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Experimental investigation on spontaneous imbibition of water in coal: Implications for methane desorption and diffusion

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ABSTRACT

During the process of coal mining and coalbed methane extraction, the application of hydraulic techniques generally leads to the spontaneous imbibition of water in coal seams. To study spontaneous imbibition of water in coal and evaluate its influence on methane desorption and diffusion, experiments of spontaneous imbibition in coal containing methane were conducted under different adsorption equilibrium pressure and water imbibition ratios. The displacement effect of water during imbibition was investigated, and methane desorption was also tested under atmospheric-pressure conditions. Imbibition test results show that adsorbed methane can be displaced by water. The displacement amount and its efficiency increase with water imbibition ratio, but an upper limit on the displacement amount exists because of the limited imbibition capacity. Desorption test results show an inhibitory effect of water blocking on methane desorption and diffusion. The desorption time increases and diffusivity decreases with the imbibition ratio. However, the time-dependent characteristics of desorption ratio indicate that the desorption process is temporarily delayed rather than completely stopped by water blocking. Moreover, the residual methane amount decreases with the water imbibition ratio based on long-time-scale desorption, suggesting that spontaneous imbibition of water can promote methane desorption on the whole. The scale effects of coal samples and actual conditions on methane adsorption, desorption and imbibition are also discussed. These findings show the multiple effects of spontaneous imbibition on methane desorption in coal and help in better understanding the overall effects of water-based treatment techniques on coalbed methane extraction and coal seam gas control for mining safety.

1. Introduction

Spontaneous imbibition refers to the process of a wetting fluid being spontaneously drawn into a porous medium by capillary force and displacing a non-wetting fluid [1–3]. Spontaneous imbibition is an important phenomenon in reservoir engineering, particularly with respect to oil recovery from fractured reservoirs [4–6]. In coal reservoirs, the phenomenon of spontaneous imbibition is also common. Typically, hydraulic measures are usually used to enhance coalbed methane (CBM) extraction or manage gas-induced disasters in coal mines, including coal seam water injection, hydraulic fracturing, hydraulic slotting, etc. [7–10]. During the application of these water-based techniques, water first penetrates into fractures via injection pressure and then flows into matrix pores via spontaneous imbibition under capillary force when the injection pressure is depleted. However, the imbibition effect in coal has rarely been studied.

During the process of imbibition, a large volume of water remains in the coal reservoir. Generally, trapped water may affect gas desorption and transport. Some reports have showed that water inhibits methane desorption in the coal matrix and influences gas extraction [11–14]. Water can cause water blocking in the coal matrix and change coal mechanical properties that have an adverse impact on coal diffusivity and permeability [15–18]. Moreover, the start-up pressure gradient and desorption ratio of gas decreased with the injection of high-pressure water [19,20]. Based on the inhibitory effect of water on gas diffusion, water-based techniques were once used for blocking gas and controlling gas-induced hazards in coal mines. Field applications showed that gas emission increased sharply during injection because of the fracturing effect on the coal seam. In addition, gas emission continued to increase for a long time, although fracturing had ceased [21–23]. This phenomenon might be related to the imbibition effect of water. Unlike conventional natural gas reservoirs, a majority of methane is in an

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adsorbed phase in the coal matrix. It is well known that the adsorption affinity of water in coal is higher than that of methane [24–26]. This means that injected water has the potential ability to displace the adsorbed methane and increase the free methane. As is known, the technology of CO_2 injection enhancing CBM extraction has been widely applied. A primary advantage of this method is the displacement effect of CO_2 on CH_4, which promotes CH_4 desorption by competitive adsorption [27–29]. It is interesting to note that the displacement effect of external water on adsorbed methane in coal has been found via experiments [30]. In particular, experiments of injection water have showed that water promotes methane desorption via this displacement effect though water blocking also occurs [31].

From previous studies, the effects of water on methane occurrence in coal include the following three components: (1) a promotional effect on desorption because of the coal seam pressure relief and permeability increase using high-pressure fluids [32–34]; (2) an inhibitory effect of water blocking on gas desorption diffusion [35–38]; and (3) a displacement effect of water on adsorbed methane [30,31]. The influence mechanism of water on methane desorption and transport is so complicated that the application of hydraulic techniques is limited in coal mines. For example, coal seam water injection was historically applied as a preventive measure against coal and gas outbursts in China's coal mines. However, this measure has lost support in new regulations because it results in unstable conditions. Particularly, the cause of the decrease in gas content in application areas is still not well understood. The fracturing effect of hydraulic measures on methane desorption is more distinct than the displacement and inhibitory effects which are closely related to spontaneous imbibition of water. Therefore, a critical strategy is to determine the overall influence of water on methane desorption and transport. However, no matter whether in the field or in the laboratory, it is difficult to differentiate the displacement and inhibitory effect. Among the main reasons is that spontaneous imbibition, as a principal transport mode of water in coal, is ignored. Further, it is not clear what type of role imbibition plays in CBM recovery or gas control when using hydraulic measures. Therefore, to gain a better understanding of water's influence particularly on methane desorption and diffusion in coal, a direct investigation of the imbibition effect is necessary and was conducted.

In this study, an innovative experimental method is developed to study spontaneous imbibition of water in coal containing methane. A series of imbibition tests are conducted to investigate the displacement effect of water on methane. And then, we investigate the water blocking effect through the natural desorption tests under atmospheric-pressure conditions. Finally, the overall effects of imbibition on methane desorption in coal are evaluated. This study therefore lays the foundation for understanding water-coal-methane interactions and especially provides an innovative way to investigate the influence mechanism of water on gas desorption and transport in coal.

2. Experimental section

2.1. Sample preparation

The bulk coal samples from No. 3 coal seam in Yonghong coal mine of Qinshui basin in Shanxi, China, was prepared for the experimental work. The sampling site is show in Fig. 1-*a*, *b*. The coal-bearing stratum of Shanxi formation in lower Permian includes No.1, 2 and 3 coal seam (Fig. 1-*c*). The bulk coal samples were collected from No. 3 coal seam. The physical parameters of coal which were evaluated using Chinese national standards (GB/T 212-2008, 217-2008, 6949-1998, 8899-2013) are shown in Table 1: ash content (A_{ad}), volatile matter (V_{ad}), moisture (M_{ad}), true relative density (TRD), apparent relative density (ARD), porosity, macerals and vitrinite reflectance (Ro, max). The bulk coals are first ground and sieved to obtain the desired sample size, giving an average radius of 0.30 mm in order to improve the homogeneity of all experiment samples. These finally were cut into cylindrical samples with 50 mm in diameter and 80 mm in length mixed with moderate pure water under the same pressure loading. The coal samples were firstly dried in the 105 °C drying oven. After dehydration, they were kept in the desiccator for use.

2.2. Experimental setup

The experiment system for imbibition simulation is shown in Fig. 2, which includes the vacuum degassing system, adsorption equilibrium system, water injection device, data processing system and desorption device. The vacuum degassing system consists of a vacuum pump, vacuum gauge and vacuum sensor. The adsorption equilibrium system includes a special coal sample cell, reference cell and thermostat. The water injection device includes four long screws and nuts, bulkhead and base. The data processing system includes high accuracy pressure sensors, data collector, and computer, which are used for collecting the gas pressure data. The desorption device includes burettes and water trough.

The original coal seams in the subsurface are usually in a adsorption equilibrium status prior to mining activities or CBM exploration. For CBM, water from hydraulic measures belongs to external fluid. To simulate the imbibition effect of water-based measures, the coal sample should reach adsorption equilibrium before injecting water. In contrast to the traditional experimental methods, water is kept in the adsorption system in advance. The volume of free space in adsorption system will not change until water is injected into sample cells.

2.3. Experimental procedure

Experiments are conducted under different imbibition ratio (IR) and initial adsorption equilibrium pressure (IEP) of methane. IR is defined as follows [39,40]:

$$IR = (m_{H_2O}/m_c) \times 100\% \tag{1}$$

where m_{H_2O} is mass of water adsorption uptake in coal (g), and m_c is the mass of coal sample (g).

A step-by-step procedure of the experiments is described in details as follows:

(1) Preparation work: Calibrate the sample cell volume and double-check the tightness of the whole test system. Weigh the distilled water according to the mass of the coal sample and scheduled IR (2%, 4%, 6%, 8%, and 10%). Then, the distilled water is transferred into the base of the sample cell and the residual space of the base is filled by the metal plate.
(2) Adsorption equilibrium: Place the coal sample into the sample cell and put the sample cell in the thermostat at a temperature of 30 °C. The void volume of free space in the sample cell is determined using helium. Vacuum the sample cell until the vacuum degree is less than 10 Pa. Then, methane is injected into the sample cell via the reference cell to reach adsorption equilibrium at the predefined IEP (0.5, 0.74, 1.0, 1.5 and 2.5 MPa). The amount of adsorbed methane in the coal sample under IEP is calculated as follows [40]:

$$Q_a = (Q_{rc} - Q'_{rc} - Q_{sc})/m_c = \left(\frac{22400PV_{rc}}{m_cZRT}\right) - \left(\frac{22400PV_{rc}}{m_cZRT}\right)' - \left(\frac{22400PV_{sc}}{m_cZRT}\right)_{sc} \tag{2}$$

where Q_a is adsorption amount (cm^3/g), Q_{rc} and Q'_{rc} are the methane volume in the reference cell before and after gas injection, respectively (cm^3), Q_{sc} is the volume of free methane in sample cell under IEP (cm^3), P is the methane pressure in reference/sample cell (MPa), V_{rc} and V_{sc} are the volume of free space in the reference and sample cell, respectively (cm^3), Z is the compressibility coefficient of methane, R is the universal gas constant, 8.314 J/(mol·K), T is the temperature (K), V_{rc} and V_{sc} are pre-determined by a series of injections using helium.