Methane displacement characteristic of coal and its pore change in water injection

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Abstract
Coalbed methane as one type of clean energy has become an important gas resource recently. High-pressure water injection in coal seams is an effective approach for improving gas extraction efficiency, which is determined by the gas displacement characteristic and pore structure of coal. To investigate the gas displacement characteristics in coal and its pore response and influential factors, gas adsorption and water injection experiments were conducted under different conditions. The results show that the gas displacement caused by the water injection undergoes three stages: rapid increase, slow increase, and almost constant. The wetting process in water injection includes three processes: wetting, soaking, and spreading, and the wettability of coking coal is best, followed by lean coal and anthracite. The amount of gas driven by the water increases with increasing water injection pressure, and it is more favorable to increase the injection pressure to improve the gas displacement effect under the relatively low injection pressure. The lower the coal rank, the better the gas displacement effect due to the higher porosity of the coal, and the longer the early gas displacement stage. The high adsorption equilibrium pressure can improve the gas displacement effect; for the relatively high adsorption equilibrium pressure, the gas displacement effect is better. After water injection in coal, the large fractures and pores dramatically increase in size, especially for the low metamorphic coals coking coal, contributing to the majority of the increase in porosity. The results of this study can provide a theoretical foundation for the wide application of water injection technology for efficient gas drainage in coal mines.

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Introduction
Coalbed methane (CBM) is one type of clean energy, but it is also the leading cause of coal mining accidents, resulting in numerous deaths. In China, 70% of coal mines are prone to coal and gas outbursts because of the poor seam permeability (Li, 2001; Lu et al., 2010; Wang, 2016; Zhou, 2017). Therefore, efficiently pre-extracting CBM cannot only increase the clean energy supply but can also improve the safety of coal mine production. However, the gas occurrence conditions of coal seams in China are relatively complex, and more than 53% of coal seams are soft and low permeability coal seams (Liu, 2014). For most mining areas, the coal seam permeability is $10^{-4}$–$10^{-3}$ mD, which is 3–4 orders of magnitude lower than that in the United States and Australia (Liu and Harpalani, 2013; Lu et al., 2019; Xiao et al., 2018; Zhang et al., 2019). This low coal seam permeability results in the low extraction efficiency of CBM. Therefore, effective measures must be taken to improve the gas drainage efficiency.

High-pressure water injection in coal seams has been widely adopted in coal exploitation due to the advantages of controlling and preventing gas disasters and dust (Aguado and Nicieza, 2007; Cheng et al., 2012; Guo and Su, 2010; Wu et al., 2008). On the one hand, water injection can increase the permeability of the coal seam, resulting in gas displacement and improving gas drainage efficiency under the action of high-pressure hydraulic forces. On the other hand, the injected water will wet the coal, increasing the water content and controlling the dust during coal exploitation (Zhang et al., 2019). Currently, there are many studies on the mechanism of water injection in coal seams. Liu et al. (2016) and Wang et al. (2016) studied the seepage laws of water injection in coal seams using numerical simulations. Cheng et al. (2012) analyzed the dynamic characteristics of water injection in coal and gas exploration by means of an experimental approach. Chen et al. (2013), Ji (2017), and Sun (2019) studied the gas desorption characteristics and permeability changes of coal under different water injection conditions. Zhang et al. (2019), Liu et al. (2017), and Zu (2014) investigated the wetting process of water injection and analyzed the wetting radius of coal seam by water injection. To improve the water injection effect in coal seams, some additives and new water injection technologies have gradually been introduced, such as using visco-elastic surfactant injection fluid and fluctuation water injection technology (Cheng et al., 2012; Wang et al., 2019). However, the existing research on water injection in coal seams mainly focuses on the coal adsorption characteristics, water and gas flow laws, coal wetting effects, and so on. While there are many factors influencing the water-driven gas effect in water injection applications, the effects of the influential factors of water injection on gas displacement are not well known.

In this study, gas adsorption and water injection experiments were carried out under different conditions. The gas displacement process and its wetting process caused by the water injection was analyzed. The effects of the key parameters, including the injection pressure, coal metamorphic degree, and adsorption equilibrium pressure, on the gas displacement effect were investigated. The pore response of the coal subjected to water
injection was analyzed. The results of this study can provide a theoretical foundation for the selection of water injection parameters in the application of water injection in coal seams.

**Water-driven gas theory in coal seams**

*Water-driven gas process in coal body*

Coal is a typical dual porous material that is composed of matrix porosity and fracture. Matrix porosity is the principal medium for storage of the gas, whose diameter is generally less than 10 nm. And most of the gas is adsorbed on the surface of matrix porosity. While the remaining gas is mainly stored in the fractures or cleats, either as free gas form or dissolved in water (Liu et al., 2011; Lu and Huang, 2018). During the process of water injection in the coal seam, pressurized water overcomes the resistance of the coal seam and enters the coal under this powerful force. The water-driven gas in water injection is mainly influenced by fluid pressure, gas pressure, viscous force, gravity, inertial force, and capillary force (Cheng et al., 2018). The major driving sources and flow resistances are the fluid pressure, gas pressure, and capillary force (Wang et al., 2004; Zhang et al., 2019). As shown in Figure 1, the dynamic process of water-driven gas can be described as follows:

Stage 1: The injected water moves rapidly into fractures under the pressure of the water injection, driving the free gas and harnessing the fractures. In this stage, the capillary force can be ignored. The flow is considered as the two-phase seepage of water-driven gas, and this process must satisfy the following condition

\[ P_w - P_g > 0 \]  

where \( P_w \) and \( P_g \) are the fluid pressure of water injection and the gas pressure in the coal seam, respectively.

Stage 2: With the continuous injection of high-pressure water, the injected water gradually enters into the pores. The capillary force plays a significant role in this stage, depending mainly on the pore diameter, water surface tension, and wetting edge angle of water to coal. For hydrophilic coal, the capillary force is favorable for water to enter pores due to imbibition, while the capillary force is regarded as resistance to prevent water from entering the pores in nonhydrophilic coal. The gas displacement in pores occurs under the following

![Figure 1. The water-driven gas process.](image-url)
conditions

\[
P_w + P_m - P_g > 0, \quad \text{for hydrophilic coal}
\]

\[
P_w - P_m - P_g > 0, \quad \text{for nonhydrophilic coal}
\]

where \( P_m \) is the capillary force of the coal seam pore, which can be expressed as

\[
P_m = \frac{2.04 \sigma \cos \theta}{r}
\]

where \( \sigma \) is the surface tension coefficient of water, \( \theta \) is the wetting edge of water on coal, and \( r \) is the radius of the pore.

When the pressured water is injected into the deeper parts of coal pores under the action of injection pressure and capillary force, the water molecules and gas molecules are adsorbed by the coal molecules. The distance between the water and coal molecules is smaller than the distance between the gas and coal molecules. The coal molecules on the surface of the coal more easily adsorb water molecules, thus resulting in gas displacement by the injected water.

Stage 3: In the matrix porosity of coal, with the water gradually filling the pores and the gas being displaced, the imbibition will gradually be weakened, resulting in the gradual stop of water-driven gas.

Wettability characteristic of the coal body in water injection

In the water injection process in coal body, wetting is a common phenomenon due to the infiltration of coal surface by water. Coal wetting can be divided into three processes: wetting, soaking, and spreading. The wetting process can be measured by the change of Gibbs function, under certain temperature and pressure (Zhang et al., 2019). The smaller the value of Gibbs function.

(i) Wetting process: Coal wetting is the process in which water and coal never touch each other first and then gradually touch each other, that is to say, gas–solid interface becomes liquid–solid interface. Gibbs function in wetting process is

\[
\Delta G_a = \gamma_{ls} - \gamma_l - \gamma_s = -\gamma_l (\cos \theta + 1)
\]

where \( \Delta G_a \) is Gibbs function; \( \gamma_{ls} \), \( \gamma_l \), and \( \gamma_s \) are the liquid–solid interfacial tension, surface tension of liquid, and surface tension of solid, respectively; and \( \theta \) is the contact angle. If \( \theta < 180^\circ \), there is \( \Delta G_a < 0 \), and the wetting process will be carried out.

(ii) Soaking process: Coal soaking wetting is the process in which coal is immersed in water, and the gas–solid interface is completely replaced by the liquid–solid interface. Gibbs function in soaking process is

\[
\Delta G_i = \gamma_{ls} - \gamma_s = -\gamma_l \cos \theta
\]

If the soaking process will be carried out spontaneously, then there is \( \Delta G_i < 0 \), namely \( \theta < 90^\circ \).
(iii) Spreading process: Coal spreading wetting is the process in which a small amount of water develops automatically on the coal surface. Gibbs function in the spreading process will be calculated as follows

\[
\Delta G_s = \gamma_{ls} + \gamma_l - \gamma_s = -\gamma_l \cos\theta - 1
\]  

(6)

If the soaking process will be carried out spontaneously, there is \(\Delta G_i < 0\), namely \(\theta = 0^\circ\) or nonexistence.

The above analysis shows that the wetting process can be initiated if \(\theta < 180^\circ\). Because the contact angle of water on the coal surface is always less than \(180^\circ\), the wetting process will be carried out between water and coal. However, the wetting degree will be different due to the difference of contact angles between water and coals with different properties. The water-driven gas process in coal seams is the process of water wetting coal body. Therefore, the contact angle between water and coal surface can be used to judge the wettability of coal, which affects the water-driven gas effect in water injection. In this paper, before investigating the gas displacement characteristic of coal in water injection, it is very necessary and significant to analyze the wettability characteristic of the coal samples with different metamorphic degrees.

Anthracite, lean coal, and coking coal are selected as the experimental target coal samples, whose specific properties will be described later. The coal sample is coal cake with a size of \(\Phi 13 \text{ mm} \times 3 \text{ mm}\), and three coal cakes are made for each coal of metamorphic degree. The experimental device is the FTA-200 contact angle measurement. The same test for each coal sample was carried out three times. The testing procedure of contact angle, including experimental device, coal samples, and testing process, is shown in Figure 2. The contact angles of coal samples with different metamorphism degrees are shown in Figure 3. The contact angle of anthracite is maximal, reaching \(100.2^\circ–102.3^\circ\), followed by lean coal \((85.3^\circ–86.4^\circ)\) and coking coal \((76.2^\circ–76.4^\circ)\), respectively. This means that the coal body will be wetted in water injection, and the wetting effect of water will be best for coking coal, followed by lean coal. And wetting effect of anthracite is relatively weaker than that of coking coal and lean coal. It can be also seen that the coking coal should be considered as the experimental coal sample due to its small contact angle and good wettability when the coal metamorphism degree needs to be controlled in the following water injection experiments.

\[ \text{Figure 2.} \text{ The experimental device, coal samples, and testing process of contact angle.} \text{ (a) FTA-200 contact angle measurement, (b) } \Phi 13 \text{ mm} \times 3 \text{ mm coal sample, and (c) testing process of contact angle.} \]
Materials and methods

Apparatus

Water-driven gas experiments were carried out using a self-developed adsorption–water injection–displacement test system. As shown in Figure 4, the experimental system is mainly composed of a vacuum evacuation unit, an injection unit (for water and gas injection), a triaxial pressure loading unit, a data collecting unit, and a gas gathering unit.

Figure 3. The contact angle of coal with different metamorphism degrees.

Figure 4. Schematic of the experimental apparatus.
The main performance parameters of the experimental apparatus are described below:

a. Vacuum evacuation unit. The vacuum pump is a 2XZ-4 Rotary Vane vacuum pump with an ultimate vacuum pressure of 150 mbar. The working pressure of the corresponding high-pressure pipeline can reach 12 MPa. An FZH-2B vacuum gauge with a range of 0–0.5 MPa is used during the vacuum evacuation.

b. Injection unit. Water injection at different pressures was performed utilizing the SB-10 MPa injection pump. This pump is a high-performance manual pressure pump with a peak pressure of 10 MPa. To ensure a continuous pressure of water injection into the coal, a sufficient pressure of water is first stored in a storage tank.

c. Triaxial pressure loading unit. The triaxial loading and control unit allows the triaxial cell to contain cylindrical samples with diameters of 50 mm. The axial stress and confining pressure on the samples were separately loaded onto samples through an electrohydraulic servo pump with a rated power of 0.75 kW. The maximum axial load is 1000 kN. The confining pressure is along the radial direction of the samples and ranges from 0 to 20 MPa.

d. Data collecting unit. The real-time data collection unit can monitor and record data, such as the axial stress, confining pressure, fluid pressure (injection water pressure, gas pressure), and fluid flow rate (gas displacement volume, injection water volume), during the experiments.

e. Gas gathering unit. The gas gathering unit is used to gather the output gas, such as CH₄. The single gathering volume can reach 1.5 l, and the maximum pressure difference is 200 mm of the water column. The system error is less than ±1.46%, and the precision is ±1 mm of the water column.

**Experimental parameters**

Based on the analysis of the water-driven gas process in coal seams, it can be seen that the water injection pressure is the main driving force of the water-driven gas. The coals at different degrees of metamorphism have different pore structure characteristics, which influence the adsorption and desorption characteristics of coal. The adsorption equilibrium pressure also has a significant influence on the coal adsorption capacity of coal, which determines the gas content in coal. Therefore, the effects of the injection pressure, coal metamorphism, and adsorption equilibrium pressure on the water-driven gas displacement were investigated using the single factor analysis method. In the water-driven gas experiments conducted under different experimental conditions, the axial pressure and confining pressure remain constant, that is they remain at 8.6 and 8 MPa, respectively. Other special parameters are described below.

a. For the analysis of the water injection pressure, the water injection pressure is set to 0.74, 1.48, 2.96, 4.44, 5.92, and 7.4 MPa. In addition, the adsorption equilibrium pressure is 1 MPa, and the coal is a coking coal.

b. During the experiments with coals at different degrees of metamorphism, the adsorption equilibrium pressure and water injection pressure are 1 and 5.92 MPa, respectively. In addition, the coal samples are the molded coals for anthracite, lean coal, and coking coal, sampled from the No. 3 coal seam of the Yicheng coal mine in Jincheng, the No. 1 coal seam of the Wangxingzhuang coal mine in Zhengzhou, and the No. 8 coal seam in the
No. 6 Pingdingshan coal mine, respectively. The samples have a size of $\Phi 50 \text{mm} \times 100 \text{mm}$ and are made by using coal powder that is less than 200 mesh in size.

c. In the study of adsorption equilibrium pressure on gas displacement, the water injection pressure is 5.92 MPa, and the coal is a coking coal. The adsorption equilibrium pressures are 0.74, 1, 1.5, and 2 MPa.

**Experimental procedures**

The main procedures of all the water-driven gas experiments can be described by the four experimental steps as follows:

a. Degassing stage. First, the gas pipe and water injection pipe are connected in an orderly manner. Before the beginning of the experiment, the airtightness of the device should be checked. Then, the experimental coal samples are placed into the sample holder, and the stable triaxial stress is applied by the triaxial pressure loading unit. Next, the vacuum pump was opened and degassing was carried out for the experimental system.

b. Gas adsorption equilibrium stage. After the degassing stage, the $\text{CH}_4$ cylinder and the gas inlet are opened. The coal sample begins to adsorb $\text{CH}_4$. During this period, the adsorption equilibrium pressure is set by the pressure reducing valve.

c. Water-driven gas stage. When the coal sample completes $\text{CH}_4$ adsorption, then the $\text{CH}_4$ cylinder is closed. Next, the water injection pump is opened and the given injection pressure is set. The water injection experiments with different conditions are conducted.

d. Data collection and analysis stage. After the water injection stage, the experimental data, such as the water injection volume and gas displacement volume, can be obtained.

**Results and discussion**

**The effect of the injection pressures**

The water injection pressure varies from 0.74 to 7.4 MPa, which is appropriate for the middle and low injection pressure commonly used in most coal mines in China. The experimental results of the different injection pressures are shown in Figure 5. It can be seen in the early stage (stage 1) of water injection that the gas displacement volume dramatically increases with the increasing water injection pressure. With the continuous injection of pressurized water, the growth rate of gas displacement gradually decreases and enters into the middle stage 2 of the water-driven gas. At the end stage of the water-driven gas, the gas displacement tends to stabilize, and the increase in gas displacement is nearly zero. Therefore, the water-driven gas process can be roughly split into three periods.

(i) Water-driven gas experiments were carried in the early stage and the injection pressure plays a significant role. Pressurized water rapidly fills the fractures and large pores and compresses the free gas in the channel, leading to the formation of a gas pressure gradient. The free gas first flows from the high-pressure zones to the low-pressure zones via pressure seepage, resulting in gas displacement. The free gas in fractures and large pores is mainly displaced in this stage. Therefore, the capillary force can be ignored because of the large pore size.
(ii) As water continues to be injected, most of the free gas in fractures and large pores is driven out by the injection water. Then the injected water gradually enters the mesopores and micropores in coal due to capillary force, which is called as imbibition, and the gas will be driven out from these pores into other fractures. Besides, the competitive adsorption of water molecules and gas molecules by coal molecules will also take effect in the deep parts of the pores. However, due to the increasing resistance of gas displacement, the gas displacement rate will decrease.

(iii) At the stage 3, the imbibition effect will gradually be weakened as the pressurized water continues to fill the pores in the coal and the gas is driven out. Near the end of this stage, it becomes more difficult for the water injected into the coal to continue to displace the gas molecules in the micropores due to increasing resistance. Therefore, the water-driven gas will gradually be stopped, and the final gas displacement volume tends to stabilize and almost remains constant, especially at low injection pressures such as 0.74 and 1.48 MPa.

As shown in Figure 5, the water injection pressure has a significant influence on the gas displacement. The higher the injection pressure, the more gas is forced out in the same injection time. After the water injection ends, the cumulative amount of gas displacement is determined. The relationship between the cumulative displaced gas amount and injection pressure is shown in Figure 6. Generally, the cumulative amount of displaced gas increases almost linearly with the injection pressure. Thus, increasing the water injection pressure can increase the gas displacement, improving the water-driven gas extraction efficiency. This observation occurs mainly because a high injection pressure can provide a stronger driving power and overcome flow resistance, thus driving more gas out of their original hosts (pores and fractures) in coal. However, it can also be seen that it is better to improve the water-driven gas effect by increasing the injection pressure when the injection pressure is low.
Therefore, when applying water injection in the field, the water injection pressure should be properly tested and selected to fully improve the efficiency of water injection in coal seams.

The effect of coal samples at different degrees of metamorphism

The coals at different degrees of metamorphism have different physical and mechanical gas reservoir properties, such as pore and fracture structure characteristics, and their ability to absorb gas is also different. Therefore, gas displacement experiments were conducted with anthracite, lean coal, and coking coal. The results are shown in Figure 7. The gas displacement amount for the coals at different degrees of metamorphism undergoes the three stages and experiences the similar change trends. And the water-driven gas effect is different in the different coals. Coal with a low metamorphic degree will experience a longer early stage of gas displacement than coal samples with a high metamorphic degree, and the cumulative gas displacement is also greater for coal with a low metamorphic degree. For the coking coal, the cumulative gas displacement reaches 0.188 mg/g at a gas driving time of 800 min, followed by anthracite and lean coal. This result occurs mainly due to the different pore structure characteristics in the coal samples at different degrees of metamorphism. As shown in Table 1, the porosity of coking coal is largest, which is 0.0332, followed by anthracite and lean coal. Therefore, the relationship between the cumulative gas displacement and porosity can be obtained as shown in Figure 8. The larger the porosity of coal sample, the more the cumulative gas displacement caused by the water injection in coal, and their relationship is almost linear. The main reason for this increase is that the coal samples at different metamorphic degrees have different porosity characteristics. Studies have shown that the pore structure of coals at different metamorphic degrees is a “U”-type distribution, that is with the increase in the metamorphic degree of coal, the porosity inside the coal decreases, and the micropore and mesopore occupy the main pore positions (Sun, 2019). In contrast,
there are more large pores and fractures in coal with a relatively lower metamorphic degree. For the coking coal, there are more large pores and large fractures than those in the anthracite and lean coal, resulting in more free gas in the coking coal. Compared with the adsorbed gas, the free gas is more easily displaced by water injection. In addition, it is more convenient for the gas to flow out via pressure seepage in coal to reduce the inhibition effect of the capillary force. Therefore, the conclusion can be drawn that the gas displacement effect of water injection in coal seams is much better in low metamorphic coals than in high metamorphic degree coals.

The effect of adsorption equilibrium pressures

The adsorption equilibrium pressure determines the gas content in coal pores of different sizes, leading to the difference in the gas displacement effect. The water-driven gas effect under different adsorption equilibrium pressures is shown in Figure 9. The gas displacement curves are composed of three stages, although the adsorption equilibrium pressure is different. The higher the adsorption equilibrium pressure is, the more gas that is replaced. In addition, the relationship between the cumulative gas displacement amount and adsorption
equilibrium pressures is also analyzed. As shown in Figure 10, as the adsorption equilibrium pressure increases, the cumulative gas displacement gradually increases. Thus, increasing the adsorption equilibrium pressure can increase the gas displacement effect of water injection in coal. However, when the adsorption equilibrium pressure is relatively small, it is not very obvious that increasing the adsorption equilibrium pressure will improve the water-driven gas effect in the coal seam.
Studies have indicated that the gas is mainly adsorbed in micropores and mesopores, which have pore sizes less than 2 nm and from 2 to 20 nm, respectively (Yin et al., 2017). In general, when the gas adsorption equilibrium pressure is low, a large amount of gas stored in the micropores is in an adsorption state. However, because the gas adsorption capacity of coal is improved with increasing adsorption equilibrium pressure, the gas gradually begins to adsorb on the surface of the mesopores. As a result, the adsorption capacity of micropores for gas is weakened. In addition, the higher the gas adsorption equilibrium pressure is, the more gas is stored in coal in an adsorption state and free gas state, especially in mesopores. On the one hand, the gas displacement amount of free gas driven out by the water injection in coal with a high adsorption equilibrium pressure is more than that in coal with a low adsorption equilibrium pressure. On the other hand, the adsorbed gas on the surface of mesopore is displaced after the free gas is driven out, which results in the more gas displacement amount of absorbed gas for the coal with a high adsorption equilibrium pressure. Therefore, as the adsorption equilibrium pressure increases, the gas displacement amount in coal also increases.

The effect of water injection on the pore structure
As shown in Figure 8, the porosity in coal directly determines the gas displacement. In contrast, in the process of water injection, the porosity of coal will also be changed by the pressurized water (Lu et al., 2020). Therefore, the effect of water injection on the coal pore structure was investigated, including the pore size and its distribution. The pore structure distributions were tested using the mercury porosimeter before and after the water injection in coals at different metamorphic degrees. A G-33 mercury porosimeter with a pore measurement range of 0.007–1000 µm was used to measure the pores. Using anthracite as an example, the mercury pressure curve of anthracite before and after water injection is
shown in Figure 11. With the mercury injection pressure, the total amount of mercury injection first rapidly increases, then slowly increases, and then tends to gradually stabilize. The injection process of mercury is similar to that of water injection. The mercury first enters the fractures and large pores in coal because of the lower injection resistance. A large amount of mercury can enter coal under low injection pressures. Then, after the large accessible pores are fully filled, the mercury will enter the small-sized pores due to the high injection pressure. Owing to the increase in resistance, relatively little mercury can enter these pores. When the mercury injection pressure stops, the mercury injected into the coal will flow out. However, there are some semiopen pores in the coal, and the amount of mercury flowing out will be less than the total amount of mercury that is injected in. Therefore, it can be seen that the mercury injection curve can better reflect the pore structure distribution in coal.

The comparisons of the mercury intake for anthracite, lean coal, and coking coal before and after water injection are given in Table 2. The mercury intake amounts increase for the coal samples after the water injection. The mercury intake is highest in the coking coal, followed by the lean coal and anthracite. These differences in the intake results are caused by the pore distribution difference. The comparison charts of the pore distribution before and after the water injection in coal samples at different metamorphic degrees are shown in Figure 12. The pores over 100μm in size increase due to water injection, and the coking coal shows the greatest incremental increase. This increase is the main reason for the increase in

Table 2. Comparison of the mercury intake for coal samples at different degrees of metamorphism before and after water injection.

| Coal samples | $Q_b$ (ml/g) | $Q_a$ (ml/g) | $\Delta Q$ (ml/g) |
|--------------|--------------|--------------|-------------------|
| Anthracite   | 0.0233       | 0.0253       | 0.0020            |
| Lean coal    | 0.0221       | 0.0262       | 0.0041            |
| Coking coal  | 0.0332       | 0.0378       | 0.0046            |

$Q_b$ and $Q_a$ are the mercury intake amount before and after water injection, respectively. $\Delta Q$ is the mercury intake increment before and after water injection.
the mercury injection after the water injection. Thus, the increasing large pores and fractures in coal will promote the gas displacement caused by water injection. In low metamorphic coal, such as coking coal, the water-driven gas effect is better. Moreover, the micropores in coal will also increase. Overall, the pore structure in coal will be changed by the water injection, increasing the porosity of coal and improving the gas flow.

Conclusions

Based on water injection experiments conducted under different conditions, the dynamic water-driven gas process and its wetting process were analyzed. The effects of injection pressure, coal metamorphic degree, and adsorption equilibrium pressure on gas displacement were analyzed. The pore characteristics were investigated after the water injection for the coals with different metamorphic degrees. The following conclusions were drawn:

1. The gas displacement process caused by the water injection can be described in three stages: the early stage, middle stage, and last stage of displacement. The gas in fractures, large pores, and micropores is successively displaced, leading to the subsequent rapid increasing, slow increasing, and almost constant gas displacement.
2. The wetting process of water injection in coal body includes three processes: wetting, soaking, and spreading. The wettability of water to coal can be judged by the contact angle between water and coal surface. And wetting effect of water to coking coal is best, followed by lean coal and anthracite, respectively, in this experiment.

3. The water injection pressure, coal metamorphic degree, and adsorption equilibrium pressure have significant influence on the gas displacement. The higher the injection pressure is, the more gas that is driven out under the same injection time. Water injection is only applicable to the low and high injection pressure, because the water-driven gas effect at relatively low injection pressures is better than that at high injection pressures. Coking coal has a better gas displacement effect because there are more fractures and large pores in that type of coal. In addition, the early stage of gas displacement is also longer for coking coal. The amount of gas displacement caused by the water injection increases with increasing adsorption equilibrium pressure. In addition, it is not obvious that increasing the adsorption equilibrium pressure will improve the water-driven gas effect in the coal seam when the adsorption equilibrium pressure is relatively small.

4. After water injection, the total porosity of coal increases, promoting gas and water flow. The large fractures and pores in coal will dramatically increase, especially in low metamorphic grade coals, such as coking coals, which is conducive to improving the gas displacement caused by water injection.

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