Research Article

The Effect of Drilling Fluid on Coal’s Gas-Water Two-Phase Seepage

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In the process of coal bed methane (CBM) production, the output of CBM is mainly related to the relative permeability of gas and water in coal seams. However, during the drilling process, the invasion of drilling fluid into CBM reservoirs changes the wettability, which may cause the gas and water’s redistribution through the pores and cracks, further changing their two-phase seepage characteristics and influencing CBM production. Therefore, studying the effect of drilling fluid on coal’s gas-water two-phase seepage has practical implications. Using a steady-state method, the influence of changing wettability and reducing the solution’s interfacial tension on relative permeability is investigated by adding different surfactants. The increase in coal’s hydrophilicity exhibits an impact on its relative gas-water permeability. At the same water saturation level, the relative gas permeability decreases and the relative water permeability increases. The hydrophilicity of coal was enhanced after adding anionic surfactants, which reduced gas permeability. Cationic surfactants are difficult to adsorb to the surface of coal due to the fact that the interfacial tension of the water and coal surface is reduced when the coal seam water is added to the cationic surfactants. After adding cationic surfactants, the gas permeability increased in favor of CBM production. The findings of this study could help to better understand the influence of drilling fluid intrusion on coal’s gas-water two-phase seepage and provide technical guidance for selecting better surfactants during the preparation of drilling fluids and help to increase CBM production.

1. Introduction

CBM presents the coal matrix porosity and natural fractures that are mostly free and adsorbed on the surface of coal, whereas the pore and natural cracks are also the main channels through which seepage occurs. When CBM is mined, with decreases in water pressure, the desorbed CBM enters the free state and becomes a water-CBM two-phase flow; therefore, the output of CBM also relates to the relative permeability of water and CBM. However, during the process of drilling for CBM, drilling fluid enters CBM reservoirs, changing the wettability and causing the gas and water’s redistribution through the pores and cracks, changing the gas and water’s two-phase seepage law, and affecting CBM production.

The permeability of a coal bed is the most vital parameter for CBM recovery and its production, and it is most significant for the prediction of reservoir performance during the production of CBM [1]. The effective migration system of CBM reservoir was controlled by the development degree and opening-closing degree of fractures, and these factors determined the permeability of the coal reservoir and can be characterized by the pore-fracture system in the extrinsic form [2]. Cai et al. established a fractal permeability model to acquire the seepage-pore permeability based on mercury intrusion porosimetry. For coals with permeability greater than 0.2 mD, the permeability generally correlates with the fracture density and connectivity. Seepage-pore-contributed permeability has no obvious correlation with total helium measure core porosity, while it correlates with seepage-pore volume.
which may change significantly. Wang and Zhang analyzed the permeability of ultralow permeability rocks such as coal and gas shale [4]. Z.T. Zhang et al. conducted porosity and permeability experiments under different depth-dependent hydrostatic stress conditions, and the coal samples were collected from the same Ji group of coal seams at five different depths in the Pingdingshan mining area [5]. A coal mass with a high porosity and a correspondingly low density typically has stress sensitivities. The stress sensitivity of coal was found to be stress-dependent and obviously increases when the effective stress in the coal mass is less than 10 MPa. The porosity and stress sensitivities of the coal were directly associated with the initial porosity and physical properties of the coal. The depth effect on the porosity and stress sensitivities of the coal permeability was closely related to specific coal fracture compression properties at different depths.

The characteristics of the gas flow in the reservoir greatly impact the capacity to exploit CBM, and many researchers studied the permeability of coal samples. Zhou et al. analyzed the Klinkenberg effect of gas flow in coal and the deformation of the cleat in coal, established the model of the variable Klinkenberg coefficient for methane with the effective stress and gas sorption effects, and discussed the evolution of that [6]. He et al. conducted the tests of gas permeability under constant confining pressure and effective stress [7]. Under constant confining pressure, the permeability decreases and then increases with the increase of the gas pressure. Under constant effective stress, the comparison of incremental permeability from the coal matrix shrinkage effect and slippage effect shows that the gas slippage effect is obvious under low gas pressure and the coal matrix expansion adsorption effect strengthens under high gas pressure. Ju et al. investigated and tested the CO₂ permeability of fractured coals sampled from the Pingdingshan coal mine through undrained triaxial tests. The CO₂ permeability of naturally fractured coal increases with the increase of injection pressure, and it significantly decreases with the increase of confining pressure [8].

The coal seam permeability is sensitive to effective stress which may change significantly with reservoir depletion [9, 10]. Wang and Zhang analyzed the effect of in situ stress on the permeability of the CBM reservoir in the southern Qinshui Basin (China), and the results showed that the permeability differences were caused by the fracture propagation shape of the rock strata under different in situ stress states [11]. Cui and Bustin have investigated quantitatively the effects of reservoir pressure and sorption-induced volumetric strain on coal seam permeability and derived a stress-dependent permeability model [12]. Pressure relief mining is used in high-gas, low-permeability coal seams. The stress sensitivity of high-gas and low-permeability coal seams directly impinges on the effectiveness of pressure relief mining [13, 14]. Permeability changes can be very large during the depletion of coal bed methane wells. The increase in the absolute permeability of coal beds is a result of matrix shrinkage caused by gas desorption, which becomes a dominant factor on cleat permeability over the effective stress effect during reservoir production [15, 16].

The permeability of crushed coal is not only mainly controlled by coal structure but also unavoidably influenced by variations of stress, particle size, moisture content, and temperature. With the establishment of the permeability calculation model of the coal samples under different temperatures, water contents, and pore pressures during the loading processes, the permeability of different locations in different environments can be speculated [17]. The stress-permeability relationship of coal samples with various particle sizes under cyclic loading and unloading was experimentally studied. Permeability stress sensitivity and permeability loss on the first loading and unloading were significantly greater than that of the succeeding cyclic loading and unloading [18]. The directional permeability of the coal under various stress states according to the repeated mining of group coal seams was studied [19]. The axial and radial permeability of coal samples was observed to increase when the effective stress decreased. With an increase in the number of loading/unloading cycles, both the radial and axial permeability stress sensitivity gradually decreased. Axial permeability was more sensitive to confining stress than radial permeability. The sensitivity of radial permeability to axial stress was much larger than that of axial permeability. With increasing confining stress and axial stresses, the influence of axial stress and gas confining stress on permeability gradually decreased.

Previous studies mainly focused on the influence characteristics of different stress conditions on coal reservoir’s permeability and the relationship between the coal seam structure and the permeability. Drilling pressure and pressure fluctuations cause drilling fluids to enter the coal reservoir and measured the amount and the rate of drilling fluids invaded into coal by studying core flow in an earlier study [20]. Unfortunately, the entering of drilling fluids into the coal reservoir during well drilling is difficult to avoid from the aspect of construction technique. After the drilling fluids invade the coal reservoir, it will damage the coal reservoir, which is mainly reflected in the permeability. However, the research on the influence of drilling fluid’s invasion on coal reservoir’s permeability was limited.

This work analyzes the impact of the inward seepage of drilling fluid on the relative permeability of CBM and water and tries to seek corresponding measures that demonstrate practical significance for enhancing the production of CBM. First, the experimental principle is discussed and the experimental section is setup. Then, experiments on the effect of different types of surfactants on the wettability of coal, the influence of wetting fluid on coal’s permeability was limited. This work analyzes the impact of the inward seepage of drilling fluid on the relative permeability of CBM and water and tries to seek corresponding measures that demonstrate practical significance for enhancing the production of CBM. First, the experimental principle is discussed and the experimental section is setup. Then, experiments on the effect of different types of surfactants on the wettability of coal, the influence of wettability change on the relative gas-water permeability, and the influence of the interfacial tension’s changing on the relative gas-water permeability are carried out, respectively. Lastly, the effects of drilling fluid on coal’s gas-water two-phase seepage are discussed according to the obtained results.

2. Experimental Background

Using the steady-state method to test the relative gas-water permeability, the basic theory is of one-dimensional Darcy seepage, assuming that the gas-water two-phase is immiscible and incompressible. During the experiment, gas and liquid were injected to a certain percentage; when the pressure of the inlet and the outlet was stable, the gas flow, the water
flow, and water saturation of the coal samples were not changing; reaching the steady state, the effective permeability of the gas and liquid was constant. According to Darcy’s law, by directly calculating the gas and liquid’s effective permeability and relative permeability values under different water saturation levels, one can generate the curves of gas-liquid relative permeability.

In the experiment, we employed surfactants, which are often applied to drilling fluid to deal with coal, to test its relative permeability before and after treatment by surfactants, and to draw the curves of gas-liquid relative permeability, in order to study the influence of drilling fluid on relative permeability. A flow chart of the experiment is depicted in Figure 1.

3. Experimental Procedure

3.1. Experimental Procedure for Measuring Relative Permeability by the Steady-State Method

(1) Dry the clean coal samples, measure the gas permeability of coal samples and evacuate them, saturate the coal samples with simulated formation water, and then let them stand for 24 hours

(2) Place the coal samples in the experimental device, which tests the gas-liquid relative permeability

(3) Under certain displacement speeds, inject the simulated formation water into the core, record the pressure difference across it, and measure the flow at the outlet. After the pressure difference between the inlet and outlet and the flow of the outlet have become steady, measure the water permeability three times consecutively, and then calculate the core’s initial water permeability

(4) Inject the humidified nitrogen into the core, build the coal samples’ irreducible water saturation, and in the meantime, measure the effective permeability of the gas phase

(5) Inject the humidified nitrogen and simulated formation water into the coal sample at a certain percentage until the flow is steady, and then measure the gas pressure, flow, water pressure, and water flow at the inlet. Then, measure the same values at the outlet, weigh the coal sample, and then calculate the water saturation and effective permeability of the gas and water

(6) When the relative permeability of the gas phase is less than 0.005, test the water permeability at the state of the residual gas

(7) In accordance with the following formulas, calculate the water saturation, effective permeability, and relative permeability of the gas and water

Effective permeability of the gas phase:

\[ K_{ge} = \frac{2p_a q_g \mu_g L}{A(p_1^2 - p_2^2)} \times 10^{-1}, \tag{1} \]

where \( q_g \) is the gas phase volume flow rate, \( \mu_g \) is the gas phase dynamic viscosity, \( L \) is the core length, \( A \) is the core cross-section area, \( p_1 \) is the absolute pressure at the inlet of the core, and \( p_2 \) is the local absolute atmospheric pressure.

Effective permeability of the water phase:

\[ K_{we} = \frac{q_w \mu_w L}{A(p_1 - p_2)} \times 10^{-1}, \tag{2} \]

where \( q_w \) is the water phase volume flow rate, \( \mu_w \) is the water phase dynamic viscosity, and \( p_2 \) is the absolute pressure at the outlet of the core.
Gas phase relative permeability:

\[ K_{rg} = \frac{K_g}{K_g(S_{ws})} \],  \quad (3) \]

where \( K_g(S_{ws}) \) is the gas phase permeability in the presence of irreducible water.

Water phase relative permeability:

\[ K_{rw} = \frac{K_{we}}{K_g(S_{ws})} \].  \quad (4) \]

Water saturation:

\[ S_w = \frac{m_i - m_o}{V_p \rho_w} \times 100\%, \quad (5) \]

where \( m_o \) and \( m_i \) are the mass of core before and after saturated water, respectively, \( V_p \) is the pore volume of the core, and \( \rho_w \) is the density of the water phase.

3.2 Experimental Procedure for Analyzing the Influence of Changes in Wettability by Surfactants’ Adsorption on Relative Permeability

(1) In accordance with the steady-state method, use coal seam water and humidified nitrogen to measure the relative permeability of gas-water two-phase

(2) Dry the cores

(3) Prepare the solution using petroleum sulfonate (anionic surfactant) at a concentration of 0.2%, where the redried core is added for saturation, and place the core in a petroleum sulfonate solution for 48 hours, in order to enable the surfactants to be fully absorbed on the surface of the core

(4) In accordance with the steady-state method, use coal seam water and humidified nitrogen to measure the relative permeability of the gas-water two-phase after the adsorption of the surfactants

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Table 2: Pulverized coal’s average self-priming height in the solution with anionic surfactants.

<table>
<thead>
<tr>
<th>No.</th>
<th>Powder pillar height (cm)</th>
<th>Surfactant</th>
<th>Concentration (%)</th>
<th>1 h</th>
<th>2 h</th>
<th>3 h</th>
<th>20 h</th>
<th>22 h</th>
<th>24 h</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20.0</td>
<td>Petroleum sulfonate</td>
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<td>0.91</td>
<td>1.42</td>
<td>1.76</td>
<td>3.79</td>
<td>3.83</td>
<td>3.85</td>
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<tr>
<td>2</td>
<td>20.0</td>
<td>Petroleum sulfonate</td>
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<td>1.53</td>
<td>2.24</td>
<td>2.71</td>
<td>8.29</td>
<td>8.84</td>
<td>9.32</td>
</tr>
</tbody>
</table>

Table 3: Pulverized coal’s average self-priming height in the solution with cationic surfactants.

<table>
<thead>
<tr>
<th>No.</th>
<th>Powder pillar height (cm)</th>
<th>Surfactant</th>
<th>Concentration (%)</th>
<th>1 h</th>
<th>2 h</th>
<th>3 h</th>
<th>20 h</th>
<th>22 h</th>
<th>24 h</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>CTAB</td>
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<td>8.16</td>
<td>9.68</td>
<td>19.77</td>
<td>21.36</td>
<td>21.82</td>
</tr>
<tr>
<td>2</td>
<td>20.0</td>
<td>CTAB</td>
<td>0.01</td>
<td>5.13</td>
<td>7.72</td>
<td>9.45</td>
<td>16.64</td>
<td>16.82</td>
<td>7.13</td>
</tr>
</tbody>
</table>

Table 4: Experimental results of the coal’s gas-water relative permeability before and after surfactant adsorption.

<table>
<thead>
<tr>
<th>No.</th>
<th>Powder pillar height (cm)</th>
<th>Surfactant</th>
<th>Concentration (%)</th>
<th>1 h</th>
<th>2 h</th>
<th>3 h</th>
<th>20 h</th>
<th>22 h</th>
<th>24 h</th>
</tr>
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<tbody>
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<td></td>
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<td>Petroleum sulfonate</td>
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<td></td>
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<td></td>
<td></td>
<td>Petroleum sulfonate</td>
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<td>43.89</td>
<td>46.28</td>
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<td>75.24</td>
</tr>
</tbody>
</table>

Figure 2: Relative permeability curves of the coal before and after surfactant adsorption.
### 3.3. Experimental Procedure for Studying the Influence of Interfacial Tension Reduced by Surfactants’ Adsorption on the Relative Permeability

1. In accordance with the steady-state method, use coal seam water and humidified nitrogen to measure the core’s relative permeability in the gas-water two-phase.
2. Redry the cores, evacuate, and saturate with coal seam water.
3. Prepare cetyl trimethyl ammonium bromide (CTAB) solution (cationic surfactant) at a concentration of 0.3%, add it to the seam water, and then follow the steady-state method to measure the relative permeability of the gas-water two-phase using formation water with the additions of CTAB solution and humidified nitrogen gas.

### 4. Results and Discussion

Select the experimental coal and grind it until pulverized, with a mesh sieve of over 100, press them into a sand-packed model, and then use two methods to discuss the effect of drilling fluid on the relative permeability of the gas-water phase. The basic data from the coal sample are shown in Table 1.

#### 4.1. Effect of Different Types of Surfactants on the Wettability of Coal

Use the method for self-priming speed to test that of a pulverized coal at a concentration of 0.2% petroleum sulfonate solution (anionic surfactant) and one of 0.01% CTAB solution (cationic surfactant) in contrast to that without surfactants; the experimental results are shown in Tables 2 and 3.

As can be seen from the data displayed in Table 2, coal’s self-priming heights at a 0.2% concentration of petroleum sulfonate are greater than that without the surfactants, indicating the hydrophilicity of the coal increases after the addition of petroleum sulfonate. According to the findings of a Fourier transform infrared experiment on the coal samples, the anionic groups on the coal surface and the anionic groups in the surfactants are mutually exclusive, hydrophobic groups that tend to adsorb on the coal’s surface, with anionic groups outward, making the coal surface exhibit hydrophilicity.

As can be seen from the data in Table 3, coal’s self-priming heights in CTAB solution at a concentration of 0.01% are less than those without the surfactants. Because the cationic surfactant does not contain the group which is mutually exclusive to the anionic group on the coal surface, the orientation adsorption is not better than the anionic surfactants. Cationic surfactants are difficult to adsorb to the surface of coal due to the fact that the interfacial tension of the water and coal surface is reduced when the coal seam water is added to the cationic surfactants. From the formulas of capillary pressure, the reduction in interfacial tension will reduce the capillary force, thereby resulting in a decrease in the rising height of water molecules.

#### 4.2. The Influence of Wettability Change on the Relative Gas-Water Permeability

The steady-state method is first used to measure the relative gas-water permeability, and then, the core is dried to absorb the surfactant and left to stand for 48 hours, after which the core’s gas-water relative permeability is measured again. The experimental coal is selected and ground until pulverized to over 100 mesh sieve and then pressed into the sand-packed model, and the experiments are carried out. The experimental results are shown in Table 4. The relative permeability curve of the coal before and after the adsorption of the surfactants is shown in Figure 2.

As can be seen from Figure 2, the increase in coal’s hydrophilicity exhibits an impact on its relative gas-water permeability. At the same water saturation level, the relative gas permeability decreases and the relative water permeability increases. This indicates that when the drilling fluid is added to an anionic surfactant that invades the coal seam,
the coal’s hydrophilicity increases, thereby reducing the permeability of CBM and affecting its production. Therefore, from the perspective of increasing the production of CBM, one should opt for the surfactant with small adsorption quantity in the preparation of drilling fluids.

4.3. The Influence of the Interfacial tension’s Change on the Relative Gas-Water Permeability. First, the steady-state method is used to measure the relative gas-water permeability, then dry the core, and finally measure the relative gas-water (solution added with surfactants) permeability. Select experimental coal and grind it until pulverized, over 100 mesh sieve, press it into the sand-packed model, and carry out experiments on it. The experimental results are shown in Table 5. The coal’s relative permeability curve before and after adding the surfactants is shown in Figure 3.

After adding the cationic surfactants of CTAB in the coal seam water at concentrations of 0.3%, it is difficult for surfactants to be adsorbed on the surface of the coal, exerting almost no effect on the coal’s wettability. However, the addition of surfactants causes the surface tension of the gas-water interface to be greatly reduced, with a greater impact on the relative gas-water permeability of coal. As can be seen in Figure 3, when the interfacial tension is reduced, the overall relative gas-water permeability curves move to the right, and the isotonic point of saturation increases. When the water saturation is more than 40%, at the same water saturation, the relative gas permeability of the coal increases, and the relative water permeability of the coal decreases. Therefore, the addition of surfactant with small adsorption quantity into the drilling fluid is conducive to the production of coal bed methane.

Furthermore, the drilling fluid that is added to the cationic surfactants is also conducive to its flow back. A chart displaying the coal’s capillary force direction of different wettability is shown in Figure 4. As is shown in Figure 4(a), when the coal’s surface is hydrophilic, the pointing direction of the capillary force toward the gas phase is resistant to drilling fluids flowing to the wellbore. When the coal’s surface is nonhydrophilic, the pointing direction of the capillary force is toward the liquid, as shown in Figure 4(b), which represents the driving force of the drilling fluids flowing to the wellbore, such that the drilling fluid’s flow back to the well bore is much smoother. After the addition of cationic surfactants, the gas-water interfacial tension is reduced, and so, the capillary force of hydrophilic porosity decreases, the resistance of gas flow is reduced, and the CBM flows more easily, and an increase in gas production occurs. It can be seen that the surfactants that are added to the drilling fluids exhibit a major impact on CBM output and the drilling fluid’s flow back, and so, we should make the reasonable choice of adding surfactants during the preparation of drilling fluids.

5. Summary and Conclusions

(1) The addition of anionic surfactants to drilling fluid causes the coal’s hydrophilicity to increase, thereby reducing the permeability of the CBM reservoir and affecting its production.

(2) After the addition of cationic surfactants, the gas-water interfacial surface tension is greatly reduced, the gas phase relative permeability of the coal increases, and the relative water phase permeability decreases, which is conducive to CBM production.

(3) In order to effectively improve CBM production, surfactants with a small amount of adsorption should be selected in the preparation of drilling fluid.

(4) The current experimental conditions are difficult to fully simulate the actual conditions of underground coal seams, and the experimental results may have some deficiencies from the real working conditions.

Nomenclature

\[ K_{ge} \]: The effective permeability of the gas phase, \( \mu m^2 \)

\[ K_{we} \]: The effective permeability of the water phase, \( \mu m^2 \)

\[ K_{rg} \]: The gas phase relative permeability, dimensionless

\[ K_{rw} \]: The water phase relative permeability, dimensionless

\[ K_g(S_{ws}) \]: The gas phase permeability in the presence of bound water, \( \mu m^2 \)

\[ q_g \]: The gas phase volume flow rate, \( cm^3/s \)

\[ q_w \]: The water phase volume flow rate, \( cm^3/s \)

\[ \mu_g \]: The gas phase dynamic viscosity, \( mPas \)

\[ \mu_w \]: The water phase dynamic viscosity, \( mPas \)

\[ L \]: The core length, cm

\[ A \]: The core cross-section area, \( cm^2 \)
Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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References