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

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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

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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

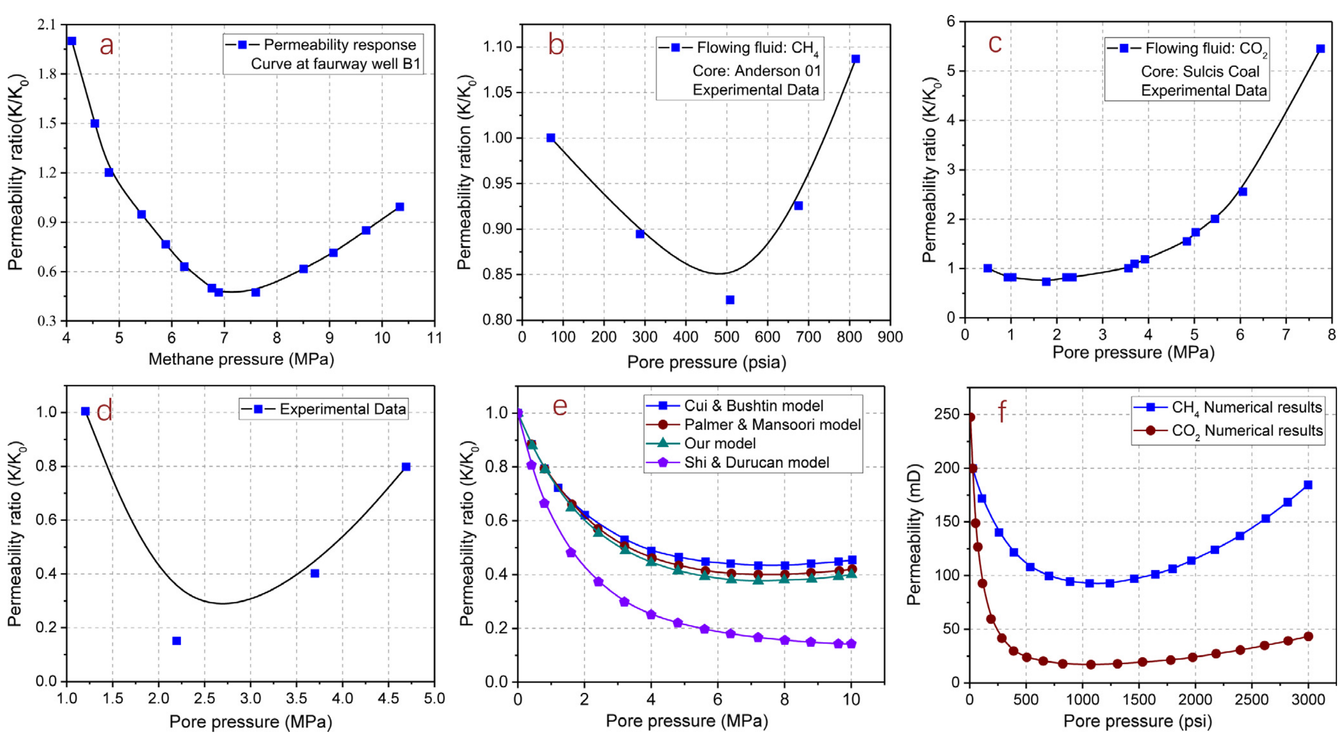

Fig. 1. Phenomena of coal permeability rebound and recovery [19–23].