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Characteristics of methane desorption and diffusion in coal within a negative pressure environment

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ABSTRACT

To study the characteristics of gas diffusion and changes in the dynamic parameters of coal under a negative pressure environment, experiments were performed to constrain the desorption process under different negative pressures in coal samples at (0.5, 1.5 and 2.5) MPa adsorption equilibrium pressures. The experimental results demonstrate that the relation curves between time and the desorption quantities of coal samples with different negative pressures have shapes similar to that of Langmuir's adsorption isotherm. In addition, all coal samples with different negative pressures have a maximum regarding methane desorption. As the negative pressure increases from 10 kPa to 40 kPa, the limitation gas desorption amount increases from 8.73 to 10.93 mL/g, from 14.91 to 17.75 mL/g, and from 18.30 to 23.27 mL/g, respectively, under 0.5 MPa, 1.5 Mpa and 2.5 Mpa adsorption equilibrium pressure. Moreover, under the same adsorption pressure, the larger the negative pressure becomes, the greater the gas desorption velocity of the first minute (V_1) is. The change of gas desorption velocity with negative pressure during the first minute is an exponential function. The performance under different adsorption equilibrium pressures demonstrates the same regularity. With the increase of negative pressure, interfacial mass transfer resistance also decreases, and the diffusion coefficient and Fourier's criterion of mass transmission increase. This indicates that the negative pressure environment changes the desorption kinetic-parameters of the coal mass and increases the amounts of methane desorption and desorption velocity, which are advantageous for desorption and diffusion of coal methane.

1. Introduction

Coalbed methane (CBM) is composed primarily of methane with low concentrations of carbon dioxide, nitrogen, hydrogen sulphide, sulphur dioxide, and heavier hydrocarbons. It is an unconventional source of natural gas produced from coal seams [1]. Because it is a major greenhouse gas, if CBM is discharged directly into the atmosphere, its greenhouse effect is 21 times greater than that of CO_2 [2–5]. According to estimates in a 2007 report by the International Panel on Climate Change (IPCC), CBM emission was projected to increase to 793 MtCO2e by 2020, of which approximately 85–90% was expected to come from underground coal mines [6,7]. Moreover, CBM is the main natural factor posing a serious threat to the safety of coal mine production in China. With the continuing increase in mining depth and mining intensity, CBM gas accidents have become the most prominent form of coal mine disaster [8,9]. Nevertheless, CBM is also a clean, highly efficient fuel [10]. The energy released in the combustion of 1 m^3 of methane is 35.9 million Joules, equivalent to the combustion of 1.2 kg of standard coal [11]. In recent years, as a result of its efficient clean burning and high calorific value, CBM has gained much attention and is being developed as a significant energy source in various parts of the world [12,13]. On all these counts, the effective extraction and recovery of CBM is of great significance in reducing air pollution, eliminating or reducing the danger in coal mining and meeting the energy requirements for sustainable development [7,14,15].

Statistically, the Chinese CBM reserve at depth of < 2000 m is estimated to be 36.81 trillion m^3, a total representing 14.2% of the resources buried at the same depth in the entire world [16]. However, at present in China, the CBM extraction rate is less than 50%. In 2015, the utilization rate of methane was merely 47.8%, which means that a large volume of methane gas was released into the atmosphere, adding seriously to the greenhouse effect. The root cause of the low utilization rate is that the methane concentration is extremely low during the extraction period. The single greatest factor influencing the methane extraction effect is suction (negative pressure), which induces a pressure gradient and drives methane to the boreholes through fractures

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Table 1
Maceral composition and proximate analysis results of the tested samples.

Vitrinite (%)	Inertinite (%)	Exinite (%)	Minerals (%)	Ash (%)	Moisture (%)	Volatile matter (%)
49.72	45.34	0	4.94	11.72	1.08	8.90

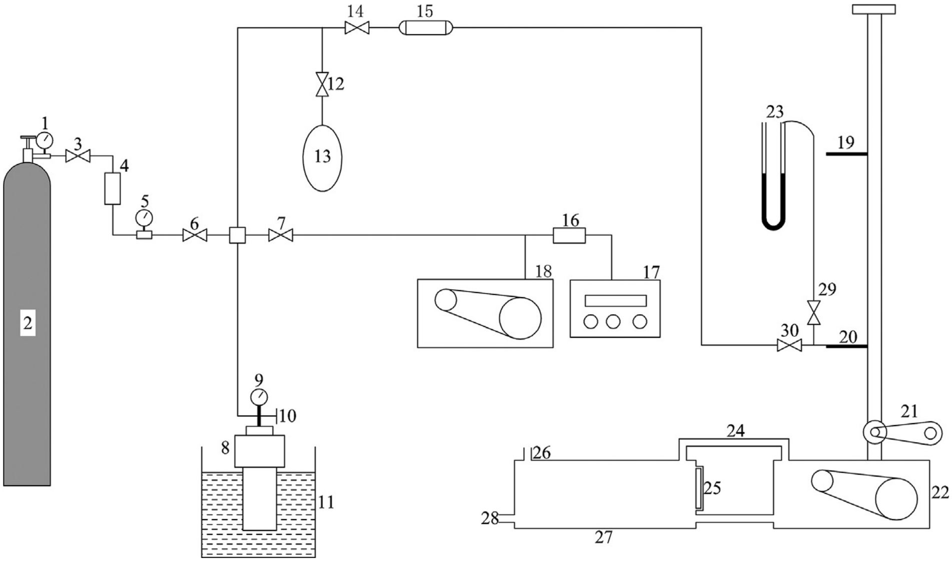

Fig. 1. Schematic of the experimental setup: The components denoted are: 1, 5, 9 – pressure gauge; 2 – gas cylinder; 3, 6, 7, 10, 12, 14, 29, 30 – globe valves; 4 – gas-charge unit; 8 – sample tank; 11 – constant temperature water bath; 13 – vacuum bag; 15 – flowmeter; 16 – pressure transducer; 17 – vacuum gauge; 18 – vacuum pump; 19, 20 – connector; 21 – pressure-regulating valve; 22 – water ring vacuum pump; 23 – pressure difference meter consisting of a U-tube; 24 – coupling hose; 25 – water level gauge; 26 – water inlet; 27 – gas/water separator and 28 – drain.

Fig. 2. Physical image of the negative pressure pipeline equipment.

[11,17]. Theoretically, the methane concentration should increase in the process of methane extraction due to increase in the negative pressure. At present, a constant negative pressure of 13 kPa is widely used in the coal mines of China; however, the methane flow conditions change with increasing extraction time. This can lead to new problems. Therefore, it is of great significance to study the effect of negative pressure on methane migration during the extraction period.

A great deal of research has indicated that CBM occurs in three forms within coal: adsorbed, free, and in solution [18,19], of which the adsorbed form accounts for 80–90% [20]. Coal reservoirs have long been known as porous substances, and the mechanism of gas flow in the pores and cracks of a coal seam is mainly diffusion [21]. Hence, enhancing the diffusion capacity of adsorbed CBM is an effective approach to improving CBM extraction and recovery [22,23]. Significant efforts have been devoted to studying the laws of methane desorption and diffusion in coal in the last few decades. Nie et al. [24,25] analysed the diffusion mechanism of gas in coal pores according to the diffusive form of gas in the porous medium, and determined that the following several modes of gas diffusion occur in a coal body: Fick's diffusion, North's diffusion, transitional diffusion, surface diffusion and crystal diffusion.

Over the past few decades, a great deal of experimental and analytical study has been conducted to measure methane desorption and diffusion in coal. Among the significant factors, the influences of gas type [12,26–30], coal properties [31–34], sample size [28,35,36], gas pressure [37–40], moisture [41,42], temperature [43–45,42] and microstructure analysis [46–48] on diffusion processes have been studied extensively. However, at present, little theoretical research has been performed to provide understanding of the gas diffusion characteristics and kinetic parameters of coal under negative pressures, resulting in the current low methane concentration and utilization rate [11]. In a negative pressure environment, the methane desorption amount, desorption velocity and desorption kinetic parameters in the coal will change. To characterize the phenomena and the effects on negative pressure, a timely investigation was required.

For the present paper, characterization of methane desorption and diffusion for the first three minutes, 30 min, and 360 min was studied by performing a series of gas desorption and diffusion experiments considering two aspects: different negative pressures and different adsorption equilibrium pressures. In addition, the effects of different negative pressures on methane desorption laws, diffusion laws and diffusion kinetic parameters of the coal mass were also analysed. Finally, an effort was made to find a new relationship between the negative pressure and diffusion potential. A concept for optimizing CBM extraction and recovery is provided, which could be used to enhance the rate of methane utilization and solve the key problem in modern coal mining.

2. Materials and methods

2.1. Experimental coal sample

Experimental coal samples were collected from the same No. 3 coal seam of the Duanshi Coal Mine in the Qinshui Basin (Shanxi Province, China). The macerals were the same and had no effect on the experimental results. This coal seam represents a typical high-rank

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