Fuel 230 (2018) 298–307

Contents lists available at ScienceDirect

Fuel

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

Full Length Article

Analysis of coal permeability rebound and recovery during methane extraction: Implications for carbon dioxide storage capability assessment

Zhengdong Liu[a,b,c], Yuanping Cheng[a,b,c,*], Liang Wang[a,b,c], Haifeng Wang[a,b,c], Jingyu Jiang[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:
CBM extraction
CO_2 storage
Energy utilization
Permeability
Internal swelling coefficient

ABSTRACT

Coal permeability rebound and recovery severely affect the efficiency of coalbed methane extraction and CO_2 storage capability of coal seams, but theoretical research on it is insufficient now. Besides, ambiguity still remains in evolution laws of coal permeability rebound and recovery pressure with the change of various influencing factors. In this work, the focus is first placed on the influences of effective stress (considering engineering-strain and natural-strain) and adsorption-induced swelling (considering matrix bridge) on fracture aperture; then, a new evolution model of coal fracture aperture is established by adopting the competition mechanism of the two. At the same time, based on the correlation between the variation of fracture aperture and permeability using the classical cubic law, the evolution model of coal permeability is set up, of which is on the basis together with some reasonable assumptions to obtain the factors influencing permeability rebound and the recovery pressure. The evolution laws of coal permeability rebound and recovery under the influence of main factors are in detailed analysis. Specifically, permeability rebounds and recovers when the initial coal reservoir pressure is greater than its switching threshold. The greater the initial pressure, the larger the numerical range dropping from the initial value to rebound value, so does the effect of coal cleat compressibility. However, only on condition that the internal swelling coefficient is smaller than its switching threshold, the permeability will rebound and recover. Besides, the influencing mechanism of CO_2 storage and CBM extraction on permeability evolution is the same, while the variation laws of permeability, of rebound and recovery especially, exert strong impact on CO_2 storage capability. Therefore, the influence of various permeability evolution laws on CO_2 storage capability is discussed macroscopically for valid assessment of it, providing guidance to select appropriate coal seams for CO_2 storage.

1. Introduction

Coalbed methane (CBM), a kind of valuable, abundant and available green resource, is mainly distributed in Russia, Canada, China, the USA, Australia and other countries [1,2]. In recent years, CBM industry experiences rapid development, because traditional coal mining causes disasters easily in addition to its great impact on geological environment, and the subsequent coal combustion threatens both the atmosphere and human health [3–8]. Although CBM is a kind of efficient and clean energy, the waste of resources may occur if effective control fails to be guaranteed in the mining process. Besides, changes are that the remaining CBM in the disturbed coal seam diffuses into atmosphere directly. The main composition of CBM is methane that is regarded as the second contributor to global greenhouse effect only to CO_2, so reasonable and effective CBM extraction meets requirements of the sustainable development of resource and environment [9,10].

In pursuit of increasing yield of CBM and decreasing CO_2 in atmosphere at the same time, CO_2-enhanced coal bed methane (ECBM) recovery technology was proposed by some scholars [11–13]. The CO_2-ECBM process mainly refers to the injection of CO_2 into deep coal seam by surface wells or boreholes to store CO_2. Entering the coal seams, CO_2 will occupy the original adsorption site of CH_4 because of its better adsorptive capacity on coal seams, thus causing the desorption of CH_4. The state transformation of CH_4 and CO_2 in the coal seams functions as the theoretical basis of CO_2-ECBM recovery technology [14]. In fact, the change of coal permeability is an important factor affecting both CBM extraction projects and CO_2 storage in CO_2-ECBM engineering. At present, most researchers are deeply involved in studying the permeability

* Corresponding author at: National Engineering Research Center for Coal and Gas Control, China University of Mining and Technology, Xuzhou, Jiangsu 221116, China.
E-mail address: ypcheng@cumt.edu.cn (Y. Cheng).

https://doi.org/10.1016/j.fuel.2018.05.057
Received 10 March 2018; Received in revised form 9 May 2018; Accepted 11 May 2018
0016-2361/

model in CBM extraction, while little attention is attached to rebound and recovery effect during permeability changing process as well as the influencing factors on them [15–17], although they exert a vital impact on CBM yield and CO_2 storage capacity of coal seams.

The permeability value of coal is positively correlated with the fracture aperture, while evolution laws of fracture aperture are controlled by competition between adsorption-induced matrix swelling and effective stress transformation. Of them, the one causing greater absolute deformation has the main controlling effect at a certain moment [18,19]. Due to the competition between the two, the influence of coal deformation on permeability is not simply linear in the processes of both CBM extraction and CO_2 storage. When studying the evolution laws of permeability during CBM extraction in the field and in the laboratories, many scholars observed that the permeability value would rebound and recover with the variation of gas pressure. Palmer and Mansoori [19] proposed a new theoretical model for calculating pore volume compressibility and permeability. In order to validate the accuracy of the model, he extracted permeability values during CBM extraction of fairway well B1 in the San Juan Basin. In the initial stage, the value of permeability ration plunged, and then it began to increase when the matrix methane pressure decreased to the range of 6.9 MPa–7.9 MPa, reaching 2 at last, as shown in Fig. 1(a). Robertson and Christiansen [20] conducted some experiments to study the adsorption-induced matrix strain on unconstrained samples for different gases. They collected coal samples from the Anderson coal bed and injected CH_4 under confining stress of 6.8 MPa, obtaining the evolution laws of samples' permeability with the changing stress of injected CH_4, as shown in Fig. 1(b). The experimental data revealed that adsorption-induced matrix deformation played a predominant role in the low-pressure stage, resulting in a decrease in permeability while effective stress effect gradually moved into the lead in the later stage of high pressure, thus leading to an increase. Similarly, Pini et al. [21] used an experimental technique to perform gas injection experiments on coal cores for improving the knowledge on the different mechanisms acting during CO_2 storage. When they injected CO_2 into coal samples from sulcis coal seam, they observed a greater rise of permeability in the later stage and the value even reached 5.5 times the initial permeability, as shown in Fig. 1(c). Liu et al. [22] established a new model to illustrate the impact of transition from local swelling to macro swelling on cola permeability. From the simulation results, they found that the permeability took the biggest drop by 86% when the pore pressure was between 1.15 MPa and 2.22 MPa. Finally, due to the permeability rebound occurring when the pore pressure was 4.58 MPa, the final value of coal permeability was reduced by only 19% compared with the initial value, as shown in Fig. 1(d). Liu et al. [23] established the permeability evolution model by means of free expansion + push back to determine the magnitude of additional stress and its effect on permeability evolution. To prove the validity and correctness of the model, same parameters were considered in some classical and self-built models. Numerical simulation was adopted to analyze the variation laws of permeability of the coal injected with CH_4 and CO_2, respectively, as shown in Fig. 1(e) and (f). They found that permeability dropped in the low-pressure stage due to coal deformation; it rebounded and increased with the rising of gas pressure. As seen from the above papers, the phenomenon of permeability rebound and recovery do exist, but no further analysis is conducted on them because these papers are not targeted to these phenomena. Hence, it is meaningful to study how to establish a rational coal permeability evolution model considering the influence of adsorption-induced matrix deformation and effective stress transformation on fracture aperture, so as to analyze coal permeability rebound and recovery effect and the influencing factors on it.

At present, the permeability value is the basis of parameters for assessing whether a coal seam is appropriate for CBM recovery [24–26]. The larger the value, the easier the CBM extraction; on the contrary, the smaller, the harder. According to general permeability evolution laws, the coal seam is regarded to be unsuitable for CBM extraction if the permeability and daily methane production decrease as the extraction proceeding. Since CBM extraction project is expensive and laborious, companies will stop the extraction immediately for timely minimizing economic losses [27,28]. However, if permeability rebound and recovery effect and their evolution laws are grasped in advance, CBM extraction projects will not be stalled and surface wells or drillings will not be abandoned just based on the current variation laws of permeability. Especially, with the awareness that coal permeability is bound

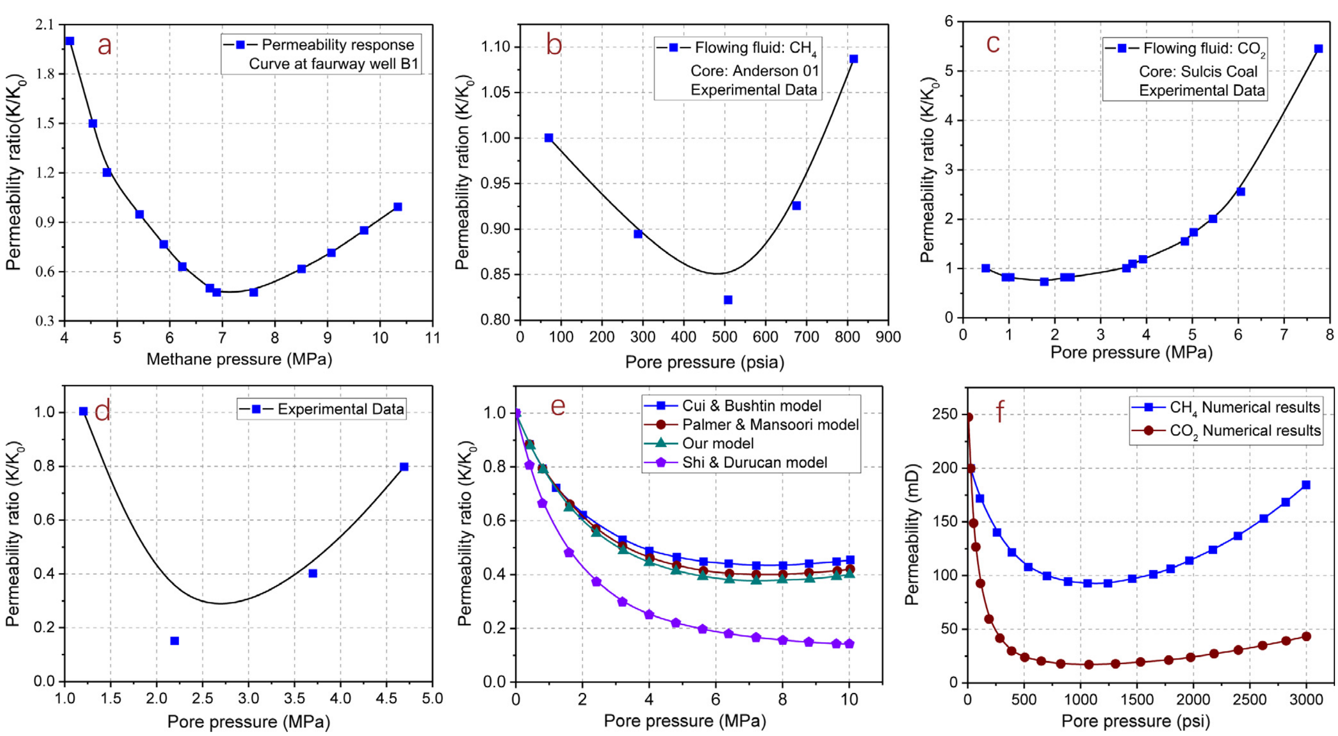

Fig. 1. Phenomena of coal permeability rebound and recovery [19–23].

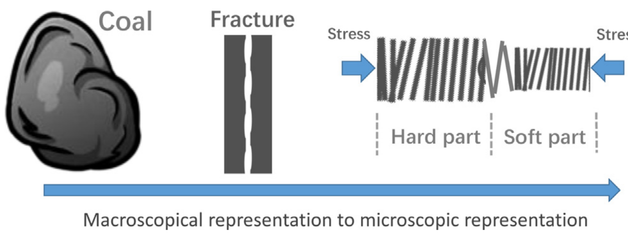

Fig. 2. Conceptual schematic diagram of coal fracture composition.

to rebound or recover in the further extraction process, methane extraction projects will be retained to witness the rise of methane yield induced by permeability rebound and recovery in the later stage. During the implementation of CO_2-ECBM project, permeability values of coal around the injection well determine CO_2 storage capability of the coal seam [14,29]. Generally, the bigger the value, the greater the range of coal seam affected by the CO_2 injection, and thus the larger the amount of CO_2 injected. In essence, CO_2 injection has the same effect as CBM extraction on coal permeability [30–32]. If the permeability rebound and recovery effect can be clarified before CO_2 injection projects, a coal seam's capability of storing CO_2 can be better assessed.

In this study, the relationship between fracture aperture and effective stress as well as the adsorption-induced matrix swelling was put forward first. Of the two, the effect of effective stress on coal deformation includes engineering-strain and natural-strain, while the matrix swelling only partly contributes to the fracture aperture due to the matrix bridge among coal matrix [33,34]. Based on the competition between adsorption-induced matrix swelling and effective stress, the model of changing fracture aperture was built and the evolution model of coal permeability was derived by utilizing the classical cubic law [35,36]. Then, based on the evolution model, the factors affecting permeability rebound and recovery pressure were gained to analyze the influences of different parameters on permeability rebound and recovery effect in the CBM extraction. Finally, the authors, enlightened by variation laws of permeability in CBM extraction, discussed the impacts of different evolution laws of permeability on CO_2 storage capability from a macroscopic perspective. Therefore, permeability rebound and recovery effect is a scientific problem worthy of research for both CBM extraction and CO_2 storage capacity assessment.

2. Theory

2.1. Formation of coal permeability

2.1.1. Assumptions of theory

As we all know, the variation of coal fracture aperture which dominates the permeability, is mainly caused by the effective stress and adsorption swelling deformation. In addition, there are other influencing factors, such as some unique gas transport mechanisms [37], gas surface diffusion [38], moisture [39], thickness of adsorbed layer [40], physical structure [17] and real gas effect [41]. However, these factors were ignored by most researchers for simplifying the establishment of coal permeability models. Therefore, it is reasonable to ignore these other factors in our permeability model.

2.1.2. Impact of effective stress on fracture deformation

Effective stress, originally proposed by Terzaghi in his study of the mechanical characteristics of soil with saturated water, is equal to the upper total stress minus the pore water pressure [42]. However, Biot [43] found in the study of triaxial compression that effective stress was inapplicable to porous media with low permeability. Hence, he proposed a modified principle of effective stress where the equivalent porous pressure was expressed by the product of pore pressure and equivalent porous stress coefficient whose value was between 0 and 1. Actually, the effective stress is an important factor contributing to the deformation of coal. Nevertheless, the principle of effective stress for traditional single-porosity media fails to describe the mechanical response of changing fluid pressure to porous media like coal [44,45]. Hence, the effective stress law for dual porous media is introduced to analyze and describe characteristics of coal deformation [46].

$$\sigma_e = \sigma - \delta(\beta_f \mathrm{p}_f + \beta_m \mathrm{p}_m) \tag{1}$$

where σ_e is the effective stress, MPa; p_f and p_m are the methane pressures in fractures and coal matrix, respectively, MPa; σ is the total stress, MPa; δ is the Kronecker delta tensor; β_f and β_m are effective stress coefficients for the fracture and coal matrix respectively.

For most part of coal, the deformation is relatively small during the variation of effective stress, while for a small part of pores or fractures, it is very large, even directly causing the complete closing of pores and fractures. To solve the problem of different deformation under the same stress, coal fracture system is abstracted to two parts, namely, the soft part and the hard part, as shown in Fig. 2. The two parts follow different principles of Hooke's law: The hard part meets the engineering-strain and the soft part meets the natural-strain [47].

For the hard part and soft part, the strain of fracture aperture can be defined by the engineering-strain and the natural-strain. The following relations are used:

$$d\varepsilon_{a,e} = -\frac{da_e}{a_{0,e}} \tag{2}$$

$$d\varepsilon_{a,n} = -\frac{da_n}{a_{0,n}} \tag{3}$$

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

$$a_e = a_{0,e}\left(1 - \frac{\Delta\sigma}{k_e}\right) \tag{4}$$

$$a_n = a_{0,n}\exp\left(-\frac{\Delta\sigma}{k_n}\right) \tag{5}$$

where k_e and k_n are the bulk modulus of the hard part and soft part of fracture system, respectively.Due to the facts that the variation of fracture aperture is the sum of natural-strain and engineering-strain and that k_e is several orders of magnitude larger than k_n, the variation of fracture aperture under effective stress is as follows:

$$a_m = a_{0,e} + (a_0 - a_{0,e})\exp(-\Delta\sigma c_f) \tag{6}$$

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

In the process of CBM extraction, the coal can be assumed to be in the state of constant load stress and uniaxial strain. By combining Eq. (1) with Eq. (6), the variation of fracture aperture caused by the change of effective stress is as follows:

$$a_m = a_{0,e} + (a_0 - a_{0,e})\exp c_f[\beta_f(\mathrm{p}_f - \mathrm{p}_0) + \beta_m(\mathrm{p}_m - \mathrm{p}_0)] \tag{7}$$

where p_0 is the initial methane pressure of coal seam, MPa.

2.1.3. Impact of methane desorption on fracture deformation

Coal is a kind of natural adsorbent with the property of adsorbing methane. It is well known that with the progress of CBM extraction, the absorbed methane desorbs when methane pressure drops below the critical pressure, leading to matrix shrinkage and thereby affecting the size of fracture aperture. However, there are different views on the influence of adsorption-induced matrix swelling on fracture aperture. Initially, most scholars simplified the physical model of coal as an ideal cube model where the matrix was separated by two non-contact fracture surfaces to establish permeability evolution model. Therefore, it was considered that the matrix deformation fully contributed to fracture aperture [19,48,49]. Accompanied with the further study on adsorption-induced coal deformation, the ideal cube model was inconsistent with actual coal. Karacan [50] and Dawson et al. [51] revealed that parts of the matrix were interconnected because inorganic minerals in the fracture linked the matrix. Due to the binding force, the connected parts will produce swelling strain in the process of deformation, preventing the expansion of matrix to fractures. Therefore, some scholars think that only part of total swelling strain contributes to the change of fracture aperture and the remaining portion leads to coal bulk deformation [52,53].To address this situation, Liu et al. [52] proposed an improved coal physical model where the matrix was connected by matrix bridge. Besides, internal swelling coefficient was applied to quantitatively describe the influence of matrix deformation on fracture aperture. Similarly, in order to study whether the matrix deformation completely attributed to the change of fracture aperture, Connell et al. [53] compared and analyzed the permeability data from the experiment and the theoretical evolution model. In addition, they proposed a coefficient to characterize the matrix-fracture interactions. It was observed from relevant references that aiming at solving this problem, other scholars had also simplified the physical model of the coal into the cube model with the matrix bridge connecting the matrix. Besides, the influence of matrix deformation on fracture aperture was expressed by internal swelling coefficient f_m which was also affected by fracture characteristics and other parameters.

Based on the aforesaid analysis of influence of matrix deformation on fracture aperture and the dual porous model of coal, together with the assumption that the coal is isotropic and perfectly elastic, the change of fracture aperture induced by adsorption swelling is as follow:

$$a_s = -\frac{1}{3}\varepsilon_s f_m b \tag{8}$$

where a_s is the change of fracture aperture induced by the swelling stain; b is the fracture spacing; ε_s is the adsorption-induced volume strain, which can be calculated with Langmuir isothermal adsorption model of $\varepsilon_s = \varepsilon_{\max}p_m/p_m + p_L - \varepsilon_{\max}p_0/p_0 + p_L$; $\varepsilon_{\max}$ is the Langmuir volumetric strain constant; p_L is the Langmuir pressure constant, MPa. The Eq. (8) can be rewritten as follows:

$$a_s = -\frac{1}{3}bf_m\left(\frac{\varepsilon_{\max}p_m}{p_m + p_L}-\frac{\varepsilon_{\max}p_0}{p_0 + p_L}\right) \tag{9}$$

2.1.4. Dynamic model for coal permeability

During CBM extraction, the changing methane pressure can cause both the effective stress and adsorption-induced swelling deformation at the same time. Combining Eq. (7) with Eq. (9), fracture aperture can be expressed as:

$$a = a_{0,e} + (a_0-a_{0,e})\exp c_f[\beta_f(p_f-p_0) + \beta_m(p_m-p_0)] -\frac{1}{3}bf_m\left(\frac{\varepsilon_{\max}p_m}{p_m + p_L}-\frac{\varepsilon_{\max}p_0}{p_0 + p_L}\right) \tag{10}$$

where a is the fracture aperture.In fact, compared with initial fracture aperture, the engineering-strain of coal is relatively insignificant because it approximates to 0 ($a_{0,e} \ll a_0$, $a_{0,e} \approx 0$), and Eq. (10) can be simplified as:

$$a = a_0\exp c_f[\beta_f(p_f-p_0) + \beta_m(p_m-p_0)]-\frac{1}{3}bf_m\varepsilon_{\max}\left(\frac{p_m}{p_m + p_L}-\frac{p_0}{p_0 + p_L}\right) \tag{11}$$

The initial fracture aperture is much smaller than the fracture spacing ($a_0 \ll b$). Based on the definition of initial fracture porosity, Eq. (12) can be obtained:

$$\phi_{f0} = \frac{(a_0 + b)^3-b^3}{(a_0 + b)^3} \approx \frac{3a_0}{b} \tag{12}$$

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

Combining Eq. (11) with Eq. (12), the expression of fracture aperture is as follow:

$$a = a_0\exp c_f[\beta_f(p_f-p_0) + \beta_m(p_m-p_0)]-\frac{a_0 f_m\varepsilon_{\max}}{\phi_{f0}}\left(\frac{p_m}{p_m + p_L}-\frac{p_0}{p_0 + p_L}\right) \tag{13}$$

According to cubic law, coal permeability can be expressed as [54]:

$$k = k_0\left[\exp c_f[\beta_f(p_f-p_0) + \beta_m(p_m-p_0)]-\frac{f_m\varepsilon_{\max}}{\phi_{f0}}\left(\frac{p_m}{p_m + p_L}-\frac{p_0}{p_0 + p_L}\right)\right]^3 \tag{14}$$

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

2.2. Analysis of recovery and rebound pressure

Eq. (14) describes the theoretical correlation between the change of coal permeability and the variation of reservoir pressure. The right side of the equation means that coal permeability is affected by two factors: effective stress and its competitor, adsorption-induced swelling. If the initial conditions of reservoirs meet corresponding requirements, the coal permeability will drop down before rise up with the falling reservoir pressure. Generally, coal permeability rebound and recovery usually appears in process of methane extraction.

First, in order to effectively analyze the phenomenon of coal permeability recovery, a function of methane pressure in fracture and matrix can be defined according to Eq. (14):

$$f(p_f,p_m) = \exp[c_f\beta_f(p_f-p_0) + c_f\beta_m(p_m-p_0)] -\frac{f_m\varepsilon_{\max}}{\phi_{f0}}\left(\frac{p_m}{p_m + p_L}-\frac{p_0}{p_0 + p_L}\right) \tag{15}$$

If $f(p_f, p_m) = 1$, then $k/k_0 = 1$. This means that the value of coal permeability is equal to the initial permeability at this time, which often corresponds to two moments, that is, the initial moment of methane extraction and the moment of permeability recovery during the extraction. Since Eq. (15) is established based on dual-porosity and dual-permeability model, it contains two variables: methane pressures in fractures and pores. However, the dual-variable model is difficult for theoretically analysis of permeability recovery. Due to the little difference between values of methane pressure in fracture and pore during methane extraction, the coal can be simplified as a single-porosity and single-permeability system, and then $p_f = p_m = p$. Based on the above assumptions, Eq. (15) can be re-expressed as:

$$f(p) = \exp[c_f\beta(p-p_0)]-\frac{f_m\varepsilon_{\max}}{\phi_{f0}}\left(\frac{p}{p + p_L}-\frac{p_0}{p_0 + p_L}\right) \tag{16}$$

The combination of the exponential function and fractional function in Eq. (16) multiplies the difficulty to solve it, so the Fourier function is applied to transforming and omitting higher-order terms in it to obtain a new polynomial function as follows:

$$f(p) = 1 + c_f\beta(p-p_0) + \frac{1}{2}c_f^2\beta^2(p-p_0)^2-\frac{f_m\varepsilon_{\max}}{\phi_{f0}}\left(\frac{p}{p + p_L}-\frac{p_0}{p_0 + p_L}\right) \tag{17}$$

Let $f(p) = 1$, then there are two analytical solutions of Eq. (17), $p = p_0$ and $p = p_{rc}$ respectively. p_0 is reservoir gas pressure at initial extraction moment; and p_{rc}, which is the reservoir gas pressure at the moment when permeability recovers to the initial value, can be expressed as

$$p_{rc} = -\frac{2 + c_f\beta(p_L - p_0)}{2c_f\beta} + \frac{\sqrt{[1-1/2c_f\beta(p_0+p_L)]^2\phi_{f0}^2(p_0+p_L)^2 - 2\phi_{f0}(p_0+p_L)f_m\varepsilon_{\max}p_L}}{c_f\beta\phi_{f0}(p_0+p_L)} \tag{18}$$

It can be observed from Eq. (18) that permeability recovery pressure is related to coal cleat compressibility, effective stress coefficient, initial reservoir gas pressure, the Langmuir pressure constant, the Langmuir volumetric strain constant, initial fracture porosity and internal swelling coefficient.Permeability rebound occurs before the recovery. The corresponding reservoir gas pressure when permeability rebounds can be defined as the rebound pressure p_{rb} that can be obtained by solving the first derivative of Eq. (17) as follows:

$$f'(\mathrm{p}) = c_f\beta + c_f^2\beta^2(\mathrm{p}-\mathrm{p}_0) - \frac{f_m\varepsilon_{\max}p_L}{\phi_{f0}(p+p_L)^2} \tag{19}$$

Let $f'(p) = 0$, then Eq. (20) is gained:

$$c_f\beta + c_f^2\beta^2(\mathrm{p}-\mathrm{p}_0) - \frac{f_m\varepsilon_{\max}p_L}{\phi_{f0}(p+p_L)^2} = 0 \tag{20}$$

The analytical solution of Eq. (20) is the rebound pressure. As the solution of the polynomial Eq. (20) is complicated, there is no specific expression of analytic solution value. However, it is clear from Eq. (20) that the permeability rebound pressure is also in connection with coal cleat compressibility, effective stress coefficient, initial reservoir gas pressure, the Langmuir pressure constant, the Langmuir volumetric strain constant, initial fissure percentage and internal swelling coefficient.

2.3. Model validation

In order to verify the permeability model that we built, the field test data of coal permeability in San Juan basin is utilized to fit the theoretical data. Some field data of coal permeability in the three CBM wells are shown in the Table 1, including the initial coal permeability and coal permeability at a specific reservoir pressure [19]. Some basic parameters used for matching the field permeability data in San Juan basin are listed in Table 2 (the Langmuir pressure, the Langmuir volumetric strain and the initial fracture porosity are obtained from Wu et al. [55]). Our model is used to fit the field data by adjusting the coal compressibility and the internal swelling coefficient, and the matching results of coal permeability for different CBM wells are depicted in Fig. 3. Moreover, the selected values of the coal compressibility and the internal swelling coefficient for different CBM wells are also shown in Fig. 3. The fitting degree of the results indicates that our model is applicable to predicting the CBM production and the value of coal permeability.

In the above comparison, the theoretical data of coal permeability is compared with field data, which verify the accuracy of our model. In addition, to verify the correctness of our model from another aspect, a set of simulation results about reservoir methane pressure from Liu et al. [39] are chosen to match the results of our model. Most basic parameters of coal are selected from their paper and others are set by us (the coal compressibility is set to 0.029 and the internal swelling coefficient is set to 1). To monitor the change in methane gas pressure at different drainage times (1 d, 100 d, 500 d), the monitoring line (y = 2.5, x ∊ [20.2 m, 40 m]) is set in the coal seam. The comparative plots are shown in Fig. 4, showing that results of our model highly agree with those of theirs.

Table 1
Field permeability data measured in San Juan basin [19].

Well No.	K_0 (mD)	Reservoir pressure (MPa)/Permeability (mD)		
		1st point	2nd point	3rd point
#1	3.9	6.36/3.9	4.78/4.9	3.92/5.6
#2	1.2	5.03/1.6	4.33/2.5	3.36/3.2
#3	1.8	4.85/7.2	3.12/16.5	2.43/20.6

Table 2
Parameters used for matching the field permeability data in San Juan basin [55].

Initial methane pressure	The effective stress coefficient	Langmuir pressure	Langmuir volumetric strain	Initial fracture porosity
6 MPa	1	4.3 MPa	0.01266	0.001

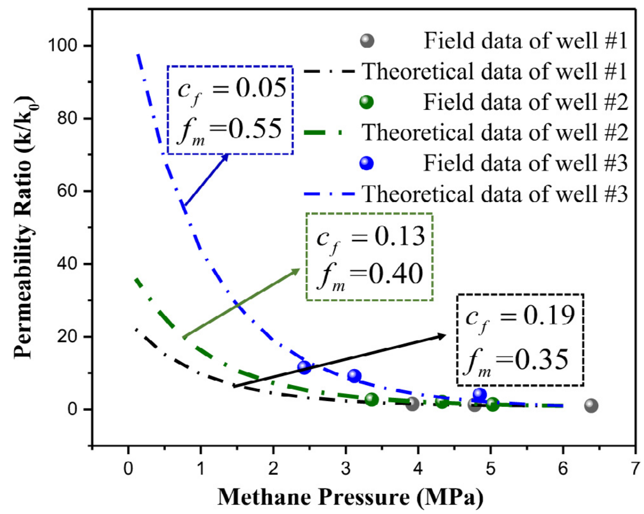

Fig. 3. Matching results of our model with field data in San Juan basin.

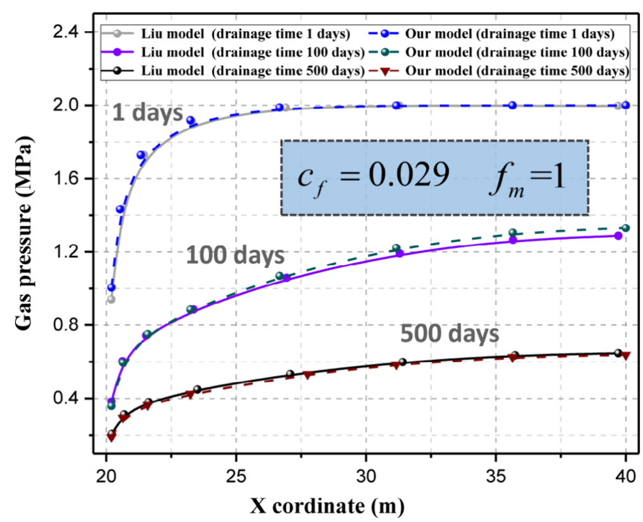

Fig. 4. Comparison of results of our model with Liu model.

3. Results and discussion

3.1. Influencing factors of permeability rebound and recovery

3.1.1. Initial coal reservoir pressure

Based on the above theoretical analysis, the initial coal reservoir pressure has a great impact on the permeability rebound and recovery effect. In order to study the evolution laws of gas pressure

Table 3
Basic parameters used for analyzing the effect of initial reservoir pressure on permeability rebound and recovery pressure.

Coal cleat compressibility	The effective stress coefficient	Langmuir pressure	Langmuir volumetric strain	Initial fracture porosity	Internal swelling coefficient
0.3	1	4.3 MPa	0.01266	0.001	0.5

corresponding to permeability rebound and recovery under different initial coal reservoir pressures, other parameters of coal are set to fixed values, as shown in Table 3. The change of permeability ratios with the variation of reservoir pressure under different initial pressures are calculated, as given in Fig. 5. According to Fig. 5(a), when initial coal reservoir pressures are 10 MPa, 9 MPa, 8 MPa, 7 MPa and 6 MPa, the permeability ratios decrease at first and then increase with the dropping methane pressure, exceeding 1 at last. Therefore, if parameters of coal reservoirs meet the combined conditions in Table 3, coal permeability will rebound and recover when the methane pressure falls to a certain extent. From the curve of permeability ratio in Fig. 5(a), there is a significant difference between the ranges from the minimum to 1 for coal with different initial reservoir pressure. In general, the larger the initial coal reservoir pressure, the greater the range. Specifically, when the initial coal reservoir pressures are 10 MPa, 9 MPa, 8 MPa, 7 MPa and 6 MPa, the minimum values of permeability ratios are 0.632, 0.726, 0.825, 0.913 and 0.981, dropping by 36.8%, 27.4%, 17.5%, 8.7% and 1.9% respectively.

There is an obvious difference in the variation laws of permeability ratio with the decrease of methane pressure between Fig. 5(a) and (b). The curves in Fig. 5(b), with no decrease in the initial stage, are always on the rise with the falling reservoir pressure, suggesting if parameters of the coal reservoir meet the fixed values in Table 3, permeability will never rebound or recover under initial reservoir pressures of 5.23 MPa, 5 MPa, 4 MPa and 3 MPa.

The value of reservoir pressure corresponding to coal permeability rebound and recovery under different initial pressures are extracted from Fig. 5(a), as presented in Fig. 6. From the variation laws of curves in Fig. 6, it can be found that the larger the initial reservoir pressure, the greater the rebound and recovery pressure. More precisely, with the initial reservoir pressures of 10 MPa, 9 MPa, 8 MPa, 7 MPa and 6 MPa, the rebound pressures are 8 MPa, 7.5 MPa, 7.1 MPa, 6.2 MPa and 5.6 MPa, and the recovery pressures are 6.25 MPa, 6.0 MPa, 5.78 MPa, 5.55 MPa and 5.3 MPa, respectively. Moreover, on condition that coal parameters are consistent with values in Table 3, there will be no permeability rebound or recover during methane extraction if the initial coal reservoir pressure is small, especially if it is lower than 5.23 MPa.

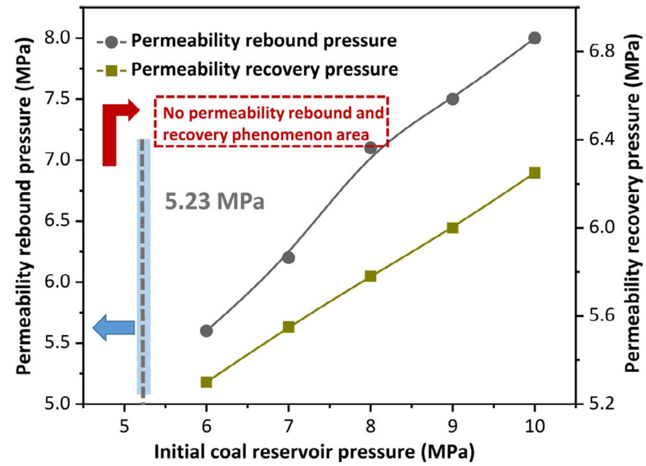

Fig. 6. Evolution laws of rebound and recovery pressure under different initial reservoir pressure.

3.1.2. Coal cleat compressibility

Similarly, the coal cleat compressibility also affects the phenomenon of permeability rebound and recovery. For effectively studying how it acts, coal parameters are set to be fixed values except cleat compressibility, as given in Table 4. The permeability ratios with different cleat compressibilities vary with reservoir pressures, as shown in Fig. 7. When the cleat compressibilities are 0.425, 0.4, 0.3, 0.25 and 0.2, the permeability ratios decline first and then grow with the reduction of reservoir pressure, and their values all exceed 1 at a certain point of time. It is demonstrated that if cleat compressibility and other parameters tally with the above combined conditions, permeability will rebound and recover as long as the methane pressure declines to a certain value. Nevertheless, it is discovered through careful observation and analysis that when permeability changes from the initial state to the rebound and recovery, there are huge differences in the range of permeability ratio for coal with various cleat compressibilities. Specifically, when cleat compressibilities are 0.425, 0.4, 0.3, 0.25 and 0.2, the permeability ratios fall to minimum values 0.4001, 0.438, 0.632, 0.753 and 0.895 with decline ranges of 59.99%, 56.2%, 36.8%, 24.3% and 10.5%, respectively. Thereby, the smaller cleat compressibility, the less the decrease of permeability ratio.

Different from the curves in Fig. 7(a), those in Fig. 7(b) keep rising constantly with the drop of reservoir pressure. This illustrates that the permeability ratio will not fall during methane extraction of reservoir with cleat compressibilities of 0.13, 0.1, and 0.05. It also reflects that there will be no permeability rebound or recovery for coal with such

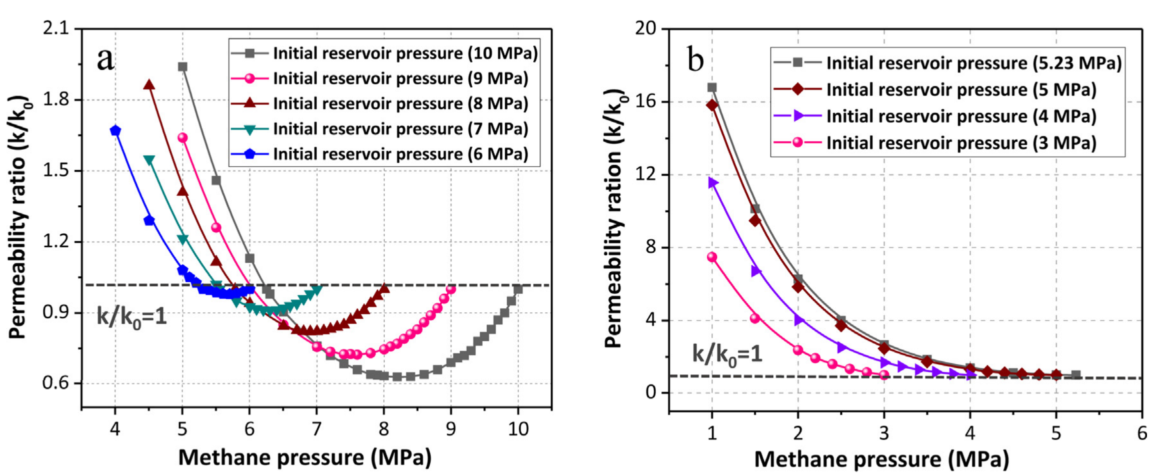

Fig. 5. Evolution laws of permeability with different initial reservoir pressures.

Table 4
Basic parameters used for analyzing the effect of coal cleat compressibility on permeability rebound and recovery pressure.

Initial reservoir methane pressure	The effective stress coefficient	Langmuir pressure	Langmuir volumetric strain	Initial fracture porosity	Internal swelling coefficient
10 MPa	1	4.3 MPa	0.01266	0.001	0.5

combined conditions.

The value of reservoir pressure corresponding to permeability rebound and recovery in coal with different cleat compressibilities from Fig. 7(a) are presented in Fig. 8. Generally, the values rise accompanied with the decline of cleat compressibility. The data in Fig. 8 reveals that with cleat compressibilities of 0.425, 0.4, 0.3, 0.25 and 0.2, the corresponding rebound pressures are 7.9 MPa, 7.8 MPa, 7.8 MPa, 8.3 MPa and 8.5 MPa, and the recovery pressures are 5.6 MPa, 5.68 MPa, 6.25 MPa, 6.77 MPa and 7.6 MPa, respectively. Besides, with the combined parameters set in this section, the permeability rebound and recovery will disappear when the cleat compressibility decreases to a certain value, and they will completely vanish if the cleat compressibility is less than 0.13.

3.1.3. Internal swelling coefficient

In addition to the initial reservoir pressure and cleat compressibility, the internal swelling coefficient is another non-negligible factor influencing permeability rebound and recovery. To study the influence of different internal swelling coefficients on permeability rebound and recovery, other coal parameters are also set to be fixed values, as shown in Table 5. The variation laws of permeability ratios corresponding to different internal swelling coefficients with the change of reservoir pressure are calculated by adopting permeability theory model, as illustrated in Fig. 9. The permeability ratios are always on the rise and the values are greater than 1 when the internal swelling coefficients are 1, 0.8, 0.6 and 0.49. On the condition of such combined parameters, the permeability fails to rebound or recover during methane extraction. It is noticeable in Fig. 9(b) that the permeability rebounds and recovers with the falling methane pressure when the value of internal swelling coefficient is smaller than 0.49. When the values are 0.4, 0.2 and 0.1, the corresponding rebound pressures are 9.6 MPa, 6.7 MPa and 4.5 MPa, and the corresponding recovery pressures are 8.5 MPa, 4.09 MPa and 0.73 MPa. However, a special phenomenon can be found in Fig. 9(b) that when the internal swelling coefficient is 0.082, the permeability rebounds at the pressure of 3.9 MPa, yet it fails to recover to the initial value.

Based on the above analysis, on the condition of combined

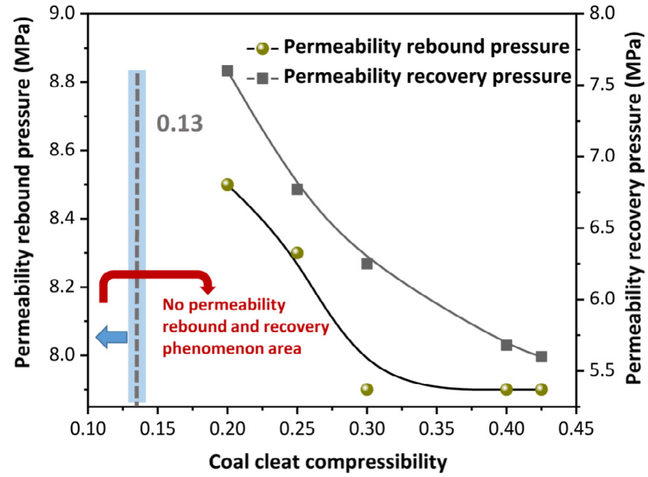

Fig. 8. Evolution laws of rebound and recovery pressure with different cleat compressibilities.

Table 5
Basic parameters used for analyzing the effect of internal swelling coefficient on permeability rebound and recovery pressure.

Coal cleat compressibility	The effective stress coefficient	Langmuir pressure	Langmuir volumetric strain	Initial fracture porosity	Initial reservoir methane pressure
0.13	1	4.3 MPa	0.01266	0.001	10 MPa

parameters in Table 5, the permeability will not rebound or recover during the extraction if the internal swelling coefficient is bigger than 0.49. For coal with the phenomenon of permeability rebound and recovery, the rebound and the recovery pressure values are extracted, as shown in Fig. 10. The impact of internal swelling coefficient on the rebound and recovery pressure is complex according to the analysis of the curve in Fig. 10. Specifically, when internal swelling coefficient lies between 0.49 and 0.01, the permeability will rebound; when between 0.49 and 0.082, it will recover; when between 0.082 and 0.01, it will only rebound; when between 0 and 0.01, the rebound and recovery will disappear simultaneously.

3.2. Implication for carbon dioxide storage capability assessment

Global warming has become one of the urgent problems of greatest importance. Greenhouse effect is being intensified due to anthropogenic

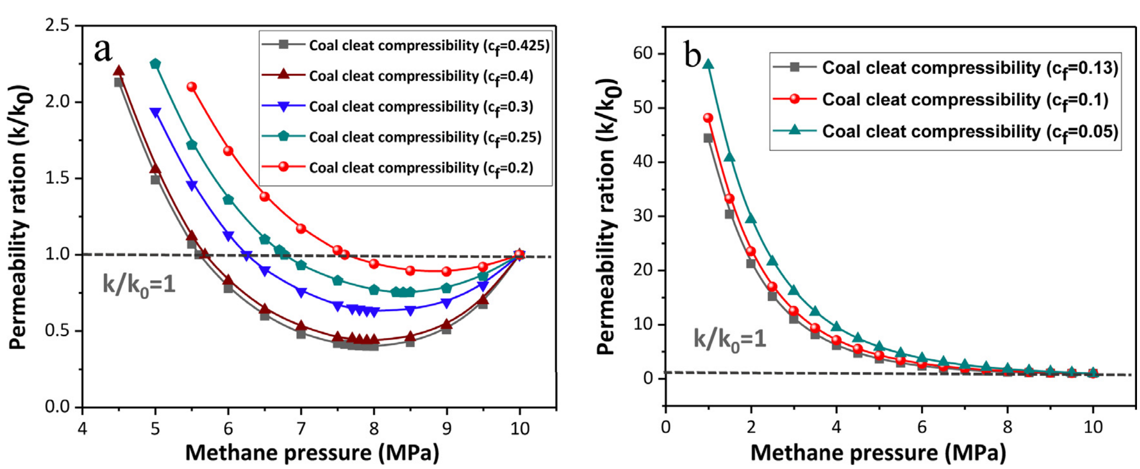

Fig. 7. Evolution laws of permeability with different cleat compressibilities.

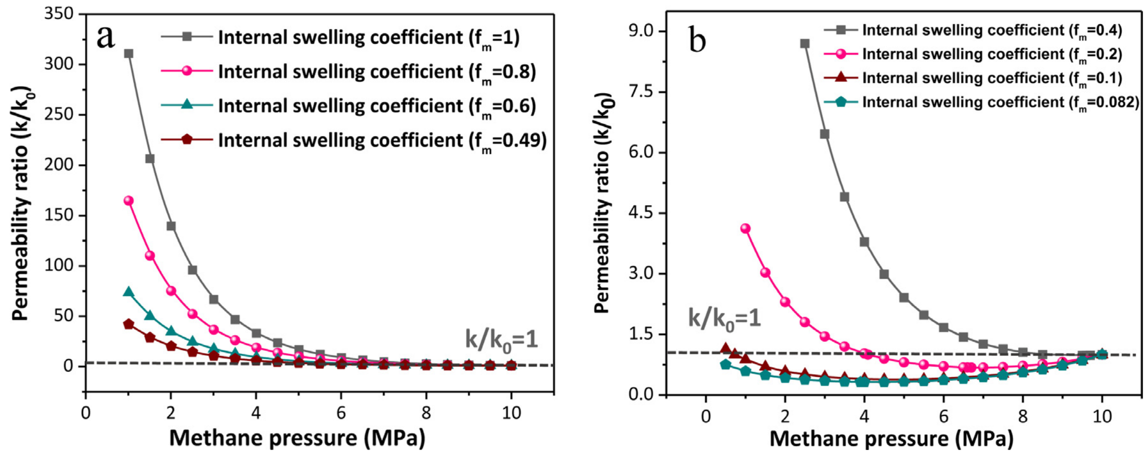

Fig. 9. Evolution laws of permeability with different internal swelling coefficients.

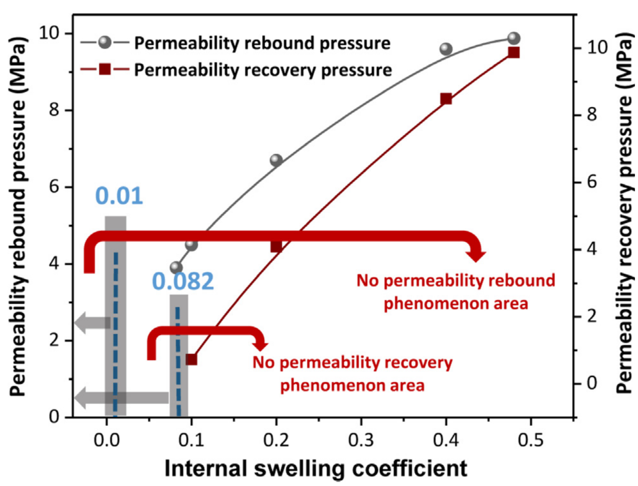

Fig. 10. Evolution laws of rebound and recovery pressure with different internal swelling coefficients.

emissions of greenhouse gases into the atmosphere. CO_2, which accounts for the biggest proportion of greenhouse gas, mainly comes from the burning of coal, oil, natural gas, as well as automobile exhaust in modern industrial society. Compared with measures, such as improving energy efficiency, cutting the use of traditional fossil fuels and expanding vegetation coverage, it is more feasible to effectively reduce the amount of CO_2 released into the atmosphere. At present, CO_2 storage in deep coal seams has become a hot research topic, and many researches have been conducted in this field with results proving its feasibility [56]. According to the prediction of Advanced Resources International, more than 220 Gt of CO_2 can be stored in worldwide deep coal seams for a reasonable cost. So far, some countries around the world have implemented CO_2 storage projects, including the USA, Canada, Poland, Australia, Japan, China, etc. Several typical CO_2 storage projects are presented in Fig. 11 [57].

To date, the research focus lies on CO_2 storage capability of coal seams which is affected by two key technologies, including the evolution laws of coal permeability and the variation of mechanical characteristics of coal after CO_2 adsorption. In light of the aforesaid studies on evolution laws of coal permeability during CBM extraction, this section discusses the influence of the permeability evolution laws on CO_2 storage capability of coal seams from the macroscopic perspective. since coal is a kind of complex porous medium containing enormous fractures and pores, the injected CO_2 enters the fracture through injection wells first, and then moves slowly into the pore system. The permeability affects the migration capacity of gas, and thus influences CO_2 storage capacity of coal seams.

Both CO_2 and CH_4 can adsorb on coal, and the adsorption capacity

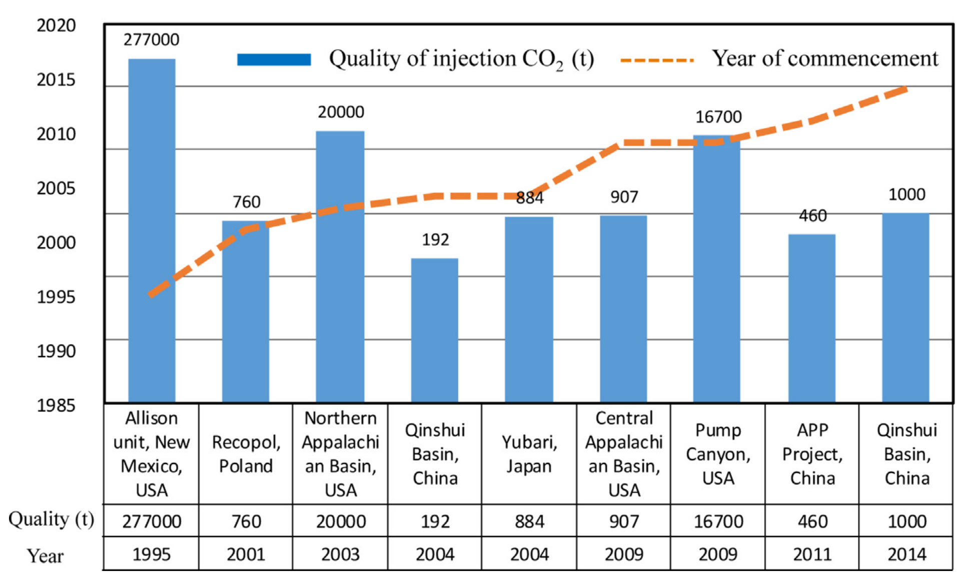

Fig. 11. Some worldwide CO_2 storage projects [57].

of CO_2 is better than that of CH_4. On the basis of existing research achievements, the pore spacing narrows significantly after adsorption of CO_2 in matrix, resulting in the reduction of permeability. The results are consistent with influence mechanism of methane adsorption in matrix on permeability. In the process of CO_2 storage, coal permeability is affected by effective stress in addition to adsorption-induced matrix swelling. The influence factors of them on permeability is the same as that of CBM extraction. Therefore, the permeability rebound and recovery during CBM extraction should be taken into consideration in the process of CO_2 storage which is directly affected by the evolution laws of permeability.

In CO_2 storage projects, surface wells are utilized to inject CO_2 into coal seams. The coal permeability around the wells, which changes first, exerts a direct impact on the following and even overall CO_2 injection capability. The injected CO_2 can smoothly migrate far to achieve remarkable CO_2 storage, if the permeability around the well maintains at high values in the injection process. However, on condition that the permeability slumps to below a certain value at the initial stage, the following CO_2 injection will be seriously affected. Low permeability, like a wall in coal seams, hinders the migration of CO_2 and thus strongly affects the CO_2 storage capability [14].

After the injection, the CO_2 pressure in the coal seam decreases gradually with the injection well as a center, as displayed in Fig. 12. Due to the variation of CO_2 pressure with the distance from the injection well, matrix deformation and effective stress effect differ remarkably at different positions, so does the permeability values. In CO_2 storage process, the variation of permeability with the change of distance from the injection well is shown in Fig. 12. Fig. 12(a) indicates that the permeability does not rebound or recover with the change of distance, which can be divided into two situations: One is that permeability value decreases but, even if the gas pressure reaches an atmosphere, does not meet economical CO_2 storage threshold 1 mD [58]; the coal with such change in permeability is relatively suitable for CO_2 storage projects because CO_2 injection will not be severely affected by the falling permeability. The other is that permeability declines to 1 mD at a certain position, forming a wall to impede CO_2 from moving away; the CO_2 storage can only be achieved in a small area around the well, so coal seams with such conditions are inapplicable for CO_2 storage. Permeability rebound and recovery with the change of distance from the injection well is shown in Fig. 12(b), which, similarly, can be introduced from two situations. If the permeability value corresponding to rebound is higher than 1 mD when the permeability changes with distance from the injection well, the permeability of the whole area reached by injected CO_2 is greater than 1 mD. Coal seams with such conditions are appropriate for storing large CO_2 especially when the position of permeability recovery is closer to the injection well. On the contrary, if permeability value is lower than 1 mD before rebound, the coal seam is unsuitable for storing massive CO_2.

The above analysis of several forms of permeability evolution with different distances from the injection well has uncovered the direct relationship between CO_2 storage capability and permeability variation. The influences of different forms of permeability evolution on CO_2 storage capability differ to a certain extent. The permeability rebound and recovery varying with positions have a more complex impact on CO_2 storage capability, which is worthy of in-depth study in the future. Different forms of permeability evolution are resulted from the difference in coal seam parameters and CO_2 injection pressures. Therefore, basic parameters of coal seam should be known and suitable CO_2 injection pressure should be selected before CO_2 storage projects, in order to understand the specific laws and forms of permeability evolution. Only in this way can massive CO_2 be injected and stored effectively.

4. Conclusions

Based on the influence of competition between effective stress transformation and adsorption-induced matrix deformation, the evolution model of fracture aperture during methane extraction is established. Classical cubic law is applied to connect fracture aperture and coal permeability to get the evolution model of permeability, and then factors influencing rebound and recovery pressure are obtained. The influences of different coal parameters on permeability rebound and recovery effect are the predominant focus in this paper. In addition, the macroscopic relationship between CO_2 storage capability and permeability rebound and recovery effect are discussed. Based on the above work, main conclusions are drawn as follows:

(1) Coal fracture system can be abstracted to the hard part and the soft part, so the coal deformation induced by effective stress can be described by engineering strain and natural strain. Due to the matrix bridge, only part of total deformation contributes to fracture aperture change. Based on the competition between effective stress transformation and matrix deformation, a new evolution model of fracture aperture varying with the gas pressure is established, and the evolution model of permeability is obtained by connecting the change of fracture aperture and permeability change using the classical cubic law.
(2) The factors influencing rebound and the recovery pressure are gained on the basis of the permeability evolution model and reasonable assumptions. An analysis is conducted on the influences of initial coal reservoir pressure, coal cleat compressibility and internal swelling coefficient on permeability rebound and recovery effect, respectively. Results show that the three factors all have great impacts on permeability rebound and recovery, yet specific variation laws of their influences vary for coal with different combinations of basic parameters. Generally, permeability will not rebound or recover when initial coal reservoir pressure or coal cleat compressibility is lower than their switching thresholds, or when internal swelling coefficient is greater than its switching threshold.

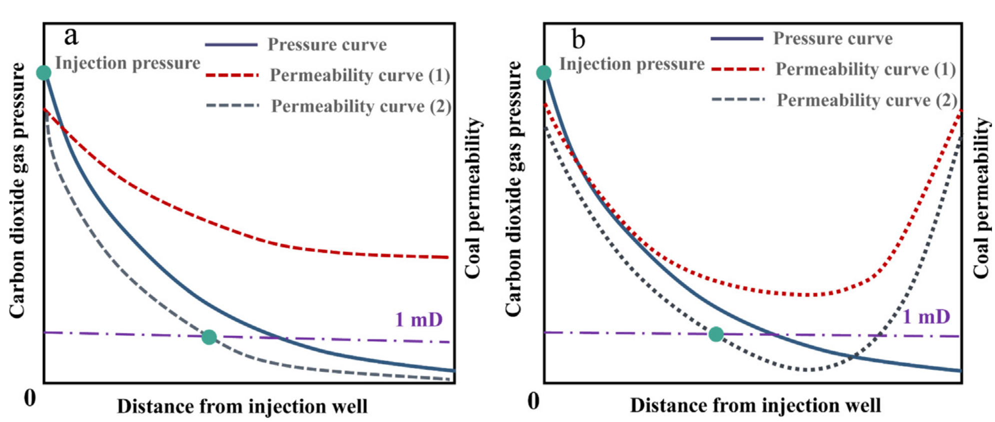

Fig. 12. Evolution laws of permeability with different distance to the injection well.

(3) CO_2 storage has the same influencing mechanism as methane extraction on coal permeability, and permeability rebound and recovery also greatly influence CO_2 storage capacity. If permeability value decreases with the increase of distance from the injection well and its minimum is not smaller than the economic threshold of CO_2 storage, the coal seam may be suitable for CO_2 storage; if it rises after falls and the value corresponding to rebound is least larger than the economic threshold of CO_2 storage together with the recovery position near the injection well, the coal seam is appropriate for huge CO_2 storage. Therefore, it is of guiding significance for CO_2 storage projects to accurately master the evolution laws of coal permeability.

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] Pillalamarry 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.
[2] Davidson RM, Sloss LL, Clarke LB. Coalbed methane extraction. London: IEA Coal Research; 1995.
[3] 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.
[4] Hebblewhite B, Galvin J. A review of the geomechanics aspects of a double fatality coal burst at Austar Colliery in NSW, Australia in April 2014. Int J Min Sci Technol 2017;27(1):3–7.
[5] Mark C. Coal bursts that occur during development: a rock mechanics enigma. Int J Min Sci Technol 2018;28(1):35–42.
[6] Hu Z-X, Hu X-M, Cheng W-M, Lu W. Influence of synthetic conditions on the performance of melamine–phenol–formaldehyde resin microcapsules. High Perform Polym 2018. 0954008318758489.
[7] Zhang Q, Hu XM, Wu MY, Zhao YY, Yu C. Effects of different catalysts on the structure and properties of polyurethane/water glass grouting materials. J Appl Polym Sci 2018;46460.
[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] Cheng Y-P, Wang L, Zhang X-L. Environmental impact of coal mine methane emissions and responding strategies in China. Int J Greenhouse Gas Control 2011;5(1):157–66.
[10] 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(2–3):121–56.
[11] 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.
[12] Baran P, Cygankiewicz J, Zarębska K. Carbon dioxide sorption on Polish ortholignite coal in low and elevated pressure. J CO2 Util 2013;3:44–8.
[13] Zhang X, Ranjith P, Perera M, Ranathunga A, Haque A. Gas transportation and enhanced coalbed methane recovery processes in deep coal seams: a review. Energy Fuels 2016;30(11):8832–49.
[14] Perera M, Ranjith P, Choi S, Airey D. The effects of sub-critical and super-critical carbon dioxide adsorption-induced coal matrix swelling on the permeability of naturally fractured black coal. Energy 2011;36(11):6442–50.
[15] Cui X, Bustin RM. Volumetric strain associated with methane desorption and its impact on coalbed gas production from deep coal seams. AAPG Bull 2005;89(9):1181–202.
[16] Ye Z, Chen D, Wang J. Evaluation of the non-Darcy effect in coalbed methane production. Fuel 2014;121:1–10.
[17] 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.
[18] 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.
[19] Palmer I, Mansoori J. How permeability depends on stress and pore pressure in coalbeds: a new model. SPE annual technical conference and exhibition. Society of Petroleum Engineers; 1996.
[20] Robertson EP, Christiansen RL. Modeling laboratory permeability in coal using sorption-induced strain data. SPE Reservoir Eval Eng 2007;10(03):260–9.
[21] Pini R, Ottiger S, Burlini L, Storti G, Mazzotti M. Role of adsorption and swelling on the dynamics of gas injection in coal. J Geophys Res Solid Earth 2009;114(B4).
[22] Liu J, Wang J, Chen Z, Wang S, Elsworth D, Jiang Y. Impact of transition from local swelling to macro swelling on the evolution of coal permeability. Int J Coal Geol 2011;88(1):31–40.
[23] Liu J, Chen Z, Elsworth D, Miao X, Mao X. Evolution of coal permeability from stress-controlled to displacement-controlled swelling conditions. Fuel 2011;90(10):2987–97.
[24] 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):8968–76.
[25] Chen D, Pan Z, Liu J, Connell LD. An improved relative permeability model for coal reservoirs. Int J Coal Geol 2013;109:45–57.
[26] Liu Z, Cheng Y, Jiang J, Li W, Jin K. Interactions between coal seam gas drainage boreholes and the impact of such on borehole patterns. J Nat Gas Sci Eng 2017;38:597–607.
[27] Black DJ. Factors affecting the drainage of gas from coal and methods to improve drainage effectiveness. Sports Biomech 2011;13(2):123–34.
[28] 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.
[29] Oldenburg CM. Geologic carbon sequestration: CO2 transport in depleted gas reservoirs. Gas transport in porous media. Springer; 2006. p. 419–26.
[30] Vishal V, Ranjith P, Pradhan S, Singh T. Permeability of sub-critical carbon dioxide in naturally fractured Indian bituminous coal at a range of down-hole stress conditions. Eng Geol 2013;167:148–56.
[31] Gathitu BB, Chen W-Y, McClure M. Effects of coal interaction with supercritical CO_2: physical structure. Ind Eng Chem Res 2009;48(10):5024–34.
[32] Perera M, Ranjith P, Airey D, Choi S-K. Sub-and super-critical carbon dioxide flow behavior in naturally fractured black coal: an experimental study. Fuel 2011;90(11):3390–7.
[33] Mavko G, Jizba D. Estimating grain-scale fluid effects on velocity dispersion in rocks. Geophysics 1991;56(12):1940–9.
[34] Berryman JG. Estimates and rigorous bounds on pore-fluid enhanced shear modulus in poroelastic media with hard and soft anisotropy. Int J Damage Mech 2006;15(2):133–67.
[35] 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;8:101–10.
[36] 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.
[37] Wu K, Li X, Wang C, Chen Z, Yu W. A model for gas transport in microfractures of shale and tight gas reservoirs. AIChE J 2015;61(6):2079–88.
[38] 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). 150311121630007.
[39] 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.
[40] 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.
[41] 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.
[42] Terzaghi K. Die Berechnung der Durchlassigkeitsziffer des Tones aus dem Verlauf der hydrodyn. Spannungsercsheinungen, Sitzber Ak Wiss Wien, Abt IIa; 1923, p. 123.
[43] Biot MA. General theory of three-dimensional consolidation. J Appl Phys 1941;12(2):155–64.
[44] Zhang J, Bai M, Roegiers J-C. On drilling directions for optimizing horizontal well stability using a dual-porosity poroelastic approach. J Petrol Sci Eng 2006;53(1–2):61–76.
[45] Rice JR, Cleary MP. Some basic stress diffusion solutions for fluid-saturated elastic porous media with compressible constituents. Rev Geophys 1976;14(2):227–41.
[46] Mian C, Zhida C. Effective stress laws for multi-porosity media. Appl Math Mech 1999;20(11):1207–13.
[47] Jaeger JC, Cook NG, Zimmerman R. Fundamentals of rock mechanics. John Wiley & Sons; 2009.
[48] Robertson EP, Christiansen RL. A permeability model for coal and other fractured, sorptive-elastic media. Idaho National Laboratory (INL); 2006.
[49] Cui X, Bustin RM, Chikatamarla L. Adsorption-induced coal swelling and stress: implications for methane production and acid gas sequestration into coal seams. J Geophys Res Solid Earth 2007;112(B10).
[50] Karacan CÖ. Swelling-induced volumetric strains internal to a stressed coal associated with CO_2 sorption. Int J Coal Geol 2007;72(3–4):209–20.
[51] Dawson G, Golding S, Esterle J, Massarotto P. Occurrence of minerals within fractures and matrix of selected Bowen and Ruhr Basin coals. Int J Coal Geol 2012;94:150–66.
[52] Liu H-H, Rutqvist J. A new coal-permeability model: internal swelling stress and fracture–matrix interaction. Transp Porous Media 2010;82(1):157–71.
[53] Connell LD, Lu M, Pan Z. An analytical coal permeability model for tri-axial strain and stress conditions. Int J Coal Geol 2010;84(2):103–14.
[54] Chilingar GV. Relationship between porosity, permeability, and grain-size distribution of sands and sandstones. Developments in sedimentology. Elsevier; 1964. p. 71–5.
[55] Wu Y, Liu J, Elsworth D, Miao X, Mao X. Development of anisotropic permeability during coalbed methane production. J Nat Gas Sci Eng 2010;2(4):197–210.
[56] Perera MSA. Influences of CO_2 injection into deep coal seams: a review. Energy Fuels 2017;31(10):10324–34.
[57] Tanaka Y, Abe M, Sawada Y, Tanase D, Ito T, Kasukawa T. Tomakomai CCS demonstration project in Japan, 2014 update. Energy Procedia 2014;63:6111–9.
[58] De Silva P, Ranjith P. Understanding the significance of in situ coal properties for CO_2 sequestration: an experimental and numerical study. Int J Energy Res 2014;38(1):60–9.