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Water Injection Into Coal Seams for Outburst Prevention: The Coupling Effect of Gas Displacement and Desorption Inhibition

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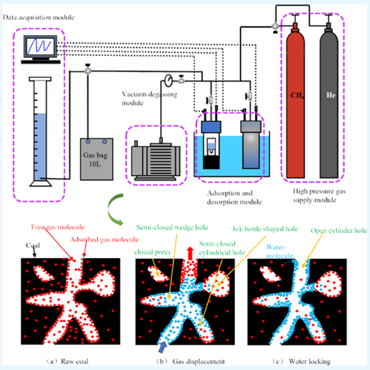
ABSTRACT: Gassy coal seams generally have low permeability and dry coal bodies, which are susceptible to coal and gas outburst hazards in the process of mining. Water injection into coal seams can significantly alter the gas release rate and flow behavior. However, water has dual effects on coal seams: gas displacement and water-locking, and the coupling mechanism of these two effects is not clear in the whole process of coal seam water injection. By measuring high-pressure gas adsorption isotherms and gas diffusion initial velocity, it was found that both the Langmuir adsorption constant *a* and gas diffusion initial velocity ΔP decrease with the increase of water content, which would reduce outburst risks. Through the self-developed integrated experimental device of "gas adsorption + water injection displacement + gas desorption", the changing rules of gas displacement amount, desorption amount, and water lock amount under different water injection conditions were studied. The results show that when the water injection ratio increases from 6 to 25%, the gas displacement would increase from 0.62 to 1.16 mL/g, with an increase of 87.09%. Also, at the same time, the gas desorption capacity would decrease from 4.86 to 4.05 mL/g after pressure relief, with a decrease of 16.67%. The amount of water-locking increased from 0.11 to 0.38 mL/g. The effect of water injection to control coal and gas outburst occurs in two different water injection stages. In the process of water injection, water plays a major role in gas displacement, which is conducive to reducing the gas content of the coal seam. After the completion of water injection, the static water pressure remaining in the coal seam can reduce the gas emission rate. The combination of these two effects can effectively reduce the risk of outbursts.



1. INTRODUCTION

Coal and gas outburst is a kind of dynamic disaster in the coal mine caused by the rapid release of deformation energy and gas expansion energy of the coal seam.[1] Poor gas extraction is an important factor that induces coal and gas outburst.[2] Coal mines often use coal seam water injection,[3] hydraulic punching,[4] hydraulic cutting,[5] hydraulic fracturing,[6] hydraulic extrusion,[7] and its integration with blasting[8] and many other hydraulic-based measures to improve coal seam permeability and gas extraction efficiency and so as to eliminate the outburst risk. After water invasion, a large number of water molecules inhibit the diffusion and seepage of gas in coal seams and reduce the desorption rate and desorption capacity of gas.[9] Studies have shown that methane molecules adsorbed on the surface of coal are replaced by water molecules in the heat release process, which releases energy and requires energy for adsorption, indicating that the adsorption capacity of coal for water molecules is stronger than that for methane molecules.[10] There is a critical injection pressure for coal injection in the coal seam. When the injection pressure is less than the critical value, the displacement time decreases rapidly with an increase in the injection pressure. When the injection pressure exceeds the critical injection pressure, the change of displacement time is not so significant.[11] When the coal seam water contents are 2, 4, and 6%, the exhaust volume increases rapidly; especially, when the water content is close to 10%, the exhaust volume almost reaches the peak.[12] In the process of water−methane displacement, with the increase of water injection, the displacement methane content increases gradually, but the displacement methane content increases first and then decreases. In addition, the water−methane displacement process has a time effect, and the methane displacement process lags behind the water injection process.[13]

Coal is a typical porous medium, and its pore structure is very complex.[14] Coal seam gas mainly exists in two forms: the adsorbed state and the free state.[15] Some scholars believe that the water entering the coal can promote the desorption of the adsorbed gas and drive the gas out through competitive adsorption.[16] Lin et al.[17] used Materials Studio to simulate this process and found that the total energy of state 1 was 9.69 kJ/

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mol higher than that of state 2. According to the principle of minimum energy, water molecules have stronger adsorption capacity than methane molecules; that is, water molecules are more easily adsorbed on the surface of the coal matrix than methane molecules, so states 1 to 2 can be spontaneous.

In a dual-porosity medium like coal, high-pressure water first drives part of the free gas from large cracks to gas drainage boreholes.[18] When water enters the small pores of coal and carries out competitive adsorption with gas, water is adsorbed on the surface of coal pores as a continuous layer of water molecules.[19] Part of the adsorbed gas is replaced by water, becomes the free state, and diffuses around, which increases the pore pressure and decreases along the flow direction of water injection. The uneven distribution of pore pressure forms the pressure gradient.[20] According to the two-phase displacement theory of porous media, free gas migrates from high pore pressure to low pore pressure areas,[21] resulting in the gas displacement phenomenon. Chen et al.[22,23] developed a test system for gas adsorption—water injection displacement—gas desorption and found that adding extra moisture had an obvious displacement effect on the gas in the adsorption equilibrium state. Under the same equilibrium pressure, the gas displacement amount and displacement rate of all coal samples increased with an increase in the external moisture. Xiao and Wang[24] injected water into granular coal in the laboratory and found that coal under a certain gas pressure showed the displacement effect during the process of water injection. According to their calculation, about 10% of the gas was replaced by water.

However, after the coal seam pressure relief, the water trapped in the pores will hinder the rapid desorption and diffusion of gas.[25] As shown in Figure 1, there are three main types of obstruction in the coal matrix.[26] First, the diffusion path of methane in a coal matrix is reduced due to water, and the effective diffusion path becomes more tortuous. Second, the water film narrows the diffusion path, leading to an increase in diffusion resistance. Third, because it is completely blocked by water in the closed pores, it is difficult for methane at the pore throat to migrate to the outside and steam inhibits methane desorption in the tiny pores where liquid water cannot penetrate.

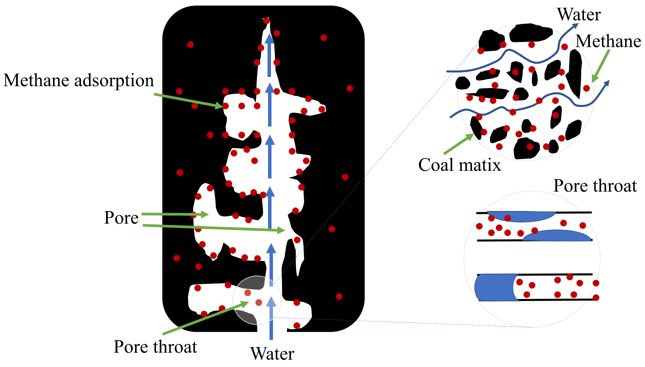


Figure 1. Schematic of water-locking in coal [Reprinted from ref 26 , Copyright (2018), with permission from Elsevier].

Therefore, some scholars believe that water inhibits gas release through the water-locking effect.[27] Zhang et al.[28] revealed the phenomenon of liquid gas storage in the process of external liquid invasion of gas-containing coal through experiments and found that the water-locking effect would reduce the amount as well as the rate of gas desorption and release. Zhao et al.[29,30] found through tests that the gas desorption rate of water-containing coal samples was only 50—70% of that of dry coal samples, and the time for gas desorption to reach equilibrium was also increased to various degrees compared with dry coal samples. Wu et al.[26] evaluated the water locking phenomenon through three indexes: desorption time, diffusion rate, and desorption ratio. Their results showed that the gas was not completely blocked by water and that the desorption process was temporarily delayed. Mou et al.[31] studied the impact of moisture content in coal samples on the gas diffusion initial velocity and found that the gas diffusion initial velocity and water content had a logarithmic relationship. The results showed that water would block part of the pore channels in coal and slow the gas diffusion initial velocity.

In summary, water injection into coal seams can not only promote gas desorption through the gas displacement effect but also inhibit gas desorption and release through the water-locking effect. However, in the whole process of water injection, there is a lack of systematic research on which effect is dominant and the coupling mechanism of these two. In this paper, an integrated experimental device of "gas adsorption + water injection displacement + gas desorption" was developed to investigate this complex process. The effect of water under different water injection conditions on the amount of gas displacement in coal and the amount of desorption after pressure relief was studied. In addition, the amount of gas release inhibited by the water-locking effect was calculated and the comprehensive influence of water injection on the gas in coal seams was analyzed, providing a reference for revealing the mechanism of water displacement in coal seams and inhibiting desorption.

2. EXPERIMENTAL RESEARCH

Water can promote the desorption and displacement of adsorbed gas by changing the adsorption characteristics of coal and inhibit the desorption and migration of gas by the water-locking effect. This chapter first tests the gas adsorption capacity of different water-bearing coal samples and then tests their gas diffusion capacity. Finally, the integrated experimental device of "gas adsorption + water injection displacement + gas desorption" was used to study the gas displacement amount and water-locking effect in coal under different water injection conditions, so as to reveal how the two seemingly contradictory processes of gas displacement and water-locking effect jointly play a role in preventing gas exceedance and outburst after water injection.

The test coal sample is taken from the Eighth Mine of Pingdingshan, Henan Province, and the industrial analysis is shown in Table 1. The coal in this mine area has a high metamorphism and strong outburst risk.

Table 1. Industrial Analysis[a]

proximate analysis (%)			
M_{ad}	A_d	V_{daf}	FC_d
0.53	23.83	32.16	51.67

[a] M_{ad} is the moisture content (air-dried basis); A_{ad} is the ash content (air-dried basis); V_{ad} is the volatile matter content (air-dried basis); and FC_d is the fixed carbon content (dried basis).[32]

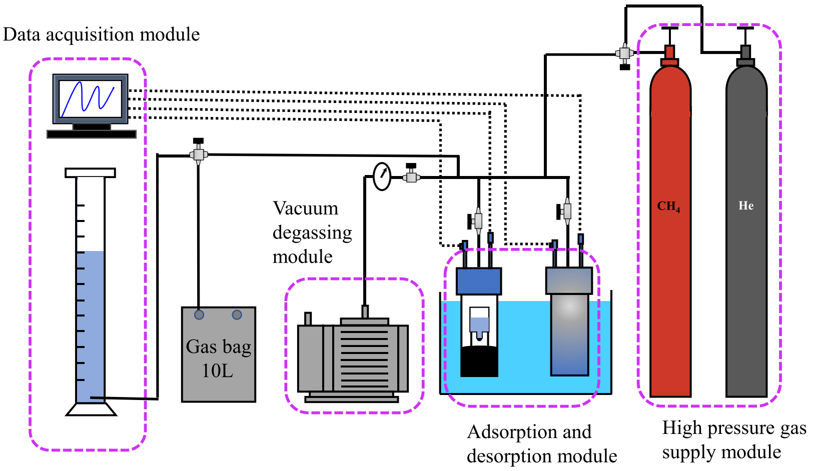


Figure 2. "Gas adsorption + water injection displacement + gas desorption" integrated experimental device.

2.1. Experiment Setup. In this paper, the following experimental platform has been developed, which can realize three main functions: coal sample gas adsorption balance, water gas displacement, and gas desorption after pressure relief. During the experiment, water is placed in the coal sample tank in advance and separated from the coal sample. When the coal sample absorbs gas in equilibrium, the coal sample tank is inverted to realize mixing of the coal sample with water. The gas content change caused by water displacement can be calculated by recording the changes in the pressure and temperature in the coal sample tank before and after mixing. After the system pressure relief, the gas desorption amount is calculated by recording the liquid level change of the desorption gauge. The basic setup of the experimental system is shown in Figure 2.

The equilibrium pressure of this experiment was set at 3 MPa. A total of 80 g of dry coal sample with a mesh number of 20−40 was selected. The water injection ratio is defined as the ratio of water mass to the total mass of water and coal. 5.11 10.91, 17.56, and 26.67 g of distilled water (water injection ratios at 6, 12, 18, and 25%, respectively) are weighed for the tests. The coal sample tank is placed in a water bath with a constant temperature of 30 °C. The specific steps are explained as follows:

1. Vacuum degassing: the dry coal sample is put into the coal sample tank, and the distilled water is poured into the isobaric water injection device. Then, the isobaric water injection device is placed in the coal sample tank and sealed. The coal sample tank is pumped by the vacuum pump for more than 8 h. When the pressure in the tank no longer changes, the valve and vacuum pump are closed.
2. Measurement of free space volume: the Helium gas cylinder is inflated to the reference tank. After the pressure indicator is stable, the reference tank is connected to the coal sample tank. The pressure and temperature after stabilization are recorded, and the free space volume of the device can be calculated. Step 1 vacuum degassing is applied again.
3. Adsorption balance: the methane gas cylinder is inflated into the reference tank. After the pressure indicator is stable, the reference tank is connected to the coal sample tank, and the initial pressure and temperature of the coal sample tank are recorded. After the adsorption equilibrium, the final pressure and temperature are recorded again. Then, the gas adsorption amount Q can be calculated according to the pressure and temperature change of the coal sample tank before and after the adsorption equilibrium.

$$Q = \left(\frac{P_1}{Z_1 R T_1} - \frac{P_2}{Z_2 R T_2} \right) V_x V_m \tag{1}$$

where P_1 and T_1 are the pressure and temperature before gas filling, respectively. P_2 and T_2 are the pressure and temperature after reaching the adsorption equilibrium. Z_1 and Z_2 are gas compression factors under the P_1 and P_2 conditions, respectively. V_x is the free space volume after placing the coal sample. V_m is the molar volume of gas at the standard condition, i.e., 22.4 L/mol.

4. Water flooding: after the adsorption balance, the coal sample tank is inverted, and the stainless-steel bead at the lower end of the isobaric water injection device rolls down, which causes the water to flow into the coal sample through the small hole to displace gas. Gas displacement Q' is calculated according to the pressure and temperature difference of coal sample tank before and after water flooding. The formula is the same as above.
5. Pressure relief and desorption: after gas displacement, the valve is opened to discharge the free gas accumulated in the coal sample tank into the gas bag. When the pressure indicator is returned to 0, the valve is quickly closed, the coal sample tank is connected to the desorption meter, and the liquid level change is recorded regularly. The accumulated gas desorption amount Q'' is calculated according to formula 2.

$$Q' = \pi(R^2 - r^2)(l_2 - l_1) \tag{2}$$

where R and r are the radii of the wire of the measuring cylinder and the liquid level transmitter, respectively. l_1 and l_2 are the initial and final liquid level heights of the measuring cylinder, respectively.

2.2. Effect of Water on the Adsorption Constant *a*.

Coal contains a large number of pores and cracks with significant surface areas for gas adsorption. At a constant temperature, the relationship between gas pressure and adsorption capacity conforms to the Langmuir equation:[33]

$$Q = \frac{abP}{1 + bP} \tag{3}$$

where Q is the content of adsorbed gas in the coal body under pressure P, cm^3/g. P is the gas pressure, MPa. a is the adsorption constant. When $P \to \infty$, $Q = a$. Thus, a represents the ultimate adsorption capacity of coal, and its unit is cm^3/g. b is another adsorption constant, which represents the ability to adsorb gas at half of the maximum pressure, and the unit is MPa^{-1}.

The adsorption constant a represents the gas adsorption capacity of coal.[34] The larger the value of a is, the more gas can be stored in the coal seam and the more gas can be used for desorption. When disturbed by external forces, it is easier for this type of coal to form fast-flowing channels and consequently, a higher outburst risk.[35]

In our experiments, coal samples with 60−80 mesh were heated and dried at 80 °C in a vacuum drying oven for 24 h. Coal samples with different water contents were prepared by using a vacuum filling tank and a halogen moisture tester, and Langmuir adsorption constant a was measured by using a high-pressure gas adsorption instrument.[36]

As can be seen from Figure 3, the larger the water content, the smaller the adsorption constant a and so is the gas adsorption capacity. Coal is a natural adsorbent. The adsorbed molecules exist in the micropores under the influence of the interaction force. The interaction force between the adsorbed molecules and the coal matrix is mainly the intermolecular force.[37] The van der Waals force between the coal matrix and methane molecules is about 207 kJ/mol. The van der Waals force and the hydrogen bond energy between the coal matrix and water molecules are about 188 and 189 kJ/mol, which add up to 377 kJ/mol. Therefore, the interaction force between the coal matrix and water molecules is much greater than that between the coal matrix and methane molecules, which makes water easily occupy a high energy position. Only low-energy sites can accommodate methane.[38] Therefore, when water and methane compete for adsorption on the surface of coal, water occupies a certain adsorption area, which leads to the reduction of the adsorption potential of methane[39] and the ultimate adsorption amount of methane in coal samples, as reflected by the decrease in the adsorption constant a. Most hydraulic-based measures to improve coal permeability are actually the seepage process involving the water and gas two-phase displacement, in which water gradually replaces gas adsorbed in the coal matrix.

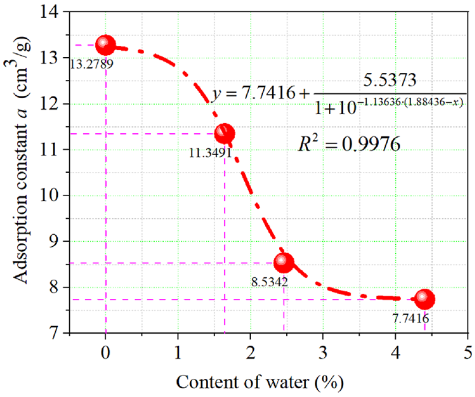


Figure 3. Effect of water content on the adsorption constant a.

2.3. Effect of Water on the Gas Diffusion Initial Velocity ΔP.

The gas diffusion initial velocity (ΔP) is an important index to assess outburst risks. It refers to the gas quantity index measured by the pressure difference ΔP (mmHg) within 10−60 s when coal samples with a specified particle size adsorb gas under 0.1 MPa and then release it to the fixed vacuum environment, which reflects the speed of gas diffusion. The higher the ΔP value, the faster the gas diffusion and the greater the outburst risk.[40] Coal samples of 60−80 mesh with different water contents were tested by the WT-1 gas diffusion velocity measurement equipment, and the ΔP of different water contents was calculated.[41]

As shown in Figure 4, the higher the water content, the lower the gas diffusion initial velocity ΔP. When the water content varies from 0.42 to 2.14%, the curve is steep, and ΔP decreases rapidly. As the increase of water content beyond 2.14%, the curve becomes smooth, and the gradient of ΔP decrease declines significantly.

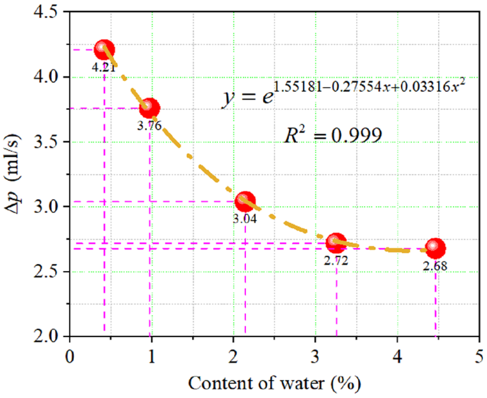


Figure 4. Effect of water content on the gas diffusion initial velocity ΔP.

With the increase of the water content, the gas diffusion initial velocity ΔP decreases, indicating that the hydrostatic water in coal pores may block gas transport in the coal body, resulting in the water-locking effect, which effectively avoids the sudden release of gas and reduces the outburst risk.

2.4. Effect of Water on Gas Displacement.

After the coal sample reaches the gas adsorption equilibrium, inverting the coal sample tank would cause the water to start getting in close contact with the coal sample. Thus, the adsorbed gas in the coal sample is gradually displaced into the tank, and the system pressure rises.

As shown in Figure 5, when water contacts the coal sample, the initial adsorption equilibrium in the coal sample tank is disrupted and the gas displacement by water starts to occur and increases rapidly. About 3 h after water injection, the slope of the curve decreased significantly, indicating the increase rate of displacement volume gradually slowed down. Finally a new equilibrium was reached after about 8 h, indicating the end of water displacing gas. By comparing the displacement curves of different water injection ratios, the maximum amount of gas displacement by water gradually increases with the increase of the water injection ratio. When the water injection ratio is 6%, 12%, 18% and 25%, the gas displacement volume is 0.62 mL/g, 0.90 mL/g, 1.07 mL/g and 1.16 mL/g, respectively. From 6% to 25% of the water injection ratio, the gas displacement effect increased by 87.09%. Therefore, under the same adsorption

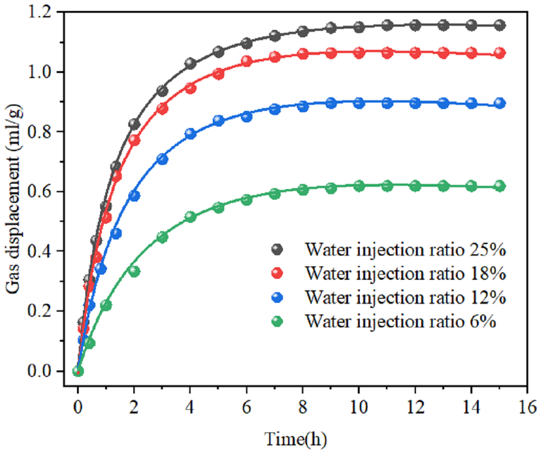


Figure 5. Evolution curves of gas displacement under different water injection ratios.

equilibrium pressure, the more water contained in the coal sample, the stronger the gas displacement effect.

2.5. Effect of water on gas desorption after pressure relief. After the water displacing gas stage, the free gas in the coal sample tank is discharged, and the coal sample tank is quickly connected to the gas desorption instrument. According to the change of liquid level reading in the measuring cylinder, the time-varying curves of gas desorption with different water injection ratios after pressure relief were calculated and drawn (Figure 6).

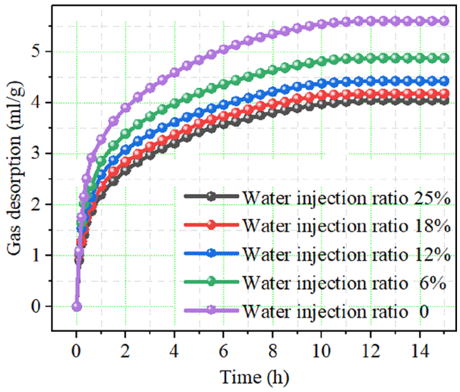


Figure 6. Evolution curves of gas desorption under different water injection ratios.

As shown in Figure 6, gas desorption after pressure relief roughly goes through three stages: rapid desorption, slow desorption, and terminal desorption. The desorption curve in the initial stage is extremely steep, and the gas desorption volume increases rapidly. The slope of the curve decreases notably and the desorption rate decreases rapidly after about 1 h. The curve eventually becomes stable, indicating the end of the pressure relief and desorption stage. By comparing the gas desorption curves of different water injection ratios, the maximum gas desorption amount gradually decreases with the increase of the water injection ratio. When the water injection ratio increases from 6 to 25%, the desorption volume decreases from 4.86 to 4.05 mL/g, with a decrease of 16.67%. When the water injection ratio is greater than 18%, compared with a water injection ratio of 0, water injection ratio of 6%, and water injection ratio of 12%, the decrease of gas desorption rate slows down and is close to the state of completely saturated coal samples. At the same time, the gas desorption amount of the dry coal sample (water injection ratio of 0%) is significantly higher than that of water-containing coal samples. In a certain range, the more moisture in coal samples, the less gas desorption amount, indicating that the suppression effect of gas desorption caused by water is stronger.

2.6. Water-Locking Effect. In the process of water injection into coal seams, the free gas in the cracks is first driven out under the action of high-pressure water. The water entering the pores of coal converts part of the adsorbed gas into a free state and displaces it into the gas drainage borehole. After pressure relief in coal seams, the gas diffusion speed slows down, and the release amount decreases to avoid the sudden increase of gas concentration. In addition, the remaining adsorbed gas in the coal seam will be temporarily “locked” in the pores by water and will not be released instantaneously in the process of mining,[26] which is known as the water-locking effect. Water lock quantity refers to the amount of gas that can be desorbed and released by water-bearing coal samples after a long time of gas displacement and pressure relief desorption. It can be calculated by the difference between the gas desorption amount of dry coal and the total amount of gas displaced and desorbed from the water-containing coal. The following formula 4 can be used to calculate the water lock quantity. The calculation results of the water lock quantity under different injection conditions are shown in Table 1.

$$Q = V_1 - V_2 - V_3 \tag{4}$$

where Q is the water lock quantity of water-bearing coal under the standard condition, mL/g. V_1 is the gas desorption amount of dry coal sample under the standard condition, mL/g. V_2 is the gas displacement amount of water-bearing coal under the standard conditions, mL/g. V_3 is the gas desorption amount of water-bearing coal under the standard conditions, mL/g.

Table 2 shows that the gas desorption capacity of the dry coal sample is 5.59 mL/g. After the water was injected into the coal sample, the water locking amount and displacement amount have the same trend: the larger the water injection ratio, the higher the water locking amount. The water injection ratio increased from 6 to 25%, and the amount of water-locked gas increased from 0.11 to 0.38 mL/g. Within a certain range, the more moisture the coal sample contains, the stronger the water-locking effect is.

Table 2. Gas Displacement, Desorption, and Water-Locking under Different Water Injection Conditions

water injection ratio (%)	displacement V' (mL/g)	desorption V'' (mL/g)	water-locking Q (mL/g)
0	0	5.59	0
6	0.62	4.86	0.11
12	0.90	4.42	0.27
18	1.07	4.17	0.35
25	1.16	4.05	0.38

3. RESULTS AND DISCUSSION

3.1. Analysis of the Effect of Water on Gas Desorption in Coal after Pressure Relief. Figure 7 is a bar chart of the gas displacement amount, gas desorption amount after pressure relief, and water locking amount of coal samples under different water injection ratios. As shown in

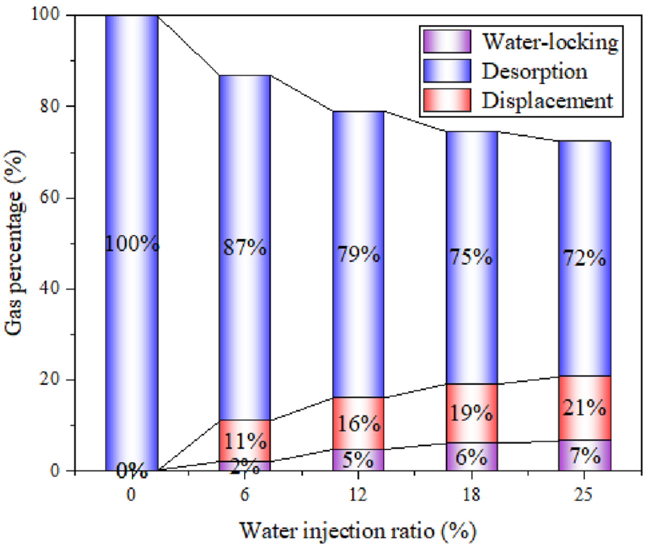


Figure 7. Quantity of gas displacement, desorption, and water-locking under different water injection ratios.

Figure 7, with the increase of the water injection ratio, the gas displacement amount and water locking amount gradually increase, while the desorption amount gradually decreases. Compared with dry coal samples, it is found that the larger the water injection ratio, the stronger the gas displacement and water-locking effect on gas, that is, the promotion of gas displacement and suppression of gas desorption in coal are enhanced.

In order to explore the influence of water on the desorption velocity of gas after pressure relief, the variation curve of the pressure relief desorption velocity is fitted according to the experimental data, as shown in Figure 8. The fitting function is listed in Formula 5. v is the desorption rate, and t is time. As t approaches 0 infinitely, $v = c$; so, c is defined as the initial desorption velocity in this paper.

$$v = \frac{c + dt}{1 + mt + nt^2} \tag{5}$$

As can be seen from the figure, when the water injection ratio ranges from 0 to 25%, the initial desorption velocities c are 5.2601 4.6358, 4.3621, 3.6874, and 3.3797 mL/g·h, respectively. After pressure relief, the initial desorption velocity of gas decreases with the increase of the water injection ratio. When the water injection ratio increases from 0 to 25%, the initial gas desorption velocity c decreases by 35.75%, which was similar to the variation of the gas diffusion initial velocity ΔP as the water content changes, indicating that water can effectively avoid the sudden release of gas in coal after pressure relief. One of the necessary conditions for the occurrence of gas outburst is the rapid desorption of the adsorbed gas in coal.[42] After the coal seam pressure relief, water injection can reduce the initial desorption velocity of the gas, avoid the sudden release of a large amount of gas, and smooth the desorption process. Therefore, water injection into coal seams can effectively avoid gas exceedances and coal and gas outbursts in underground mines.

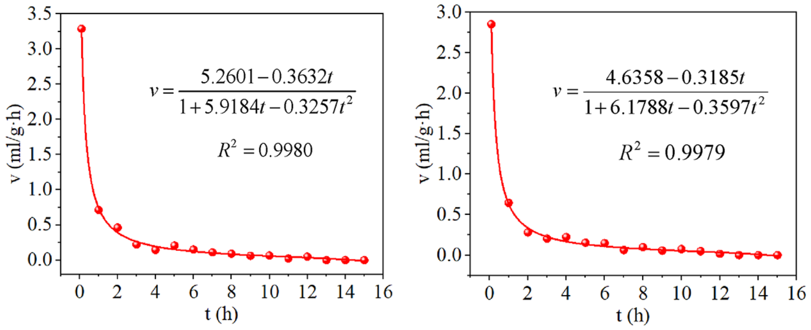
3.2. Outburst Prevention Mechanism Using Water Injection: the Coupling of Gas Displacement and Water-Locking Effect.

The complex pore structure of coal provides a broad adsorption space and migration channels for gas.[43] Methane desorption is a process in which gas molecules adsorbed on the surface of the coal matrix fall off from the pore surface and become free gas.[44] Water can spontaneously adsorb on the surface of a coal substrate which originally adsorbed methane, resulting in gas displacement. At the same time, because the water is trapped in the pores of the coal, the migration path of gas is reduced, and surface tension and interfacial tension are generated,[45−47] which is not conducive to gas discharged from the coal matrix.[48]

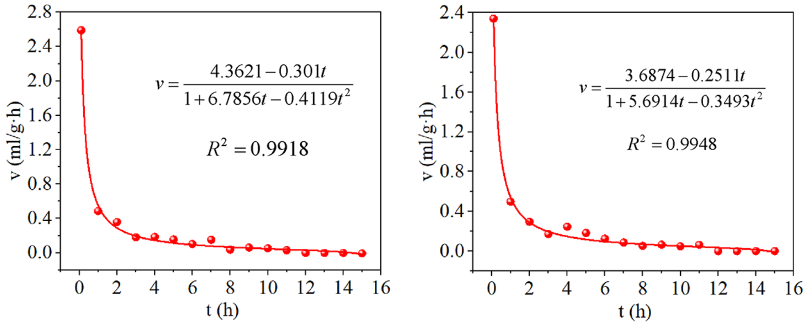
According to the pore structure of coal, its pores can be divided into open pores, semiopen pores, and closed pores.[49] Open pores are most conducive to gas migration due to the connectivity of large and visible pores. However, because the pores are mostly concentrated in the micropore stage, the pore channel is not smooth, which makes gas migration more difficult. Among them, water displaces gas mainly in open and semiopen pores. Compared with open pores, the gas displacement effect in semiopen pores is worse, but the water-locking effect is stronger.

According to pore shape and openness, nonclosed coal pores can be roughly subdivided into three categories. The first category is open holes, including cylindrical holes with two ends opening and parallel plate holes or slit holes with four sides opening to produce adsorption channels, as shown in Figure 9a,b. The second category is a semiopen hole with one closed end, including a cylindrical hole with one closed end, a wedge hole, or a conical hole with one closed end, as shown in Figure 9c,d. The third category is a special kind of semiopen hole, the ink bottle-shaped hole, as shown in Figure 9e. Low-rank coal contains a large number of open pores, which are open at all stages and have good connectivity between pores, and they are conducive to the diffusion and migration of gas in coal seams. However, there are a lot of semiopen transition pores and micropores in the middle or high-rank coals, which create poor connectivity between the pores and difficulties for gas migration in the coal seams.[50] Compared with the low-rank coal, the gas displacement effect of the middle or high- rank coal is worse, but the water-locking effect is stronger.

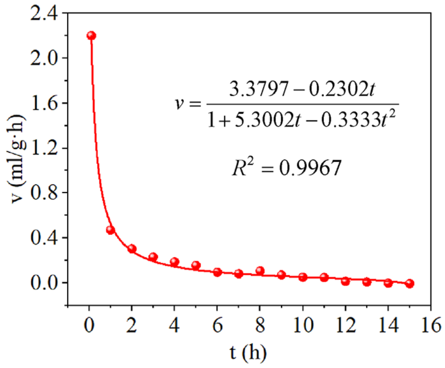
Water injection into coal seams can produce gas displacement and a water-locking effect. Seemingly contradictory, they can be united to effectively avoid gas exceedance and coal and gas outburst because they play a leading role in different times. As shown in Figure 10b, in the process of water injection, free gas is first driven out under the action of high-pressure water. In addition, as the water moistened the coal body more deeply, the adsorption constant a of the coal body decreased and the maximum adsorption amount of gas decreased. The gas originally adsorbed in the pores of the coal seam was dislodged and gradually migrated to the gas extraction boreholes under the action of capillary force and pressure gradient.[50] The gas displacement effect of semiclosed hole is worse than that of open hole. Among the semiclosed holes, the ink bottle-shaped holes have the worst gas displacement effect. As shown in Figure 10c, at the end of water injection, the water in the coal seam exerts a water-locking effect on the gas. In the process of coal seam mining, the gas diffusion initial velocity Δp decreases obviously due to residual hydrostatic water in the pores. Part of the gas is blocked in the coal body. The water-locking effect of semiclosed holes is stronger than that of open holes. Among the semiclosed holes, ink bottle-shaped holes have the strongest water-locking effect. After pressure relief, because the gas is blocked, it is difficult to release or exude at a slow speed, which can effectively avoid the gas exceedance and reduce the outburst risk.[51] Water flooding gas can promote the



(a) Dry coal sample (b) Water injection ratio 6%



(c) Water injection ratio 12% (d) Water injection ratio 18%



(e) Water injection ratio 25%

Figure 8. Pressure relief and desorption rate of gas under different water injection ratios.

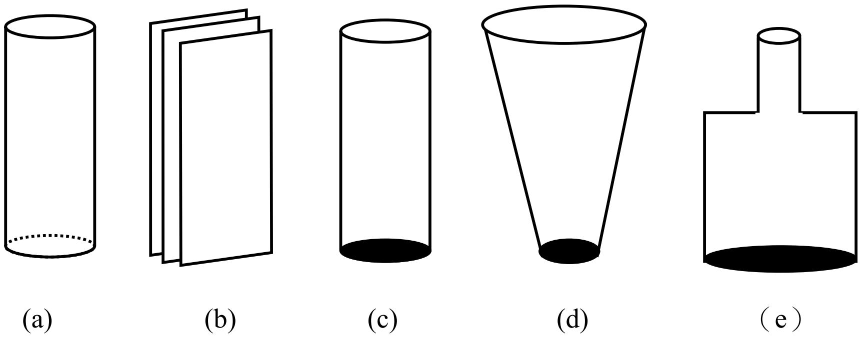
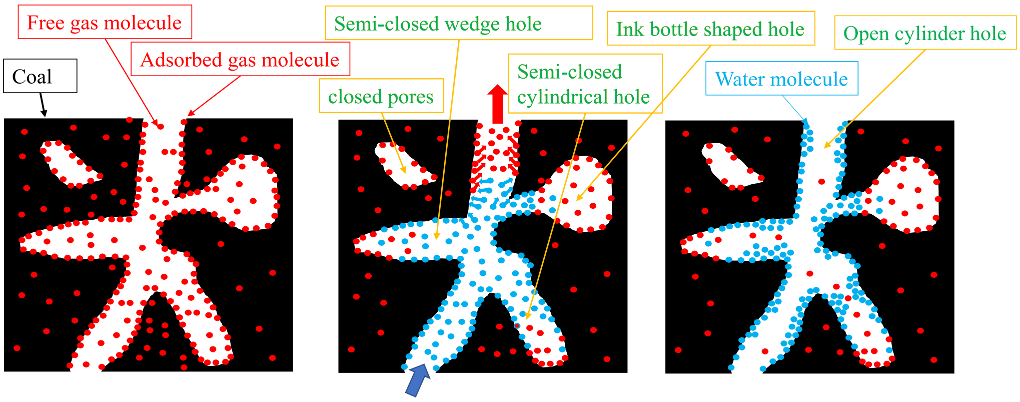


Figure 9. Shapes of the nonclosed hole. (a) Cylindrical hole. (b) Parallel plate hole. (c) Cylindrical hole with one closed end. (d) Conical hole with one closed end. (e) Ink bottle-shaped hole.

efficiency of gas extraction and reduce the gas content of the coal seam. Meanwhile, the water lock effect can inhibit the rapid desorption and release of gas during coal seam mining. The two functions act in different time periods, so after water



（a） Raw coal （b） Gas displacement （c） Water locking

Figure 10. Schematic of gas displacement and water locking in the coal pore structure.

injection plays a role in gas displacement and water locking successively, it can effectively reduce the gas content of coal seams.

3.3. Implications for Field Application. Coal seam water injection is widely used in coal seam gas treatment, which can effectively improve the efficiency of gas extraction and avoid coal and gas outbursts at the same time. The effect of coal seam water injection on gas can be divided into two aspects: gas displacement and water retention. For the latter, however, the prevailing view is that water locking greatly reduces the efficiency of gas extraction, and its impact should be minimized. However, its positive effect on the control of the gas overlimit and coal and gas outburst is often ignored. According to the research in this paper, gas drive plays a leading role in the waterflood stage, and water lock plays a leading role in the late waterflood stage to prevent gas outburst. Therefore, considering the negative influence of the water locking effect on gas extraction, a large amount of water can be injected into coal before coal seam mining to avoid the sudden mass release of gas by using the water locking effect.

4. CONCLUSIONS

1. With the increase in water content, the Langmuir adsorption constant a of coal samples decreases, indicating that the ultimate adsorption capacity of gas decreases. The gas displacement rises with the increase of the water injection ratio, and when the water injection ratio rises from 6 to 25%, the gas displacement increases by 87.09%. Water preempts the adsorption site of gas and displaces gas from coal to improve the efficiency of gas extraction.
2. With the increase of water content, more gas is blocked in the coal body and is difficult to release or oozes out at a slow speed, that is, the water-locking effect, and the gas diffusion initial velocity ΔP decreases. After pressure relief, the amount of gas desorption decreases, the initial gas resolution becomes slower, and the amount of water lock increases, which avoids the sudden mass release of gas after coal seam pressure relief.
3. Water has the dual function of displacing and locking coal seam gas, and the time of preventing outburst is different. In the process of water injection, water drive gas plays a leading role, resulting in the increase of free gas in coal seam. After the completion of water injection, the standing water in the coal seam mainly plays the role of water locking, and part of the gas is blocked in the coal body, which is difficult to release quickly. The combination of the two can effectively avoid the occurrence of gas overlimit in the process of coal mining and reduce the risk of outburst.

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Notes

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