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

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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 CO_2 [4]. According to statistics, a total of 793 $MtCO_2e$ 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

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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, Pillalamarry 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 can 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, Pillalamarry [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;