;
- (2) The CBM reservoir system is isothermal and methane behaves as an ideal gas;
- (3) The CBM reservoir can be regarded as an isotropic, homogeneous and dual poroelastic medium;
- (4) The skeleton of coal is incompressible and the strain is infinitesimal;

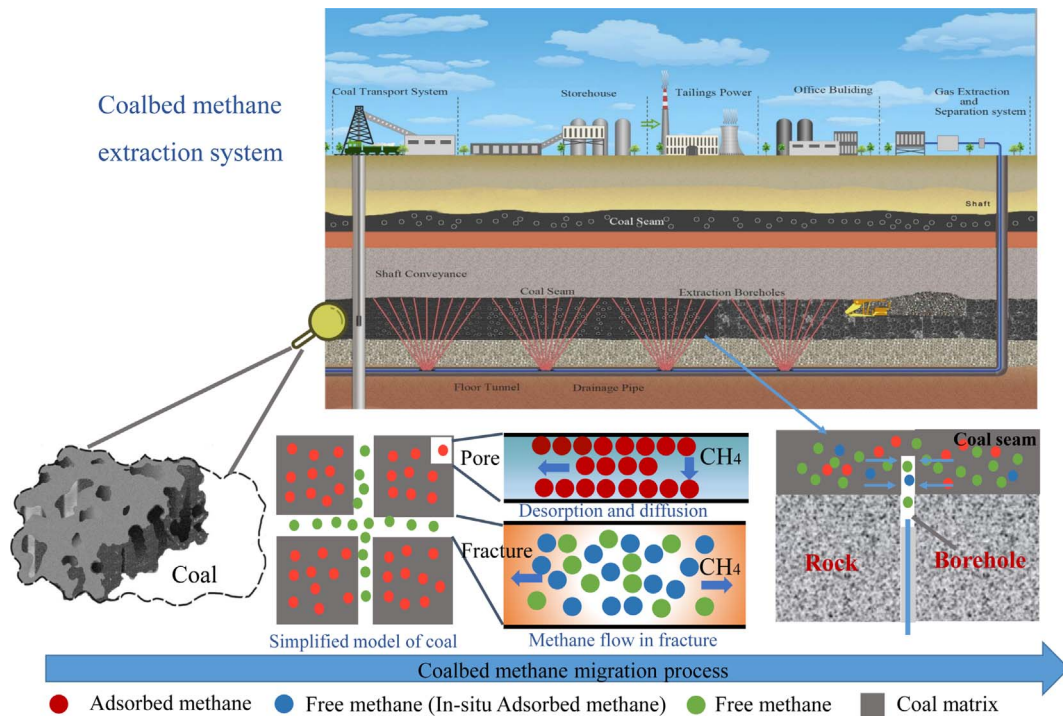


Fig. 1. Coalbed methane migration process of the dual-porosity model.

(5) The adsorbed methane in the matrix all transformed into free methane in the fracture system, and then it flows into the extraction borehole.

As we all know, water in coal plays an important role in CBM production, and moreover, it is uniquely physical phenomena, especially in the matrix of coal [29]. However, due to the underground borehole extraction, rather than drainage wells, adopted for the CBM extraction in this paper, only the suction pressure need to be adjusted (with no need for draining water). Besides, the coal seam was commonly assumed to be dry in order to simplify the establishment of the methane migration model [27,30]. The above reasons prove the reasonability of Assumption (1). In addition, some macro physical parameters of gas, such as gas compressibility factor, MFP and viscosity, are different under the conditions of real and ideal gas [31]. The differences in physical parameters also exert influence on the gas migration model. However, for simplifying the methane migration model, the gas is assumed to be an ideal gas in the CBM reservoir in the establishment of models [32,33].

Assumptions (3) and (4) are common assumptions for establishing a methane migration model. Assumption (5) is specially proposed for the master role conversion model of diffusion and seepage on CBM production. Due to the limited contact area between the extraction borehole and coal, only a trace amount of adsorbed methane within the matrix can directly diffuse into the borehole, which is negligible.

2.2. Evolution of coal permeability and diffusion coefficient

2.2.1. Relationship between fracture aperture and coal permeability

As the main factor affecting the methane seepage capability, coal fracture aperture distributes in a very complicated pattern with various distribution regularities in different coals. Some statistical data of coal fracture aperture distribution extracted from a case study was presented in Fig. 2 [34]. However, factors influencing the fracture aperture are the same during CBM extraction. The fracture aperture is mainly affected by changes of methane pressures within the fracture and within the matrix. On the one hand, the lowering of CBM pressure contributes

to the increase in effective stress of coal, causing the compression of coal structure and then the reduction of fracture aperture; on the other hand, it results in coal matrix desorption and shrinkage deformation that are responsible for the enlargement of fracture aperture. The fracture aperture changes as a result of the two effects [3,35].

The deformation quantity is relatively small for most areas of coal, in the process of effective stress change, while it is huge for a small part of pores or fractures even directly resulting in the fully-closed pores and fractures. In order to deal with the two different deformation conditions, the fracture system of coal is abstracted into two parts for solving the problem of different deformation quantities under the same stress condition [3,36]. Specifically, a part of the fracture system is regarded as the soft part, and the other as the hard part. Different parts follow different Hooke's laws. That is, the hard part meets the engineering strain, while the soft part meets the natural strain.

For the two parts, the strain of fracture aperture can be defined by the engineering-strain and the natural-strain, respectively [37]. The following relations are used:

$$d\epsilon_{a,e} = -\frac{da_e}{a_{0,e}} \tag{1}$$

$$d\epsilon_{a,n} = -\frac{da_n}{a_{0,n}} \tag{2}$$

where $a_{0,e}$ and $a_{0,n}$ are the unstressed fracture aperture for the hard part and the soft part, respectively; a_e and a_n are the fracture aperture for hard part and soft part under current stress state, respectively. Using the conditions $a_e = a_{0,e}$ and $a_n = a_{0,n}$ for $\sigma = 0$, the engineering strain and natural strain can be obtained:

$$a_e = a_{0,e} \left(1 - \frac{\Delta\sigma}{k_e} \right) \tag{3}$$

$$a_n = a_{0,n} \exp \left(-\frac{\Delta\sigma}{k_n} \right) \tag{4}$$

where k_e and k_n are the bulk moduli of the hard part and the soft part of fracture system, respectively.

The above analyses indicate that the change of fracture aperture

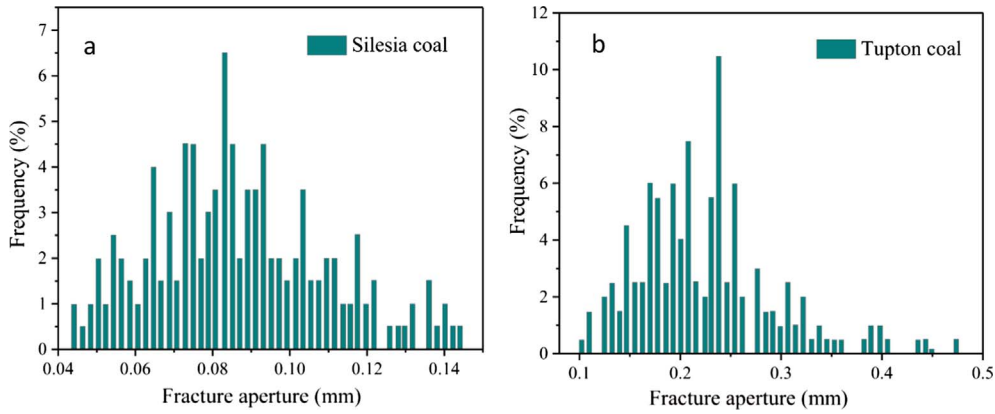


Fig. 2. Distribution of the fracture aperture in coal [34]

equals the sum of natural strain and engineering strain. Moreover, as k_e is several orders of magnitude larger than k_n , the change of fracture aperture under the action of stress is as follow:

$$a_m = a_{0,e} + (a_0 - a_{0,e}) \exp(-\Delta\sigma c_f) \tag{5}$$

where a_m is the fracture aperture change induced by effective stress; a_0 is the initial unstressed fracture aperture; c_f is defined as $c_f = 1/k_n$.

During methane extraction, the coal can be assumed to always maintain a constant load and in a uniaxial strain state [2,13]. Thus, the effective stress change of coal approximately equals the methane pressure change in the reservoir. The fracture aperture change can be expressed as:

$$a_m = a_{0,e} + (a_0 - a_{0,e}) \exp[c_f \beta_f (p_f - p_0) + c_f \beta_m (p_m - p_0)] \tag{6}$$

where p_f and p_m are the methane pressures within the fracture and matrix, MPa; p_0 is the initial methane pressure of coal seam, MPa; β_f and β_m are the effective stress coefficients for the fracture and matrix, respectively.

As the CBM pressure falls below the desorption pressure, the adsorbed methane within the matrix is desorbed and then diffuses into the fracture, with the shrinkage and deformation of coal matrix as a result, thus influencing the size of fracture aperture. The coal temperature is generally assumed to be constant in the process of methane adsorption and desorption, so the volumetric strain induced by the adsorption deformation of coal can be calculated by using the Langmuir isothermal adsorption model [33,38,39]:

$$\varepsilon_{a,s} = \frac{\varepsilon_{\max} p}{p + p_L} \tag{7}$$

where $\varepsilon_{a,s}$ is the sorption-induced volume strain; ε_{\max} is the Langmuir volumetric strain constant; p_L is the Langmuir pressure constant, MPa.

With the assumption that the coal is perfectly elastic and isotropic and the set of setting the fracture spacing as b , when methane pressure within the coal matrix drops from p_0 to p_m , the change of fracture aperture caused by adsorption swelling deformation is:

$$a_s = -\frac{1}{3} b \left(\frac{\varepsilon_{\max} p_m}{p_m + p_L} - \frac{\varepsilon_{\max} p_0}{p_0 + p_L} \right) \tag{8}$$

where a_s is the fracture aperture change induced by the swelling stain.

Combining Eqs. (6) and (8), the fracture aperture can be expressed as:

$$a = a_{0,e} + (a_0 - a_{0,e}) \exp[c_f \beta_f (p_f - p_0) + c_f \beta_m (p_m - p_0)] - \frac{1}{3} b \left(\frac{\varepsilon_{\max} p_m}{p_m + p_L} - \frac{\varepsilon_{\max} p_0}{p_0 + p_L} \right) \tag{9}$$

where a is the fracture aperture.

In fact, the engineering strain of coal is inconsiderable in

comparison with the fracture aperture, so its value almost approximates 0 ($a_{0,e} \ll a_0$, $a_{0,e} \approx 0$). Therefore, Eq. (9) can be simplified as:

$$a = a_0 \exp[c_f \beta_f (p_f - p_0) + c_f \beta_m (p_m - p_0)] - \frac{1}{3} b \left(\frac{\varepsilon_{\max} p_m}{p_m + p_L} - \frac{\varepsilon_{\max} p_0}{p_0 + p_L} \right) \tag{10}$$

Since the coal is simplified as a dual poroelastic cube model whose fracture aperture is far smaller than its fracture spacing, Eq. (11) can be obtained according to the definition of initial porosity of coal:

$$\phi_{f0} = \frac{(a_0 + b)^3 - b^3}{(a_0 + b)^3} \approx \frac{3a_0}{b} \tag{11}$$

where ϕ_{f0} is the initial fracture porosity, %.

Combining Eqs. (10) and (11), the expression of fracture aperture is given below:

$$a = a_0 \exp[c_f \beta_f (p_f - p_0) + c_f \beta_m (p_m - p_0)] - \frac{a_0}{\phi_{f0}} \left(\frac{\varepsilon_{\max} p_m}{p_m + p_L} - \frac{\varepsilon_{\max} p_0}{p_0 + p_L} \right) \tag{12}$$

According to cubic law, the permeability of coal can be expressed as [40]:

$$k = k_0 \left[\exp(c_f \beta_f (p_f - p_0) + c_f \beta_m (p_m - p_0)) - \frac{1}{\phi_{f0}} \left(\frac{\varepsilon_{\max} p_m}{p_m + p_L} - \frac{\varepsilon_{\max} p_0}{p_0 + p_L} \right) \right]^3 \tag{13}$$

where k_0 is the initial permeability of coal, mD; k is the coal permeability, mD.

2.2.2. Empirical equation for dynamic diffusion coefficient

With close relation to pore structure characteristics of coal, the diffusion coefficient is an important parameter reflecting methane diffusion performance. At present, coal particle method is the most widely adopted to test the diffusion coefficient together with the uni-pore model to obtain that under corresponding conditions. Of the most fundamental assumptions of the uni-pore model, one is a constant diffusion coefficient. In fact, the uni-pore model with the assumption of constant diffusion coefficient cannot yield accurate results because the diffusion mode of methane molecules will change inevitably due to the change of methane pressure in the process, and methane adsorption/desorption on coal also has a certain impact on the pore structure. This paper holds that in the study of the process of gas diffusion in the coal matrix, the gas pressure (concentration) within the matrix and gas pressure (concentration) gradients in the fracture system will change with the passage of extraction time, so it is of great significance to establish a Fick's law of variable diffusion coefficient that takes pressure into account. Although the temperature is another important factor that affects the diffusion coefficient [41], its effect on diffusion model can be ignored due to the big size of coal seam and the basically unchanged

coal temperature during the underground extraction boreholes are working [27,32,42].

The original definition of diffusion coefficient states that diffusion coefficient refers to the amount of gas diffusing through a unit area per unit time when the concentration gradient is a unit. Crank [43] regarded it as a variable that changed with multiple parameters, primarily including time, concentration and position. At present, some scholars have carried out a certain research on the effect of time on the diffusion coefficient. However, this paper thinks that it is not appropriate to express the diffusion coefficient as a function of time under the pseudo-steady-state conditions of CBM extraction because diffusion coefficient should essentially result from the interaction between the methane molecular diffusion mode and the pore structure. Therefore, effects of the other two factors on the diffusion coefficient should be taken into consideration, and based on simple analyses, their impacts on the diffusion coefficient of methane are essentially caused by the change of methane pressure in coal reservoir. There have been many studies on the relationship between the reservoir pressure change and the diffusion coefficient. For example, Harpalani [44] concluded from a methane-helium diffusion experiment using a cylindrical coal sample that the change of diffusion coefficient can be described by a simple function with the pressure as a variable. Cui et al. [45] calculated gas diffusion coefficients under different adsorption gas pressure conditions using a bi-disperse diffusion model, finding that diffusivities of gases in the coal matrix decrease significantly with the rise of gas pressure, and the two are negatively correlated. Researches of other scholars also yield similar results [46,47].

Actually, many researchers have estimated the diffusion coefficient by modeling experimental data [14,48,49], as presented in Fig. 3. The diffusion coefficient can be expressed as:

$$D(p_m) = D_0 \exp(-\lambda p_m) \quad (14)$$

where D is the diffusion coefficient, m^2/s ; D_0 is the diffusion coefficient when the methane pressure of coal seam is 0, m^2/s ; λ is attenuation index of diffusion coefficient.

Eq. (14) indicates that the relationship between the diffusion coefficient and the methane pressure in the matrix agrees with the exponential function. For expressions of diffusion coefficients of different coals, the only difference lies in is the attenuation coefficient which is related to pore characteristics of coal. In addition, it is known that methane exists simultaneously in the coal matrix in a free state and an adsorbed state, corresponding to Fick diffusion and surface diffusion, respectively [50,51]; meanwhile, Eq. (14) is an empirical formula obtained by fitting experimental data, so it covers the effect of both Fick diffusion and surface diffusion.

2.3. Interpretation of master role conversion

2.3.1. Methane diffusion in coal matrix

The pore of coal, the major site for methane adsorption, storage and diffusion migration, is one of the main factors affecting methane

diffusion. For different-sized pores, methane diffusion can be classified into three types: molecular diffusion, Knudsen diffusion and surface diffusion [52,53]. In the coal matrix system, when the pore size is considerably larger than or close to the mean free path of gas molecules or smaller than 2 nm, the gas diffusion belongs to molecular diffusion, Knudsen diffusion or surface diffusion, respectively [51]. All types of diffusion are driven by the concentration difference despite the difference in them. For the coal of cube model structure, the rate of methane exchange between matrix and fracture can be expressed as:

$$Q_s = D_0 \exp(-\lambda p_m) \frac{3\pi^2}{b^2} \left(\frac{M_c p_m}{RT} - \frac{M_c p_f}{RT} \right) \quad (15)$$

where Q_s is the methane gas source or sink, that is, the methane exchange rate per volume of matrix blocks, $kg/(m^3 \cdot s)$; M_c is the molar mass of methane, g/mol ; R is the universal gas constant, $J/(mol \cdot K)$; T is the coal seam temperature, K .

Then, the mass conservation equation for methane diffusion in coal matrix can be given:

$$\frac{\partial}{\partial t} \left(\frac{V_L p_m}{p_m + p_L} \frac{M_c}{V_M} \rho_c + \phi_m \frac{M_c}{RT} p_m \right) = -Q_s \quad (16)$$

where V_L is the Langmuir volume constant, m^3/t ; ρ_c is the coal density, kg/m^3 ; ϕ_m is the porosity of coal matrix, %.

2.3.2. Methane seepage law in coal fracture

The magnitude differences of scales of fracture and pore contribute to the huge discrepancy of methane storage and migration. With pressure gradient between external environment and fracture system, methane in the fracture generally migrates in the form of Darcy seepage. Assuming effects of gas gravity to be negligible, the volumetric flow in coal fractures can be defined as:

$$V = -\frac{k}{\mu} \nabla p_f \quad (17)$$

where V is the gas velocity in the fracture, m/s ; and μ is the methane viscosity, $Pa \cdot s$.

For free-phase methane seepage in the coal fracture, the variation of free-phase methane can be expressed by the mass conservation equation for the per unit volume of coal in the unit time [11,42].

$$\frac{\partial}{\partial t} (\rho_g \phi_f) = -\nabla (\rho_g V) + Q_s (1 - \phi_f) \quad (18)$$

where t is the time; ϕ_f is the porosity of the fracture, %; and ρ_g is the methane density, kg/m^3 .

According to the ideal gas law, the relation between methane density and pressure of fracture is described as,

$$\rho_g = \frac{M_c}{RT} p_f \quad (19)$$

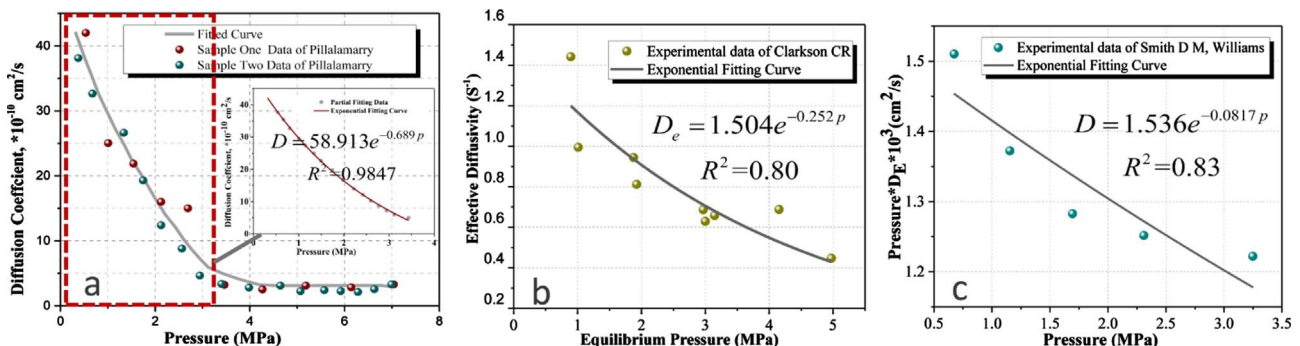


Fig. 3. Variation law of diffusion coefficient with methane pressure [14,48,49].

2.3.3. Description of conversion threshold

Of adsorbed methane, only a trace amount can be directly desorbed before diffusing into the borehole due to the limited contact area between the extraction borehole and coal seam, while the majority transforms into free methane and seeps into the borehole after diffusing from the matrix into the fracture. Therefore, all the methane entering the borehole is in a free state, including not only in-situ free methane, but also free methane converted from in-situ adsorbed methane through desorption and diffusion into the fracture system.

The contributions of in-situ adsorbed methane and in-situ free methane to CBM production are controlled by matrix diffusion and fracture seepage, respectively, which can be analyzed to study the master role of diffusion and seepage on CBM production. The contribution of in-situ adsorbed methane to CBM production can be expressed as:

$$\eta = \frac{m_a}{m_a + m_f} \tag{20}$$

where η represents the proportion of in-situ adsorbed methane mass to the CBM production in time Δt , %; m_a and m_f stand for the mass of extracted in-situ adsorbed methane and in-situ free methane in time Δt . When $\eta < 50\%$, the CBM production can be defined as mainly controlled by seepage; $\eta = 50\%$, it is equally controlled by seepage and diffusion; $\eta > 50\%$, it is mainly controlled by diffusion.

CBM can migrate in the form of seepage and diffusion primarily because of the exertion of extraction pressure on borehole. After extraction pressure is exerted on borehole, the pressure difference between fracture system and borehole is formed in a short time, driving the free methane in the fracture to quickly migrate into borehole. For the matrix system, the methane concentration difference between fracture and matrix systems is formed during the reduction of free methane, which is relatively slower than the process of forming a pressure difference in the fracture system. In the case of small concentration difference, due to the existence of pore throat, the shrinkage channel will function as an energy barrier impeding fluid molecules from diffusing out of the matrix pores, which, however, will be failed if the concentration difference between the matrix inside and outside is too high or if the energy reaches a certain scale [54,55]. Before the concentration difference in the matrix system reaches the diffusion threshold, all the extracted methane is provided by the in-situ free methane in matrix system, that is, $m_a = 0$, then $\eta = 0$. At this time, the CBM production is completely controlled by seepage and, in other words, the seepage capability of coal determines CBM production.

The diffusion of adsorbed methane into the fracture system occurs when the diffusion threshold is reached, making the extracted methane a mixture of in-situ free methane and in-situ adsorbed methane, both of which jointly affect the CBM production. Eq. (20) can be re-expressed as:

$$\begin{cases} \eta = 0, & c_d < c_c \\ \eta = \frac{m_a}{m_a + m_f}, & c_d \geq c_c \end{cases} \tag{21}$$

where c_d is the methane concentration difference between fracture and matrix systems; c_c is that in the matrix when the diffusion threshold is reached.

It can be known from Eq. (16) that at extraction times t and $t + \Delta t$, the masses of methane in the coal matrix per unit volume can be expressed as:

$$m_{at} = \frac{V_L P_m(t)}{P_m(t) + P_L} \frac{M_c}{V_M} \rho_c + \phi_m \frac{M_c}{RT} P_m(t) \tag{22}$$

$$m_{a(t+\Delta t)} = \frac{V_L P_m(t + \Delta t)}{P_m(t + \Delta t) + P_L} \frac{M_c}{V_M} \rho_c + \phi_m \frac{M_c}{RT} P_m(t + \Delta t) \tag{23}$$

where m_{at} and $m_{a(t+\Delta t)}$ represent the mass of methane in the matrix per unit volume when the extraction time is t and $t + \Delta t$, respectively.

Based on Eqs. (22) and (23), the mass of in-situ adsorbed methane

during the whole CBM extraction can be calculated as follow:

$$m_a = \int \int \int_{\Omega} (m_{at} - m_{a(t+\Delta t)}) dv \tag{24}$$

According to Assumption (5), the extracted methane m_{af} consists of the mass of in-situ adsorbed methane m_a and the mass of in-situ free methane m_f :

$$m_{af} = m_a + m_f \tag{25}$$

where m_{af} represents the mass of extracted methane in time Δt .

As can be known from Eq. (18), the masses of methane in the coal fracture system per unit volume at extraction times t and $t + \Delta t$ can be respectively expressed as:

$$m_{ft} = \frac{M_c}{RT} P_f(t) \phi_f(t) \tag{26}$$

$$m_{f(t+\Delta t)} = \frac{M_c}{RT} P_f(t + \Delta t) \phi_f(t + \Delta t) \tag{27}$$

where m_{ft} and $m_{f(t+\Delta t)}$ represent the masses of methane in the fracture per unit volume at extraction times t and $t + \Delta t$, respectively.

From Eqs. (26) and (27), the mass of methane in Δt can be obtained:

$$m_{af} = \int \int \int_{\Omega} (m_{ft} - m_{f(t+\Delta t)}) + m_{at} - m_a(t + \Delta t) dv \tag{28}$$

Combining Eqs. (21), (24) and (28), the proportion η of the mass of in-situ adsorbed methane to the total production in time Δt is can be solved:

$$\eta = \frac{\int \int \int_{\Omega} (m_{at} - m_{a(t+\Delta t)}) dv}{\int \int \int_{\Omega} (m_{ft} - m_{f(t+\Delta t)}) + m_{at} - m_{a(t+\Delta t)} dv} \tag{29}$$

2.4. Methane migration theory verification

Many methane migration theories have been put forward by scholars from different perspectives, which can be used to analyze the evolution laws of pressure and coal permeability. The accuracy of the proposed methane migration theory should be verified before its application. Model results in this paper were compared with some experimental data of coal permeability extracted from core NO. 1 considering only the effect of sorption-induced strain with the impact of effective stress on coal permeability change ignored [3]. The Langmuir volumetric strain constant and the Langmuir pressure constant were set to $\epsilon_{max} = 0.052$ and $P_L = 5.2$ MPa, respectively. The fitting results of coal permeability for coal with different initial porosities are shown in Fig. 4(a) where curves exhibit a high fitting degree.

In the above comparison, the effect of effective stress on the change of coal permeability was ignored. To make up this defect, another set of simulation results from Liu [30] were adopted to verify our model. The new methane migration theory was applied to his geometric model with coal parameters from his paper. The pressure monitoring line ($y = 2.5$, $x \in [20.2 \text{ m}, 40 \text{ m}]$) was set to monitor the change in gas pressure at different drainage times (1 d, 100 d and 500 d). From comparative plots in Fig. 4(b), our results well agree with his.

3. Results and discussion

3.1. Model description and input parameters

Some numerical simulation models were created to study the master role conversion of diffusion and seepage on CBM production as well as the influence of the initial permeability and diffusion coefficient on the time node for master role conversion. From the simplified physical model of coal seam borehole extraction in Fig. 5, thicknesses of the coal seam, the overlying stratum and the underlying stratum were 5 m, 10 m and 10 m, respectively; three extraction boreholes with a radius of 0.1 m were evenly distributed in the coal. To obtain the evolution law

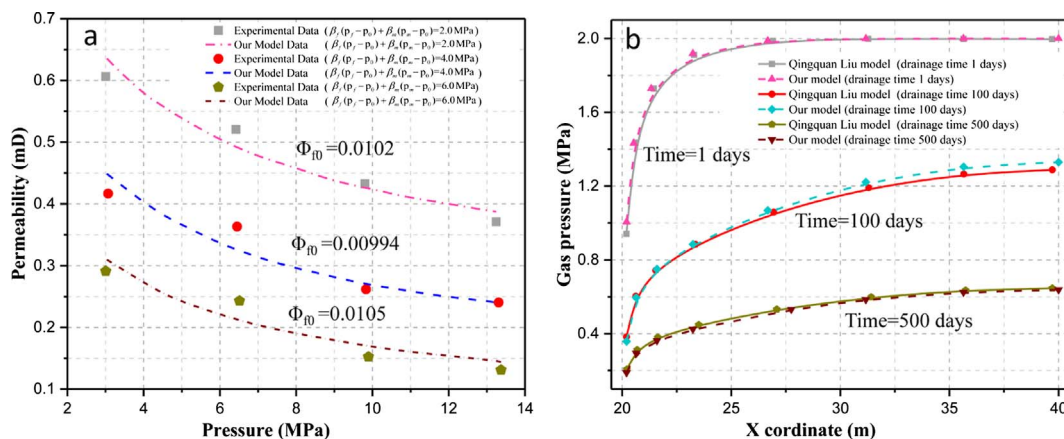


Fig. 4. Comparison of results of different models: (a) coal permeability; (b) methane pressure.

of each parameter during CBM extraction using COMSOL software, boundary conditions of the physical model were set as follows. Left and right sides of the whole model were rollered with the top exposed to constant stress and a fixed-end boundary given to the bottom. Moreover, flow conditions were applied to none of the sides of coal seam. Parameters selected in the numerical simulation are listed in Table 1.

3.2. Master role conversion analyses

The coal seam with evenly distributed methane is extracted under a constant extraction pressure for 500 d, and the production of different forms of methane with varying time is given in Fig. 6. The daily extraction amount of in-situ adsorbed methane is presented in Fig. 6(a). From the variation tendency of the curve in Fig. 6(a), with the passing of time, the methane production soars from the initial low level to a maximum of 2.6 kg/d in a short time. In the initial stage, only a trace amount of in-situ adsorbed methane entering the borehole through the fracture because of the large quantity of in-situ free methane whose rapid reduction contributes to the concentration gradient of methane between fracture and matrix running up quickly. Therefore, more in-situ adsorbed methane is desorbed and diffuses into the fracture and then into the borehole. From the second half of the curve in Fig. 6(a), it can be noticed that the curve exhibits a gradual downward trend after the maximum value is reached and keeps for a while. Owing to the fixed total amount of in-situ adsorbed methane in coal matrix, the concentration gradient of methane between fracture and matrix falls gradually with the influx of a portion of the in-situ adsorbed methane into the borehole, causing the gradual reduction of methane diffusion power in the matrix, as well as the decrease of diffusion amount.

The time-varying daily extraction of free methane is shown in

Table 1
Property parameters used in the numerical simulation model.

Parameter	Value	Reference
Young's modulus of coal, E	2713 MPa	Zhang et al. [33]
Thermodynamic temperature, T	305.15 K	Chen et al. [39]
Young's modulus of coal matrix, E _m	8139 MPa	Zhang et al. [33]
Young's modulus of rock, E _r	24500 MPa	Liu et al. [30]
Density of coal, ρ _c	1250 kg/m ³	Zhang et al. [33]
Density of rock, ρ _r	2500 kg/m ³	An et al. [56]
Methane density at standard conditions, ρ _{ga}	0.717 kg/m ³	Zhang et al. [33]
Universal gas constant, R	8.314 J/(mol*K)	Liu et al. [30]
Langmuir volume constant, V _L	0.027 m ³ /kg	Chen et al. [39]
Langmuir pressure constant, P _L	2.96 MPa	Chen et al. [39]
Langmuir volumetric strain constant, ε _{max}	0.01266	Chen et al. [39]
Initial pressure of coal seam, p ₀	3 MPa	Self-defining value
Initial pressure of extraction boreholes, p _n	88 kPa	Dong et al. [27]
Passion's ratio of coal, ν	0.35	Chen et al. [39]
Initial fracture porosity of fractures, Φ _f	0.012	An et al. [56]
Initial porosity of coal matrix, Φ _m	0.06	An et al. [56]
Initial gas permeability, k ₀	0.02 mD	Dong et al. [27]
Diffusion coefficient, D ₀	5.89 * 10 ⁻¹³ m ² /s	Mallikarjun Pillalamarry [14]
Attenuation index of diffusion coefficient, λ	0.689	Mallikarjun Pillalamarry [14]
Molar mass of methane, M _c	0.016 kg/mol	An et al. [56]
Dynamic viscosity of methane, μ	1.84 * 10 ⁻⁵ Pa*s	Chen et al. [39]
In situ stress, F	6 MPa	Liu et al. [30]
Coal cleat compressibility, c _f	0.29 MPa ⁻¹	Chen et al. [39]

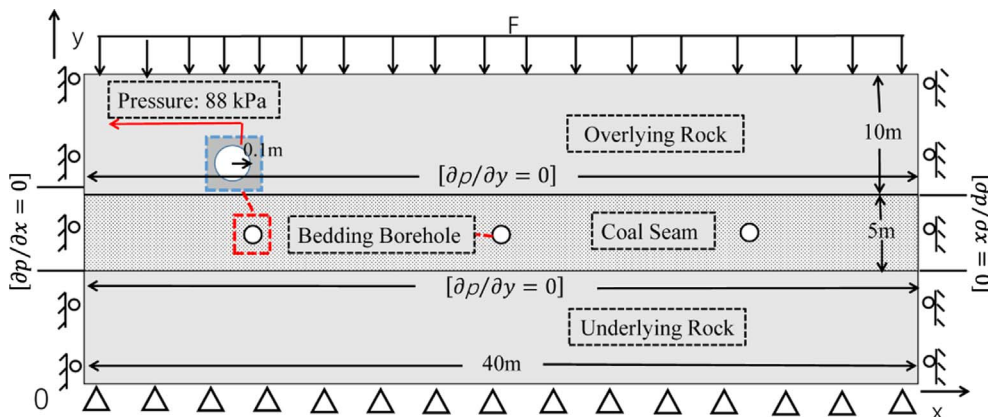


Fig. 5. Physical models and solution boundary conditions of coal seam and rock formation.

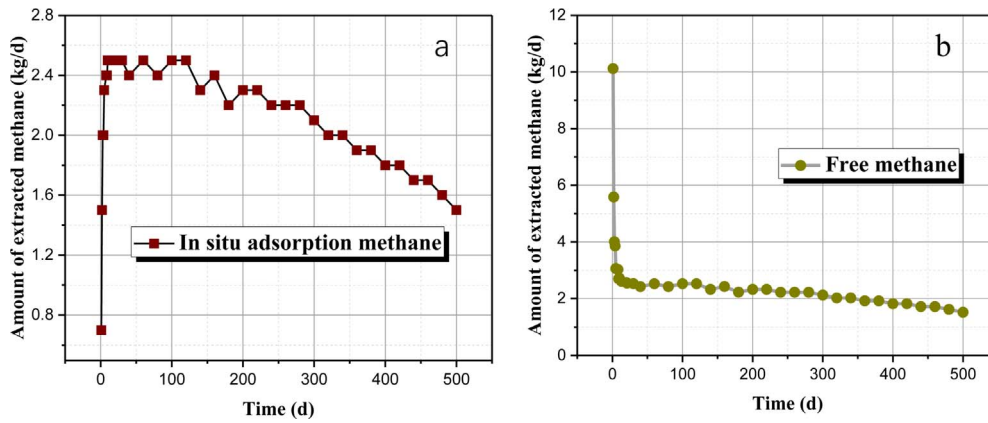


Fig. 6. Productions of different forms of methane at different moments.

Fig. 6(b). It is noteworthy that the production of free methane is the sum of in-situ adsorbed methane and in-situ free methane extracted because all the extracted methane is free due to the transformation of the in-situ adsorbed methane into the free state in the process of diffusing into fractures and then passing into the borehole via fractures. The variation tendency of methane production curve in Fig. 6(b) reflects that the free methane production has reached a maximum of 10.12 kg/d in the initial stage but slumps with the passage of time and ultimately stabilizes at about 2 kg/d. The analyses reveals that the variation tendency of methane production curve is mainly caused by the large yet limited amount of initial in-situ free methane in the fracture, of which most can seep into the borehole in a short time, leading to a rapidly declining curve, and the relatively stable methane diffusion in the matrix contributing to the stable methane production in middle and late stages.

The time-varying productions of different forms of methane have been elaborated in the above part. To analyze master role conversion of diffusion and seepage on CBM production, the master role conversion theory was applied to productions of different forms of methane. The time-varying proportion of in-situ adsorbed methane production to the total production is shown in Fig. 7, from which it can be known that the production of in-situ adsorbed methane amounts to 50% of total production after 3 day’s CBM extraction, that is, methane production is primarily controlled by seepage in the first 3 d and by diffusion in the later period, according to the master role conversion theory. The curve in Fig. 7 also illustrates that the production of in-situ adsorbed methane reaches 99% of total yield and stabilizes at this amount when the extraction time reaches 30 d, indicating that methane production is almost completely controlled by diffusion in middle and late stages and

the contribution of in-situ free methane to the total yield is negligible.

3.3. Effect of initial coal permeability on conversion node

In the process of methane extraction, the initial permeability of coal exerts significant influence on the dynamic variation of permeability that affects both methane seepage migration in the fracture and methane diffusion in the matrix, thus having impact on the time node for master role conversion of seepage and diffusion on methane production. To study the effect of initial permeability on conversion node, numerical models of different initial permeability were established. According to the master role conversion theory of diffusion and seepage on methane production, the conversion nodes for different initial permeability models were calculated (the initial permeability from 0.002 mD to 1 mD), for example, the time node when the production of in-situ adsorbed methane accumulates to 50% of the total production, as shown in Fig. 8. From the variation tendency of conversion node curve, the larger the initial permeability, the earlier the time node for diffusion to hold dominant position. Meanwhile, Fig. 8 also indicates that the time periods for seepage to play the master role are 1.5 d and 4.6 d corresponding to the initial coal permeability of 1 mD and 0.002 mD, respectively. The comparison of the time for master role conversion with the whole extraction period suggests the brief time for seepage to control the methane production during the extraction of coals with different initial permeabilities. This primarily results from the smaller amount of in-situ free methane compared with that of total CBM production, and the quick migration of large quantities of in-situ free methane into the borehole in the early extraction stage.

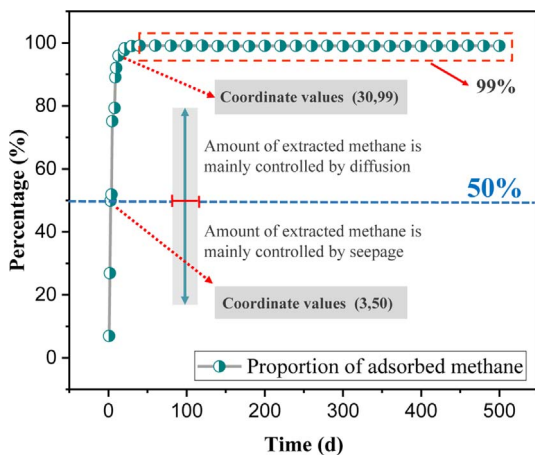


Fig. 7. Proportion of in-situ adsorbed methane production to total production at different moments.

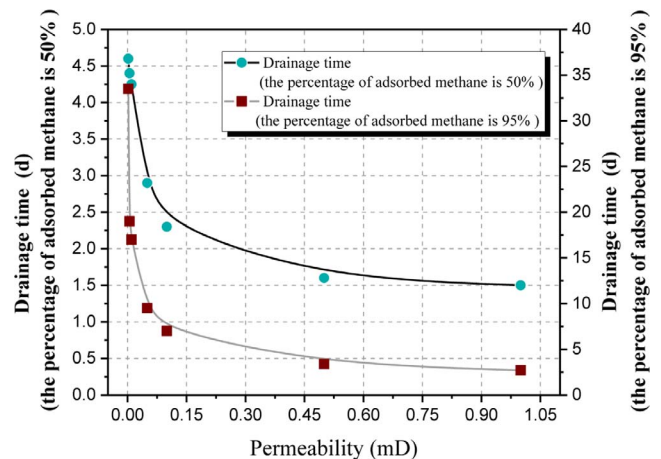


Fig. 8. Time for in-situ adsorbed methane production to reach 50% and 95% of total production of coal with different initial permeabilities.

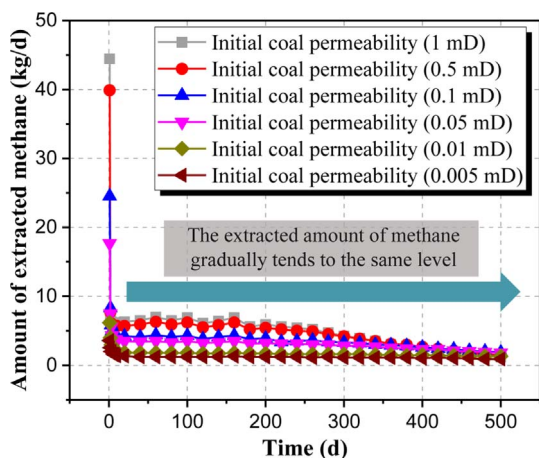


Fig. 9. Daily CBM production of coal with different initial permeabilities.

To further illustrate the effect of diffusion on CBM production in the CBM extraction period, it is defined that CBM production is almost completely controlled by diffusion when the in-situ adsorbed methane production exceeds 95% of total production. Fig. 8 shows the time when the methane production of coals with different initial permeabilities are completely controlled by diffusion. As shown in Fig. 8, methane productions are fully under the control of diffusion on 2.7 d and 33.5 d, corresponding to initial permeabilities of 1 mD and 0.002 mD, respectively. Compared with the whole extraction period, methane production is completely subjected to the control of diffusion for a long term.

Apart from the quantitative description of effects of diffusion and seepage on methane production in the above part by using master role conversion theory, master role conversion can also be explained qualitatively through changes of daily methane production of coals with different initial permeabilities. From the time-varying curve of daily methane production in Fig. 9, it is evident that the higher the initial permeability, the greater the daily production in the initial stage. For the coal of initial permeability of 1 mD and 0.005 mD, the maximum methane production is 44.5 kg/d and 3.6 kg/d, respectively, which mainly results from different initial permeabilities. Methane production is primarily controlled by seepage in the early extraction stage, and higher initial permeability is conducive to the extraction of more abundant in-situ free methane and thus the greater methane production at the preliminary stage. However, Fig. 9 suggests that the daily methane production of coals with different initial permeabilities are close to reach the same level in the later stage, basically maintaining 1–1.5 kg/d, which is mainly ascribed to the same diffusion coefficient D_0 in models of different initial permeabilities. Due to the little difference in diffusion coefficient in the later extraction stage, there are slight discrepancies between amounts of methane diffusion in the matrix in the same time, proving that CBM production is mainly controlled by diffusion in the later extraction stage.

3.4. Effect of diffusion coefficient on conversion node

Just as permeability, the dynamic change of diffusion coefficient also has an impact on methane seepage migration in the fracture and methane diffusion in the matrix, thus affecting the time node for master role conversion of seepage and diffusion on methane production. The conversion node for models of different D_0 (diffusion coefficient from $1 \times 10^{-13} \text{ m}^2/\text{s}$ to $5 \times 10^{-9} \text{ m}^2/\text{s}$) is solved in accordance with the master role conversion theory to study the effect of D_0 on the node, as exhibited in Fig. 10. It can be observed from Fig. 10 that the larger the D_0 , the earlier the conversion node when diffusion plays the master role in methane production. When D_0 is $1 \times 10^{-13} \text{ m}^2/\text{s}$ and $5 \times 10^{-9} \text{ m}^2/\text{s}$, the corresponding conversion node is 10.85 d and 0.46 d, respectively.

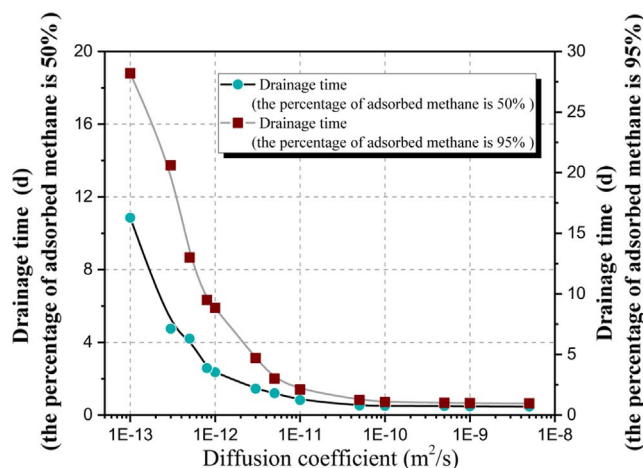


Fig. 10. Time for in-situ adsorbed methane production to reach 50% and 95% of total production of coal with different D_0 .

The higher the D_0 is, the larger the amount of in-situ adsorbed methane that is desorbed and diffuses into the fracture per unit time, thus the earlier the time node for diffusion to play the master role due to the same amount of in-situ free methane in the fracture.

Similarly, the CBM production is defined as almost completely subjected to diffusion when the production of in-situ adsorbed methane exceeds 95% of the total yield in order to analyze the effect of diffusion on methane production in the whole extraction process. Fig. 10 presents the time node for diffusion fully masters the methane production corresponding to models of different D_0 . Based on Fig. 10, the larger the D_0 , the earlier the conversion time node for diffusion to play the master role on CBM production. For example, the methane production is totally controlled by diffusion on 28.2 d and 0.96 d corresponding to the D_0 of $1 \times 10^{-13} \text{ m}^2/\text{s}$ and $5 \times 10^{-9} \text{ m}^2/\text{s}$, respectively. In comparison with the whole extraction cycle, diffusion has long control of methane production.

To further illustrate different roles that diffusion and seepage play in controlling CBM production in various time during the whole extraction period, the time-varying curve of daily methane production is plotted by solving different models of D_0 , as shown in Fig. 11. From Fig. 11, when D_0 is $5 \times 10^{-9} \text{ m}^2/\text{s}$ and $1 \times 10^{-10} \text{ m}^2/\text{s}$, the initial methane production is large with a maximum of 20.91 kg/d and 14.99 kg/d, respectively, because a great amount of in-situ adsorbed methane gets desorbed and diffuses into the fracture and then into the borehole due to the extremely large D_0 in the early stage. The aforementioned analyses suggest that under such diffusion coefficient condition, diffusion exerts a major influence on methane production in a short time.

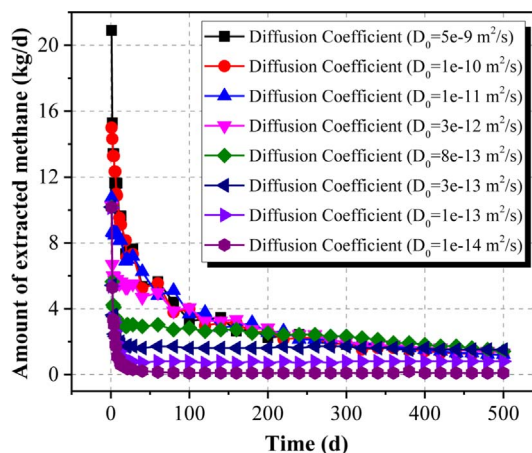


Fig. 11. Daily methane production of coal with different D_0 .

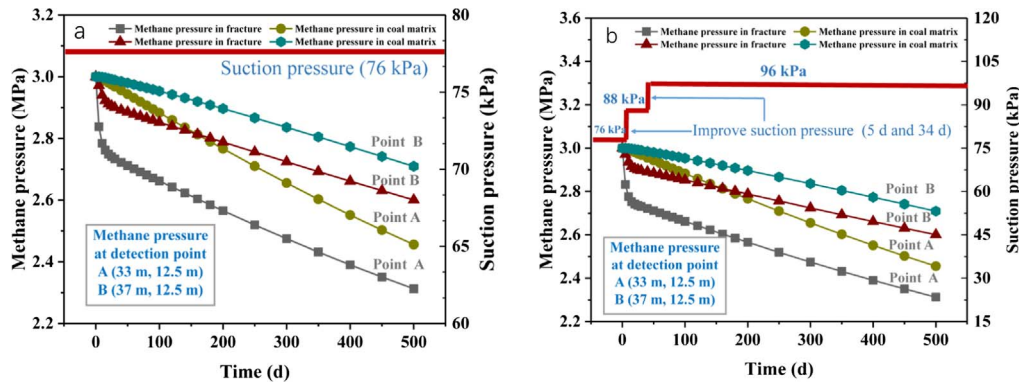


Fig. 12. Matrix and fracture methane pressures at monitoring points corresponding to different given pressure regulating method.

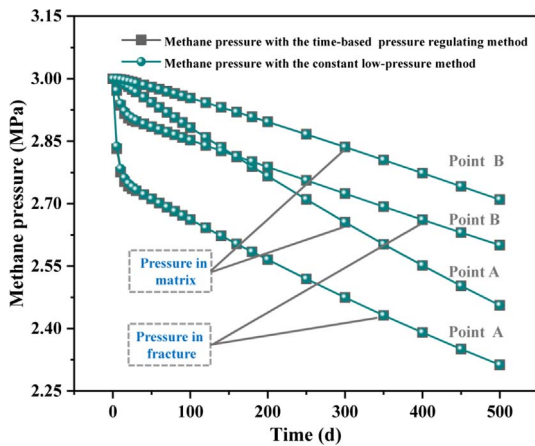


Fig. 13. Comparison of methane pressure distribution using different given pressure regulating method.

However, when D_0 is given other hugely varied values, the initial daily methane production basically maintains about 10 kg/d without any significant difference. As the methane production is mainly controlled by seepage in the early stage, the initial methane production is basically consistent because of the same amount of in-situ free methane due to the identical initial permeabilities of models with different D_0 . However, obvious differences can be observed in Fig. 11 in methane production of coals with different D_0 in the later stage. The greater the D_0 , the larger the daily methane production in the later stable stage, indicating that the methane production is mainly controlled by diffusion in this stage.

3.5. Implication for adjusting suction pressure

Because of the difficulty to extract CBM by surface boreholes caused by the deep location and low permeability of the majority of China's coal seams in addition to the failure of daily production of most extraction boreholes to reach the standard of industrial production, at present, China's CBM recovery primarily depends on underground boreholes where the exertion of extraction pressure through the boreholes is an important procedure. The values of pressure are generally set within the range of 0–101 kPa which is below atmospheric pressure, so as to ensure continuous entrance of methane into borehole, which is driven by the pressure difference between extraction pressure and methane gas pressure in the fracture. The continuous seepage of methane into the borehole results in the pressure difference between the fracture and the matrix, driving diffusion of methane from the matrix into the fracture. This is a complete process of methane migration.

Generally, the lower the extraction pressure, the larger the methane production per unit time, and the greater the amount of air flowing into

the borehole. The imperfectly sealed borehole, as well as some primary fractures and construction-induced secondary fractures, allows air to enter the borehole. The air flowing into the borehole has no decisive effect on methane concentration in the early stage owing to the large methane production, yet it dramatically lowers the concentration of extracted methane in middle and late stages of extraction because its amount remains unchanged while the methane production drops significantly. According to general rules, CBM companies have to stop the extraction of methane when the methane concentration drops to 6%, because economic losses will be caused by further extraction since the low-concentration methane is of no industrial value. If the borehole were given high pressure in the early stage, although a high methane concentration could be guaranteed, the efficient safe extraction would not be ensured, if the amount of CBM could not be reduced rapidly, which seriously delays the mining project. After weighing pros and cons of the two, companies generally take a small constant value as the extraction pressure.

This traditional method is still adopted for setting borehole extraction pressure for lack of an appropriate method that can ensure both the extraction efficiency and the methane concentration. Actually, analyses reveal that the efficiency mainly depends on the early-stage extraction while the concentration relies on the later-stage extraction. Therefore, the problem can be solved by ensuring the extraction efficiency in the early stage and the methane concentration in the later stage. Both of them are closely related to extraction pressure. The smaller the value of pressure, the higher the extraction efficiency, the lower the methane concentration; and vice-versa [57,58]. To solve this problem, this paper proposes a simple and effective extraction pressure regulating method, namely, the time-based pressure regulating method which means exerting various numerical pressures to the borehole in different stages. The value is set to be small in the initial stage to improve the extraction efficiency and large in the later stage to raise the methane concentration by preventing air from flowing into the borehole.

The key to the time-based pressure regulating method is to determine the time node for pressure regulation, which can be guided by the master role conversion theory of diffusion and seepage on methane production. In the extraction process, there are two important conversion nodes that can be applied for regulating the pressure. One is the time node for master role conversion of seepage and diffusion ($\eta = 50\%$), and the other is the time node for diffusion to almost completely master methane production ($\eta = 95\%$). To study the effect of time-based pressure regulating method, the model with the initial permeability $k_0 = 0.002$ mD and the diffusion coefficient $D_0 = 5.89 \times 10^{-13}$ m²/s is chosen as the research object to be extracted for 500 d under constant pressure (76 kPa) and time-based pressure (76 kPa, 88 kPa and 96 kPa), respectively, and the time in accordance with time-based pressure regulating method is: 0–5 d, 5–34 d and 34–500 d. Methane pressures of monitoring points A (33 m, 12.5 m)

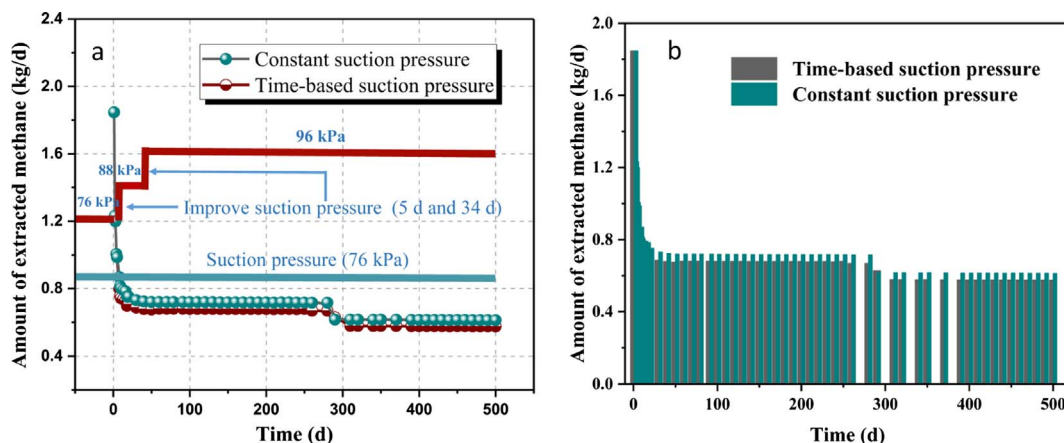


Fig. 14. Daily methane production with different types of extraction pressure regulating method.

and B (37 m, 12.5 m) and daily methane production in different time are extracted separately, as shown in Figs. 12 and 14. As can be observed from Fig. 12, by time-based pressure regulating method, about 93% of extraction period is in the stage of high-pressure which can guarantee higher concentration of methane production compared with the low-pressure method [27,57,58], and thus the relatively high concentration of methane in middle and late stages can be ensured.

In addition, Figs. 13 and 14 also present that the pressure values of monitoring points and the amount of daily methane production obtained by time-based pressure regulating method basically agree with those of the coal seam obtained by constant low-pressure method. Thus, it is concluded that the time-based pressure regulating method has an extremely slight impact on the extraction effect and CBM production. Compared with the constant low-pressure extraction method, the time-based pressure regulating method can not only ensure the extraction efficiency, but also raise the concentration of extracted methane. The above analyses prove that it is reasonable and effective to guide time-based pressure regulation by master role conversion theory of diffusion and seepage on methane production.

4. Conclusions

This paper obtained the migration characteristics of methane diffusion and seepage based on the dynamic diffusion coefficient and permeability model, and then it established the theoretical master role conversion model of diffusion and seepage on CBM production according to contributions of different forms of methane to total production. The primary research is carried out on the master role conversion and daily methane production of coals with different initial permeabilities and diffusion coefficients. Besides, it also took into account the given pressure regulating method for borehole extraction. Based on the above work, the main conclusions are drawn as follows:

- (1) During CBM extraction, the diffusion coefficient and permeability both change depending on methane pressure in the reservoir. Specifically, the change of diffusion coefficient results from the variations of gas concentration and position, while that of permeability is mainly induced by fracture aperture. Taking dynamic diffusion coefficient and dynamic permeability into account, the methane migration model proposed in this paper can describe the CBM migration law more faithfully and more effectively.
- (2) The initial permeability and diffusion coefficient of coal not only affect the methane migration law, but also influence the time nodes for the master role conversion of diffusion or seepage on CBM production and for diffusion to almost completely control CBM production. Moreover, the larger the initial permeability and diffusion coefficient, the earlier the master role conversion. The same

conclusion is also applicable to the time node when the production is under the full control of diffusion. The change curves of daily methane productions of coals with different initial permeabilities or diffusion coefficients indicate that the production is primarily controlled by seepage and diffusion in the early and later stage of extraction, respectively.

- (3) The value of borehole extraction pressure affects the extraction efficiency and methane concentration. The lower the extraction pressure, the greater the amounts of methane and air entering the borehole per unit time. In the later extraction stage, the concentration of methane extracted drops sharply, because the amount of methane entering the borehole is smaller while that of air is unchanged. To raise the concentration of methane extracted, the traditional constant low-pressure extraction method is replaced by the time-based pressure regulating method to witness the coal can stay in a low-pressure state and relatively high-pressure state in the early and later stage of extraction, respectively. The experimental results suggest that this new method can effectively raise the concentration of methane extracted without lowering the efficiency of methane extraction.

Acknowledgements

The authors are grateful to the Fundamental Research Funds for the Central Universities (2017XKZD01) and the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD).

References

- [1] Clarkson CR, Mcgovern JM. Optimization of coalbed-methane-reservoir exploration and development strategies through integration of simulation and economics. *SPE Reservoir Eval Eng* 2005;8(6):502–19.
- [2] Pan Z, Connell LD. Modelling permeability for coal reservoirs: a review of analytical models and testing data. *Int J Coal Geol* 2012;92:1–44.
- [3] Chen Z, Liu J, Pan Z, Connell LD, Elsworth D. Influence of the effective stress coefficient and sorption-induced strain on the evolution of coal permeability: model development and analysis. *Int J Greenhouse Gas Control* 2012;8(5):101–10.
- [4] Olivier JGJ, Aardenne JAV, Dentener FJ, Pagliari V, Ganzeveld LN, Peters JAHW. Recent trends in global greenhouse gas emissions: regional trends 1970–2000 and spatial distribution of key sources in 2000. *Environ Sci* 2005;2(2–3):81–99.
- [5] Team CW, Pachauri R, Reisinger A. Contribution of working groups I, II and III to the fourth assessment report of the intergovernmental panel on climate change. Geneva, Switzerland: IPCC; 2007.
- [6] Fan C, Li S, Luo M, Du W, Yang Z. Coal and gas outburst dynamic system. *Int J Mining Sci Technol* 2017;27(1):49–55.
- [7] Cheng W, Hu X, Xie J, Zhao Y. An intelligent gel designed to control the spontaneous combustion of coal: fire prevention and extinguishing properties. *Fuel* 2017;210:826–35.
- [8] Shi Q, Qin B, Liang H, Gao Y, Bi Q, Qu B. Effects of igneous intrusions on the structure and spontaneous combustion propensity of coal: a case study of bituminous coal in Daxing Mine, China. *Fuel* 2018;216:181–9.
- [9] Bruce H, Jim G. A review of the geomechanics aspects of a double fatality coal burst at Austar Colliery in NSW, Australia in April 2014. *Int J Mining Sci Technol*

- 2017;27(1):3–7.
- [10] Cheng W-M, Hu X-M, Zhao Y-Y, Wu M-Y, Hu Z-X, Yu X-T. Preparation and swelling properties of poly (acrylic acid-co-acrylamide) composite hydrogels. *e-Polymers* 2017;17(1):95–106.
- [11] Liu Z, Cheng Y, Liu Q, Jiang J, Li W, Zhang K. Numerical assessment of CMM drainage in the remote unloaded coal body: insights of geostress-relief gas migration and coal permeability. *J Nat Gas Sci Eng* 2017;45:487–501.
- [12] Si L, Li Z, Xue D, Zhou J, Yang Y, Zhou Y. Modeling and application of gas pressure measurement in water-saturated coal seam based on methane solubility. *Transp Porous Media* 2017;2:1–17.
- [13] Palmer I. Permeability changes in coal: analytical modeling. *Int J Coal Geol* 2009;77(1):119–26.
- [14] Pillalamarri M, Harpalani S, Liu S. Gas diffusion behavior of coal and its impact on production from coalbed methane reservoirs. *Int J Coal Geol* 2011;86(4):342–8.
- [15] Izadi G, Wang S, Elsworth D, Liu J, Wu Y, Pone D. Permeability evolution of fluid-infiltrated coal containing discrete fractures. *Int J Coal Geol* 2011;85(2):202–11.
- [16] Perera MSA, Ranjith PG, Choi SK. Coal cleat permeability for gas movement under triaxial, non-zero lateral strain condition: a theoretical and experimental study. *Fuel* 2013;109(7):389–99.
- [17] Pan Z, Connell LD. Modelling of anisotropic coal swelling and its impact on permeability behaviour for primary and enhanced coalbed methane recovery. *Int J Coal Geol* 2011;85(3):257–67.
- [18] Liu HH, Rutqvist J. A new coal-permeability model: internal swelling stress and fracture-matrix interaction. *Transp Porous Media* 2010;82(1):157–71.
- [19] Wang Y, Liu S. Estimation of pressure-dependent diffusive permeability of coal using methane diffusion coefficient: laboratory measurements and modeling. *Energy Fuels* 2016;30(11).
- [20] Pan Z, Connell LD, Camilleri M, Connelly L. Effects of matrix moisture on gas diffusion and flow in coal. *Fuel* 2010;89(11):3207–17.
- [21] Ried G, Towler B, Harris H. Simulation and economics of coalbed methane production in the Powder River Basin: SPE rocky mountain regional meeting. Society of Petroleum Engineers; 1992.
- [22] Sparks D, McLendon T, Saulsberry J, Lambert S. The effects of stress on coalbed reservoir performance, Black Warrior Basin, USA. SPE annual technical conference and exhibition. Society of Petroleum Engineers; 1995.
- [23] Gilman A, Beckie R. Flow of coal-bed methane to a gallery. *Transp Porous Media* 2000;41(1):1–16.
- [24] Zuber M, Sawyer W, Schraufnagel R, Kuuskraa V. The use of simulation and history matching to determine critical coalbed methane reservoir properties. Low permeability reservoirs symposium. Society of Petroleum Engineers; 1987.
- [25] Hyman DM. A review of the mechanisms of gas outbursts in coal. US Department of the Interior, Bureau of Mines; 1987.
- [26] Karacan CÖ, Ruiz FA, Cotè M, Phipps S. Coal mine methane: a review of capture and utilization practices with benefits to mining safety and to greenhouse gas reduction. *Int J Coal Geol* 2011;86(2):121–56.
- [27] Dong J, Cheng Y, Jin K, Zhang H, Liu Q, Jiang J, et al. Effects of diffusion and suction negative pressure on coalbed methane extraction and a new measure to increase the methane utilization rate. *Fuel* 2017;197:70–81.
- [28] Valliappan S, Wohua Z. Numerical modeling of methane gas migration in dry coal seams. *Int J Numer Anal Meth Geomech* 2015;20(8):571–93.
- [29] Wu K, Chen Z, Li J, Li X, Xu J, Dong X. Wettability effect on nanoconfined water flow. *Proc Natl Acad Sci* 2017;114(13):3358–63.
- [30] Liu Q, Cheng Y, Zhou H, Guo P, An F, Chen H. A mathematical model of coupled gas flow and coal deformation with gas diffusion and Klinkenberg effects. *Rock Mech Rock Eng* 2015;48(3):1163–80.
- [31] Wu K, Chen Z, Li X, Xu J, Li J, Wang K, et al. Flow behavior of gas confined in nanoporous shale at high pressure: real gas effect. *Fuel* 2017;205:173–83.
- [32] Xia T, Zhou F, Liu J, Hu S, Liu Y. A fully coupled coal deformation and compositional flow model for the control of the pre-mining coal seam gas extraction. *Int J Rock Mech Min Sci* 2014;72:138–48.
- [33] Zhang H, Liu J, Elsworth D. How sorption-induced matrix deformation affects gas flow in coal seams: a new FE model. *Int J Rock Mech Min Sci* 2008;45(8):1226–36.
- [34] Mazumder S, Wolf KHAA, Elewaut K, Ephraim R. Application of X-ray computed tomography for analyzing cleat spacing and cleat aperture in coal samples. *Int J Coal Geol* 2006;68(3–4):205–22.
- [35] Liu J, Chen Z, Elsworth D, Miao X, Mao X. Evaluation of stress-controlled coal swelling processes. *Int J Coal Geol* 2010;83(4):446–55.
- [36] Berryman JG. Estimates and rigorous bounds on pore-fluid enhanced shear modulus in poroelastic media with hard and soft anisotropy. *Int J Damage Mech* 2005;15(2):133–67.
- [37] Jaeger JC, Cook NG, Zimmerman R. Fundamentals of rock mechanics. John Wiley & Sons; 2009.
- [38] Harpalani S, Schraufnagel A. Measurement of parameters impacting methane recovery from coal seams. *Int J Mining Geol Eng* 1990;8(4):369–84.
- [39] Chen D, Pan Z, Liu J, Connell LD. An improved relative permeability model for coal reservoirs. *Int J Coal Geol* 2013;109–110(2):45–57.
- [40] Chilingar GV. Relationship between porosity, permeability, and grain-size distribution of sands and sandstones. *Dev Sedimentol* 1964;1:71–5.
- [41] Wu K, Chen Z, Li X. Real gas transport through nanopores of varying cross-section type and shape in shale gas reservoirs. *Chem Eng J* 2015;281(281):813–25.
- [42] Liu Q, Cheng Y, Wang H, Zhou H, Wang L, Li W, et al. Numerical assessment of the effect of equilibration time on coal permeability evolution characteristics. *Fuel* 2015;140(8):81–9.
- [43] Crank J. The mathematics of diffusion. Oxford University Press; 1979.
- [44] Harpalani S, Ouyang S. A new laboratory technique to estimate gas diffusion characteristics of naturally fractured reservoirs. 2nd North American rock mechanics symposium. American Rock Mechanics Association; 1996.
- [45] Cui X, Bustin RM, Dipple G. Selective transport of CO₂, CH₄, and N₂ in coals: insights from modeling of experimental gas adsorption data. *Fuel* 2004;83(3):293–303.
- [46] Busch A, Gensterblum Y, Krooss BM, Littke R. Methane and carbon dioxide adsorption-diffusion experiments on coal: upscaling and modeling. *Int J Coal Geol* 2004;60(2–4):151–68.
- [47] Saghaei A, Faiz M, Roberts D. CO₂ storage and gas diffusivity properties of coals from Sydney Basin, Australia. *Int J Coal Geol* 2007;70(1–3):240–54.
- [48] Clarkson CR. The effect of coal composition, moisture content, and pore volume distribution upon single and binary gas equilibrium and nonequilibrium adsorption: implications for gas content determination. University of British Columbia; 1998.
- [49] Smith D, Williams F. Diffusional effects in the recovery of methane from coalbeds. *Soc Petrol Eng J* 1984;24(24):529–35.
- [50] Wu K, Li X, Guo C, Wang C, Chen Z. A unified model for gas transfer in nanopores of shale-gas reservoirs: coupling pore diffusion and surface diffusion. *SPE J* 2016;21(05):1583–611.
- [51] Wu K, Li X, Wang C, Yu W, Chen Z. Model for surface diffusion of adsorbed gas in nanopores of shale gas reservoirs. *Ind Eng Chem Res* 2015;54(12):2079–88.
- [52] Mason EA, Malinauskas A. Gas transport in porous media: the dusty-gas model. Elsevier Science Ltd; 1983.
- [53] Krishna R, Wesselingh JA. The Maxwell-Stefan approach to mass transfer. *Chem Eng Sci* 1997;52(6):861–911.
- [54] Bae JS, Bhatia SK, Rudolph V, Massarotto P. Pore accessibility of methane and carbon dioxide in coals. *Energy Fuels* 2009;23(6):3319–27.
- [55] Monin JC, Barth D, Perrut M, Espitalié M, Durand B. Extraction of hydrocarbons from sedimentary rocks by supercritical carbon dioxide. *Org Geochem* 1988;13(4):1079–86.
- [56] An FH, Cheng YP, Wang L, Li W. A numerical model for outburst including the effect of adsorbed gas on coal deformation and mechanical properties. *Comput Geotech* 2013;54(10):222–31.
- [57] Clark D, Battino S, Lunarzewski L. Prevention and control of outbursts by pre-drainage of seam gas at Metropolitan colliery – a review. Alleviation of coal and gas outbursts in coal mines-seminar 3; 1983.
- [58] Black DJ. Factors affecting the drainage of gas from coal and methods to improve drainage effectiveness. *Sports Biomech* 2011;13(2):123–34.