Influence of water injection on the desorption characteristics of coalbed methane

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Abstract
Hydraulic methods have been extensively employed to improve the production rate of commercially viable coalbed methane and prevent potential mining disasters resulting from the production of this methane by increasing the permeability of coal seams. In this paper, an experimental system with a stirrer was utilized to study the effects of water injection on the gas desorption characteristics of coal seams. Pressure-released desorption values and total gas desorption values under conditions of different adsorption equilibrium pressures and water contents were determined. The results show that both the free gas and the adsorbed gas could be replaced by the injected water, causing the system pressure to increase significantly. When releasing the system pressure, the gas desorption value of the water-injected coal sample was reduced. After water injection, the total desorption value of the coal was increased. Thus, water injection could help to promote coal gas desorption.

KEY WORDS
desorbed gas replacement, gas desorption, injected water, pressure released

1 | INTRODUCTION

The main component of coalbed methane is CH4; other gases in coalbed methane include carbon dioxide and nitrogen. Coalbed methane has been regarded as the cause of explosions and coal and gas outbursts in underground coal mining since the 1800s.1-5 which becomes a more serious issue as mining extends to deeper seams.6,7 However, coalbed methane liberated from coal via vertical wells in front of the mine face was not considered a natural gas resource and viable commercial commodity until the 20th century.8 Compared to the conventional natural gas reserve, the total amount of coalbed methane in the world is estimated to be $8.94 \times 10^{13}$ m$^3$, and the recoverable reserve is nearly $1.35 \times 10^{13}$ m$^3$,9 which indicates a significant value in terms of scientific research and profit.10 Nevertheless, coal seams have a higher gas absorption capacity due to their
metamorphic pores and fractures providing larger micropore volumes. Adsorbed gas and free gas are two main states of coalbed methane in coal seams, with the majority as adsorption gas.\textsuperscript{11-14} The desorption properties of coalbed methane are closely associated with coal physical properties and the external environment.\textsuperscript{15,16} As the permeability is often very low for complex coal structures, hydraulic methods that enable an increase in the water content and thus reduce the gas pressure of coal seams, including coal seam water injection,\textsuperscript{17} hydraulic punching, and hydraulic extrusion, are the main techniques used to improve permeability before coal mining.\textsuperscript{18-20} Field tests have shown that the gas emission from coal increases during the water injection process \textsuperscript{18,21-23}, in contrast, experimental results have shown that an increase in the moisture content of coal has a significant inhibitory desorption effect on the adsorbed gas.\textsuperscript{24,25} Thus, it is necessary to determine the influence of external water on the desorption character of the adsorbed coalbed methane in coal.

To determine the influence of water injection on the desorption characteristics of coalbed methane, an apparatus with a stirrer was developed to inject high-pressure water into a coal sample tank. The gas desorption processes of coal samples were tested under different adsorption equilibrium pressures and injected water conditions. According to the experimental data, the influences of water injection on gas desorption in coal were studied to improve the basic theory of the effect of water injection on coal gas adsorption and desorption.

2 | EXPERIMENTAL APPARATUS AND PROCESS

Figure 1 is a schematic of the experimental apparatus. A sample tank with a stirrer was used to ensure uniform mixing of the injected water. A thermostatic water bath with an accuracy of 0.1°C was employed to keep the system temperature constant, and a real-time gas flow meter with a maximum measurement value of 1000 mL and accuracy of 0.5 mL was used to measure the desorbed gas volume.

Coal samples were taken from the Lvtang coal mine of the Shandong Energy Guizhou Mining Co., Ltd., which is located in Bijie, Guizhou Province, in northwest China. The exploration area of the mine is 84.88 km\textsuperscript{2}, with geological reserves of 660 million tons and recoverable reserves of 150 million tons. Because the mine is located in a karst landform, karst, karst collapse, faults, and folds occur throughout the mining area, and the average thickness of topsoil is approximately 25 m. There are three layers of recoverable coal seam in the shallow mining area, which are numbered fields 6, 7, and 8, with seam thicknesses of 1.71, 0.92, and 0.68 m, respectively. Coal seam 6 is anthracite with a high coalbed methane pressure and a high fracture degree and is easily affected by landslides because of its shallow burial depth. Therefore, coal seam 6 was identified as being at risk of coal and gas outbursts. All the coal samples were collected from seam 6 at an in situ pressure of 1.2 MPa and a temperature of 35°C. The proximate and ultimate analyses indexes of the coal samples are determined, as shown in Table 1.

The pore characteristics of the coal samples were measured by intrusive mercury. Figure 2 shows a typical mercury intrusion curve. The amount of mercury forced into a coal sample increased rapidly when the injection pressure was low because the mercury preferentially entered the large pores. As the injection pressure increased, the mercury gradually entered the mesopores, small pores, and micropores, the volume of which was equal to the increase in mercury volume.

Table 2 shows the pore distribution of the coal samples. Large pores account for nearly 50% of the pore volume, more than twice the figure for small pores, which
constitute the capillary condensation and the gas diffusion space. Micropores have the largest proportion of specific surface area at approximately 70%, and the percentages for other pores are significantly lower, in agreement with the results of other scholars.

The coal samples were sieved at a particle size of 1–3 mm and dried in nitrogen at 65°C for more than twenty-four hours. Each experiment followed the procedure described here: (a) after loading 75 g of dried sample into the sample tank, the experimental system was continually degassed for more than eight hours until the vacuum gauge was less than 133 Pa. (b) The experimental system was kept at a constant temperature of 35°C using a thermostatic water bath, and the balance tank and sample tank were filled with helium with a purity of 99.9% at a predetermined pressure. After eight hours of adsorption, the tanks were degassed, and the flow volume of the helium was recorded as the free space of the tanks. (c) The balance tank and the sample tank were filled with methane with a purity of 99.9% at a predetermined pressure. The system was kept at a constant temperature of 35°C for at least eight hours to ensure the completion of the adsorption process. (d) A certain amount of water was added to the sample tank by the metering pump, and the water and coal samples were mixed by the stirrer for thirty minutes. The experimental system was kept at 35°C until the pressure in the tanks was constant. The temperature and pressure of the system were recorded at time intervals to calculate the amount of adsorbed and desorbed gas during the experimental process. (e) The coal sample tank was opened to connect the atmospheric pressure, and the desorption velocity of methane gas was measured by a gas flow meter.

### RESULTS AND DISCUSSION

#### 3.1 Methane molecules replaced by water molecules

Injecting water into the coal sample causes a significant pressure change in the sample tank. Figure 3 shows the typical
pressure vibration of the sample tank caused by water injection. The gas pressure increases rapidly in the water injection process, and it continues to increase slowly after the water injection until reaching a re-adsorption balance pressure, which is markedly higher than before. The pressure change in the sample tank can be attributed to the volume change caused by the injected water and subsequent free gas increase owing to water replacement. As shown in Figure 4, in the water injection process, the injected water will occupy a certain volume of the sample tank by compressing the free gas volume of the sample tank, and this is the main reason for the pressure change. The water molecules will compete with the adsorbed methane molecules once the coal sample contacts the injected water. The water molecules are able to bind with the coal matrix because of the abundant hydrophilic groups in coal, which causes the replacement of adsorbed methane by water.

Figure 5 shows the amount of adsorbed methane replaced by the injected water at different equilibrium pressures. The amount of replaced adsorption methane increases gradually but significantly with the increase in moisture content. In addition, there is a critical moisture content, after which the further increase in injection water has less of an impact on gas replacement. A higher gas adsorption equilibrium brings about a higher critical moisture content of the coal samples.

### 3.2 Amount of desorbed gas after pressure release

Figure 6 shows the change in the amount of desorbed gas with moisture content after the pressure is released. Compared to that of coal samples with high moisture contents under the same adsorption pressure, more desorbed gas is observed in coal samples with lower moisture contents. This difference is more obvious when the moisture content in coal samples is low.

A scanning electron microscope with 5000× magnification was used to observe the morphological changes in the coal samples before and after water injection. As shown in Figure 7, a coal sample is dry before water injection, and the surface of the anthracite is clearly visible. The pores of a coal sample are irregularly shaped and have rough surfaces and complex fractal characteristics due to the water injection. It is known that moisture plays an important role in the shrinkage and swelling of coal, and consequently, pore formation plays an important role in diffusion control. The test coal samples in the present research are anthracite with a high metamorphic grade and porosity. The abundant oxygen functional groups in the coal samples are strongly hydrophilic and have a high methane gas absorption capacity. The oxygen functional groups endow the coal samples with colloidal features; thus, the volume shrinkage and expansion of coal samples will occur in the process of degassing and adsorbing methane gas, respectively. The released methane gas initially desorbs from the surface of the coal sample. The volume of methane gas that fills the free space, as well as the adherent gas on the surface of the large pores, is primarily reduced. Afterward, methane gas desorption proceeds at the surfaces of the micropores and mesopores. As shown in Figure 7, some of the absorption spaces and micropore channels are occupied as the water replaces the methane gas. After opening the pressure relieve valve, the absorbed methane gas is desorbed under the influence of the gas pressure and concentration gradient. In addition, the absorbed space in the micropores in the coal sample is reduced, and the micropore channel formed by methane gas desorption is closed or blocked by water molecules. Therefore, the communicating pores connect the methane gas absorption space and the desorption space. Thus, the desorption capacity of absorbed methane gas is reduced and
that of the released methane gas is simultaneously reduced. Considering the different equilibrium absorption methane gas pressures and uniform water contents in the coal samples, the larger the equilibrium absorption methane gas pressure is, the higher the desorption volume of the released methane gas.

3.3 | Comprehensive effects of water injection on gas desorption

The analysis above indicates that the influences of water injection on gas desorption include the influence of the water injection process and the effect of the pressure release after water injection. The comprehensive effects of water injection on gas desorption can be studied by analyzing the change in the total amount of desorbed gas. The effects of water injection on gas desorption can be discussed by comparing the difference in the total amounts of desorbed gas between the wet and dry coal samples. If the total amount of desorbed gas in the coal samples that underwent water injection is larger than that of the dry coal samples, the injected water promotes gas desorption. If the opposite trend is observed, water injection inhibits gas desorption. Otherwise, the injection water has no effect on the gas desorption. Figure 8 shows the difference in the total amounts of desorbed gas between the wet and dry coal samples.

FIGURE 5 Amount of adsorbed methane replaced by injection water

FIGURE 6 Change in the amount of desorbed gas with moisture content after pressure release

FIGURE 7 Schematic of coal shrinkage and channel blocking due to water
Table 3 shows that only three groups of data of the total amount of desorbed gas are negative, accounting for 15%. The rest of the test data are positive, indicating that moisture contributes to the gas desorption of coal samples. From the experimental data, the total amount of desorbed gas in the coal is 0.92 mL/g under a 0.50 MPa adsorption equilibrium pressure, and the effect of moisture on the promotion gas desorption is significant. The increase in the total amount of desorbed gas increase with the moisture content under the same adsorption equilibrium pressure, also indicating that the injection water promotes coal gas desorption. The results show that injecting water into the coal seam is can improve the production rate and the permeability of coal seams. This also promotes gas desorption via water replacement. Thus, coal seam water injection is an effective method to prevent coal and gas outbursts.

![Figure 8](image_url)  
**Figure 8** Difference in the total amounts of desorbed gas between wet and dry coal samples

**Table 3** Amount of desorbed gas at different moisture and equilibrium pressures

| $P_e$(MPa) | $M$(%) | $V_r$(mL/g) | $V_p$(mL/g) | $V_c$(mL/g) |
|------------|--------|-------------|-------------|-------------|
| 0.50       | 0      | 8.53        | 0           | 0           |
| 0.96       | 0.30   | 8.17        | 0.06        | 2.92        |
| 3.13       | 2.83   | 5.82        | 0.12        | 2.52        |
| 7.06       | 7.30   | 4.15        | 2.92        |             |
| 12.05      | 7.60   | 3.45        | 2.52        |             |
| 1.00       | 0      | 15.20       | 0           | 0           |
| 0.65       | 0.67   | 14.33       | 0.20        | 0.44        |
| 2.81       | 5.70   | 9.63        | 0.13        | 0.62        |
| 5.10       | 9.47   | 6.17        | 0.44        |             |
| 8.40       | 11.00  | 4.82        | 0.62        |             |
| 1.50       | 0      | 18.25       | 0           | 0           |
| 2.78       | 3.73   | 13.34       | 1.18        |             |
| 3.77       | 7.35   | 11.38       | 0.48        |             |
| 6.09       | 8.33   | 10.28       | 0.36        |             |
| 11.25      | 10.97  | 7.92        | 0.64        |             |
| 2.00       | 0      | 24.66       | 0           | 0           |
| 1.37       | 3.35   | 21.46       | 0.33        |             |
| 4.35       | 6.27   | 18.75       | 0.36        |             |
| 7.25       | 8.47   | 17.23       | 1.04        |             |
| 10.05      | 11.88  | 13.92       | 1.14        |             |

*Note: $P_e$ is the adsorption equilibrium pressure, $M$ is the moisture content of the coal sample, $V_r$ is the amount of desorbed gas replaced by water, $V_p$ is the amount of desorbed gas after pressure release, and $V_c$ is the change in the total amount of desorbed gas.*

Table 3 shows that only three groups of data of the total amount of desorbed gas are negative, accounting for 15%. The rest of the test data are positive, indicating that moisture contributes to the gas desorption of coal samples. From the experimental data, the total amount of desorbed gas in the coal is 0.92 mL/g under a 0.50 MPa adsorption equilibrium pressure, and the effect of moisture on the promotion gas desorption is significant. The increase in the total amount of desorbed gas increase with the moisture content under the same adsorption equilibrium pressure, also indicating that the injection water promotes coal gas desorption. The results show that injecting water into the coal seam is can improve the production rate and the permeability of coal seams. This also promotes gas desorption via water replacement. Thus, coal seam water injection is an effective method to prevent coal and gas outbursts.

### 4 CONCLUSIONS

The effects of water injection on the gas desorption characteristics of coal were experimentally studied by employing a high-pressure adsorption and water injection experimental system with a mixing device. The negative effects of water injection into coal seams include the swelling of the coal resulting from the shrinkage of pores, the blockage of the pore channels caused by the water molecules, and the limitation of the gas desorption. The positive effects of water injection into coal are more significant, including the improvement in the permeability by coal seam crushing and the replacement of adsorbed coalbed molecular methane, which can promote coalbed methane desorption. The experimental results are summarized as follows:

1. There is a critical moisture content above which continued water injection will have less of an impact on gas replacement. A higher gas adsorption equilibrium pressure will lead to a higher critical moisture content of coal samples.
2. The difference in the total amounts of desorbed gas between wet and dry coal samples increases with increasing moisture content, which indicates that the injected water promotes gas desorption.

The experimental results indicate that water injection is an effective method to prevent the occurrence of coal and gas outbursts, and it can also improve the production rate of coalbed methane.

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