

Study on the Wettability and Methane Desorption Characteristics of Coal under High Pressure with Different Surfactants

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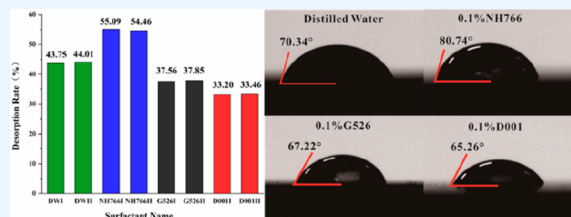
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ABSTRACT: In the process of coalbed methane extraction, due to the strong hydrophilicity of coal, the surface interaction force between water and the coal matrix is strong. The hydrophobic effect of the coal seam during drainage and pressure reduction is not significant, and adsorbed methane is difficult to desorb. In order to reduce the surface interaction force promoting methane desorption between water and coal, the surfactants NH766, G526, and D001 with a concentration of 0.1% were selected. A pressure of 12 MPa, which is close to that used for the on-site mining of coalbed methane in Baode, was selected as the experimental condition to simulate hydraulic fracturing of high fat coal, and the influence of different surfactants on methane desorption characteristics was analyzed. Combining contact angle experiments and infrared spectroscopy experiments, we explored the changes in wettability and methane desorption characteristics and explored the similarities between these changes. The experimental results showed that after NH766 treatment, the content of oxygen-containing functional groups in coal rock decreased by 30%, and the contact angle of the coal matrix surface increased by 10°. Furthermore, its hydrophobicity was enhanced, and the desorption amount increased by 24%. In contrast, the oxygen-containing functional groups in coal rock after G526 and D001 treatments increased by 5% and 16%, respectively, and the contact angle of the coal matrix surface became smaller. Furthermore, its hydrophilicity was enhanced, and the desorption amount was reduced by 12.5% and 20%, respectively. NH766 reduces wettability and promotes methane desorption, and it can be applied to improve CBM extraction efficiency. G526 and D001 enhance wettability and inhibit methane desorption, which make them suitable for dust prevention and gas control in coal mines.



1. INTRODUCTION

The efficient extraction of coalbed methane not only ensures the safe mining of coal mines but also provides strong support for the supply of clean energy.^{1–5} In China, more than two-thirds of coal less is than 1 millidarcy (mD),^{6,7} and these coalbed methane (CBM) wells must undergo hydraulic fracturing to realize industrial gas production.⁸ Coal is a porous medium that is rich in a large number of capillary structures. High-pressure water intrudes into pore fissures of the coal matrix during hydraulic fracturing, generating the water lock effect and inhibiting coalbed methane desorption.^{9–13}

To reduce the inhibitory effect of the water lock effect on CBM, the measure commonly used in engineering is to add surfactants into the fracturing fluid to change the wettability of coal, reduce the capillary force, and improve the recovery of coalbed methane wells.^{14,15} Lyu et al. investigated the action of the NPEO-12 active agent on the surface of sub-bituminous coal and measured contact angle, heat of adsorption, and X-ray photoelectron spectroscopy (XPS) data to validate the simulation results, which indicated that the addition of the active agent NPEO-12 improves the hydrophobicity and flotation performance of sub-bituminous coal.¹⁶ Liu et al. used low surface tension FC177 and FC134 surfactants to soak

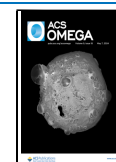
coal samples from the Jincheng Yuxi coal mine, which realized a shift in the surface wettability of the coal samples from hydrophilic to hydrophobic and increased the methane desorption rate.¹⁷ Zheng et al. addressed the differences in moisture type and changes in moisture distribution caused by differences in wettability of different coal rock fractions, and they concluded that liquid water improves the ability of the coal matrix to adsorb gases, suggesting that the wettability of the coal surface, which is a manifestation of the microscopic role of the coal–water interface, is an important factor influencing methane adsorption/desorption.¹⁸ Ma et al. conducted desorption experiments on coal samples modified with three surfactants using an AST-2000 coalbed methane isothermal adsorption/desorption experimental instrument, which indicated that surfactants alter the wettability of coal, thereby affecting the desorption ability of coal.¹⁹ Atta et al.

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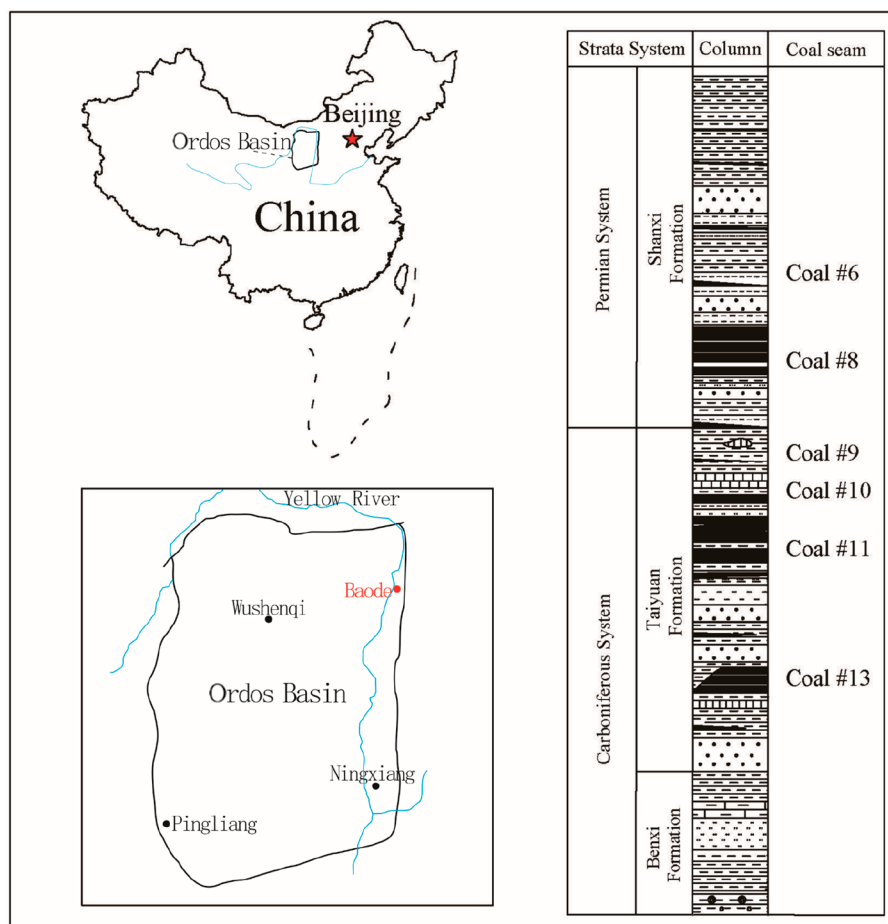


Figure 1. Geological and stratigraphic map of the Baode coal mine.

summarized the advantages of natural surfactants and the challenges they pose to oil field applications based on their evaluation indicators, including interfacial tension, wettability, and rock surface adsorption.²⁰

Ni et al. investigated the changes in critical micelle concentration, surface tension, and contact angle of three different surfactants (anionic, cationic, and nonionic), on the surface of coal, and believed that capillary force and viscous hysteresis effects were one of the reasons for the water locking effect of fracturing fluids.²¹ Su et al. achieved the purpose of reducing capillary resistance, improving coal permeability and promoting desorption by mixing the surfactant AN and potassium chloride in a certain proportion and adding them into the fracturing fluid.²² In order to solve the water lock effect in the process of hydraulic fracturing a coal seam, Zheng et al. chosen to add surfactants to the fracturing fluid and screened out anionic surfactant SDRS.²³ Chen et al. studied the changes of functional groups in coal treated with 14 kinds of composite surfactants and the relationship between wettability and functional groups through contact angle experiments and infrared spectrum experiments, and they considered that C=O was the main reason that affected the contact angle, while -OH and C-O-C were the main functional groups that affected the moisture content of coal samples.²⁴ Nie et al. simulated the effects of three different surfactants, namely SDBS, rapid penetrating agent T, and CAB, on the wettability of coal dust through molecular dynamics and analyzed their wetting mechanisms, and they believed that surfactant molecules adsorbed coal and water molecules

through hydrophobic bonds and electrostatic interactions, forming an adsorption configuration where hydrophobic groups adsorbed on the coal surface and hydrophilic groups extended into water, thereby achieving wetting of coal.²⁵

Although there are more current studies on surfactants and factors such as wettability and the water locking effect, relevant studies on the effects of surfactants on the desorption characteristics of methane still need to be further investigated. In this paper, the #8 coal seam in the Baode coal mine at the eastern edge of the Ordos Basin in China was selected as the object, and three kinds of surfactant solutions were prepared to conduct high-pressure hydraulic fracturing experiments on gas-bearing coal and test the desorption characteristics of methane. By analyzing the change characteristics of the contact angle and oxygen-containing functional groups, the influence mechanism of different surfactants on methane desorption characteristics was discussed in depth. The research results provide technical support for the efficient fracturing reconstruction of coalbed methane wells in reservoirs with similar geological characteristics.

2. EXPERIMENTAL SECTION

2.1. Coal Samples. The samples were collected from the #8 coal seam of the Shanxi formation Baode coal mine that is located at the eastern edge of the Ordos Basin in China (Figure 1). The two coal-bearing formations in the coal mine, Shanxi and Taiyuan, contain four recoverable coal seams including #8, #10, #11, and #13, and coal seam #8 is being

mined currently (Figure 1). The thickness of coal seam #8 is 2.15–10.8 m with an average of 7.62 m. The proximate and minerals of the samples were analyzed based on the national standards.^{26,27} The results are shown in Tables 1 and 2. The

Table 1. Basic Parameters of Experimental Coal Samples^a

proximate analysis				
M_{ad} (%)	A_d (%)	V_{daf} (%)	FC_{ad} (%)	$R_{o,max}$ (%)
2.50	9.34	31.27	56.89	0.89

^a M_{ad} : air dry moisture content; A_d : dry ash yield; V_{daf} : dry ash free volatile matter; FC_{ad} : dry ash free fixed carbon; and $R_{o,max}$: vitrinite maximum reflectance.

Table 2. Mineral Composition of Experimental Coal Samples

kaolinite (%)	boehmite (%)	quartz (%)	calcite (%)
61	16	8	7

maximum vitrinite reflectance is 0.89%, belonging to the category of low bituminous coal. The fixed carbon content is 56.89%, and the volatile matter is 31.27%. The ash content is 9.34%, and the moisture content is 2.5%. The mineral composition of the coal samples is 61% kaolinite, 16% boehmite, 8% quartz, and 7% calcite.

2.2. Surfactants. Three different surfactants, namely the nonionic surfactant NH766, the anionic surfactant G526, and the cationic surfactant D001, were used in this study. Surfactants can change the surface tension of water, reduce surface tension, and facilitate the spreading and wetting of liquids at solid interfaces.²⁸ In the initial stage of the study, four different concentrations of surfactant solutions were prepared: 0.05%, 0.1%, 0.2%, and 0.3%. After using the German KRUSS brand surface tension tester to test each surfactant solution 5 times, the average value was calculated, and the results are shown in Table 3. The surface tension

Table 3. Surface Tension (mN/m) of Surfactants with Different Concentrations

concentration	0.05%	0.1%	0.2%	0.03%
NH766	59.34	50.08	72.13	71.60
G526	71.48	66.28	71.90	71.50
D001	71.64	71.78	71.87	71.80

values of the three surfactants are relatively similar to that of distilled water. When the concentration is 0.1%, the surface tension of the three surfactants is the smallest. All of the surfactants were diluted to 0.1% concentration, respectively, and their surface tension, pH, and viscosity were tested. The results are shown in Table 4. The minimum surface tension of NH766 is 50.1 mN/m, while that of G526 and D001 is larger (66.3 and 71.8 mN/m, respectively), similar to the surface tension of distilled water.

2.3. Methane Desorption Experiment. **2.3.1. Preparation of Experimental Samples.** The raw coal was processed into particles of 3–6 mm using a jaw crusher, ensuring that the original pore-cracks in the coal were not disturbed by the crushing process. The particle samples were placed in an air blower box, dried for 12 h at 55 °C, and then vacuum packed for subsequent experiments.

Table 4. Basic Parameters of Different Surfactants

basic parameter	units	distilled water	nonionic surfactant NH766	anionic surfactant G526	cationic surfactant D001
surface tension	mN/m	72.1	50.1	66.3	71.8
viscosity	MPa/s	1.0	0.9	1.0	0.9
pH	/	7.02	5.93	6.00	4.34

The desorption experimental system (Figure 2) consists of a ① methane gas injection device, ② constant temperature water bath device, ③ hydraulic fracturing device, ④ desorption gas collection device, and ⑤ pressure monitoring device. This experimental system combines isothermal adsorption together with desorption and has an added hydraulic fracturing device, which can simulate the impact of hydraulic fracturing on methane desorption efficiency.

2.3.2. Experimental Procedure.

- (1) Weigh the coal sample, place it in the sample cylinder, and perform vacuum degassing on the testing system for 30 min.
- (2) Use helium gas to calibrate the free volume of the sample cylinder and then vacuum the helium out of the coal.
- (3) Based on the temperature, sample mass, reference cylinder volume, and free volume of the sample cylinder, calculate the reference cylinder methane pressure P_0 when the methane adsorption volume of the coal sample is 9.22 cm³/g (referring to the field gas content of the coal seam of 9–10 cm³/g) and the coal sample cylinder pressure P_2 (2.56 MPa) at the adsorption equilibrium.
- (4) Inject methane into the reference cylinder to pressure P_0 first. Then, turn the valve with the coal sample cylinder to start gas adsorption. When the pressure reaches P_2 in the sample cylinder, inject the prepared surfactant solution into the sample cylinder at a pressure slightly higher than P_2 to drive out the free methane using a constant pressure pump.
- (5) As the free methane is driven out completely, the surfactant solution is continuously injected into the sample cylinder until a pressure of 12 MPa is reached. Maintain this pressure for 2 h, which is similar to the field process of hydraulic fracturing in the CBM industry.
- (6) Slowly reduce the pressure in the sample cylinder to P_2 (2.56 MPa) through the constant pressure pump, and turn off the constant pressure pump. Open the valve that connects the sample cylinder and the desorption device, and immediately start to record the desorbed gas volume and the pressure of the sample cylinder drops. The desorption will continually last for about 3500 min.

Follow the above steps to complete the fracturing desorption experiments of distilled water and the three surfactant solutions. During the experiments, a constant temperature water bath was always maintained at 25 °C.

2.4. Contact Angle Measurement. Contact angle indicates the wettability of liquid to solid.²⁹ First, a linear cutting machine was used to cut the same coal sample into four coal slices with a diameter of 50 mm and a height of 10 mm. Then, 240, 600, 1000, and 2000 mesh sandpaper were used to polish the surface of the coal sample smoothly, ensuring that the surface roughness of each sample remained consistent.

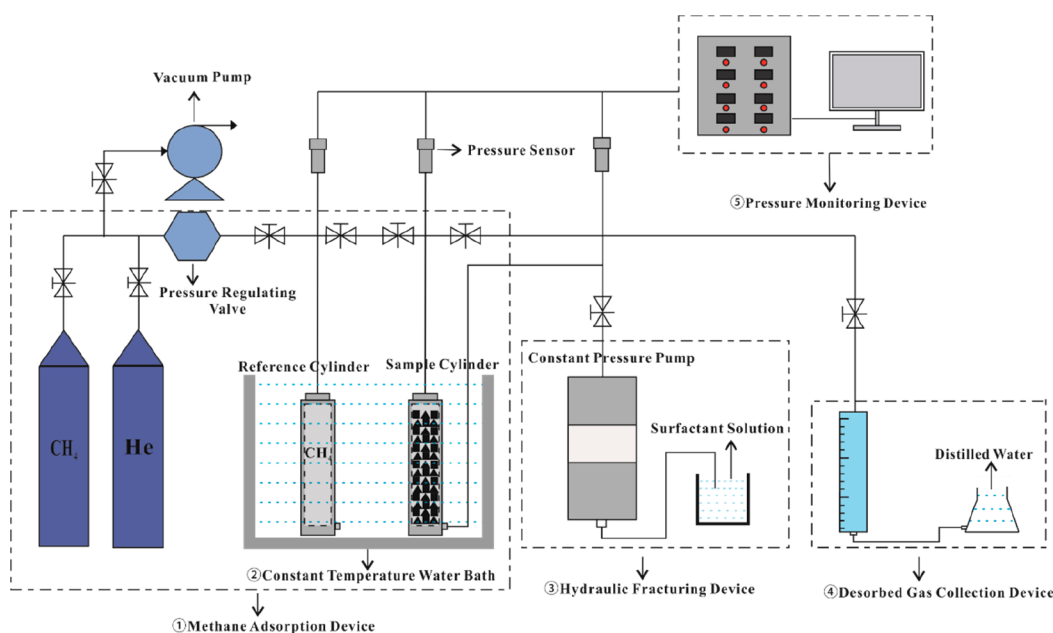


Figure 2. Desorption experimental setup diagram.

Each sliced sample was immersed into the three surfactant fluids and distilled water, respectively, for 12 h. The immersed samples were taken out for drying for 12 h at 55 °C in a drying oven.

Static contact angles of the dried samples were measured using a KRUSS-DSA25 optical measuring instrument under atmospheric conditions. The measurement of the contact angle was made by titrating the coal sample with distilled water. Five measurements were carried out for each sample, and the average was taken to characterize the contact angle of the coal samples.

2.5. Infrared Spectroscopy Test. The low bituminous coal sample has a high content of oxygen-containing functional groups in its chemical structure. Therefore, the index of oxygen-containing functional groups was tested to evaluate the influence of different surfactants on the chemical structure of the samples. The coal samples were ground into powder with a mesh size of 400+ and soaked in the three different surfactant fluids and distilled water for 12 h. After filtering the water out, the coal powder was dried for 12 h at 55 °C in an oven.

A Nicolet iS10 infrared spectrometer was employed to test the 400–4000 cm^{-1} wavenumber region of the coal samples using the potassium bromide compression method. Then, the PeakFit software was used for normalizing the area of the 400–4000 cm^{-1} wavenumber region and analyzing the changes in the peak area percentage of oxygen-containing functional groups in the wavenumber range of 1000–17000 cm^{-1} .

3. RESULTS

3.1. Methane Desorption. *3.1.1. Methane Desorption Volume.* The methane desorption data of 3500 min for each coal sample treated with different fluids were recorded and are shown in Figures 3 and 4. As indicated in Figure 3, the desorption volumes of methane are 4.054, 5.083, 3.502, and 3.086 cm^3/g for distilled water, NH766, G526, and D001, respectively. NH766 always produced the highest desorption gas in the 3500 min period and resulted in 24% more than that of distilled hydrolysis. The desorption gas of G526 and D001 is

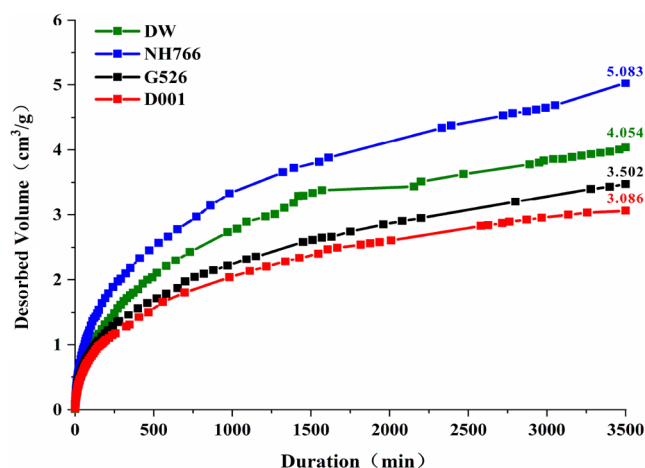


Figure 3. Methane desorption volume of coal samples treated with different surfactant fluids.

12.5% and 20% lower than that of distilled hydrolysis, respectively.

Compared with the total adsorbed methane of 9.22 cm^3/g for each sample, the desorption rates over 3500 min for distilled water, NH766, G526 and D001 are estimated to be 43.88%, 54.775%, 37.70%, and 33.33%, respectively (Table 5 and Figure 4). NH766 achieved the best desorption result.

3.1.2. Methane Desorption Velocity. When the surfactant enters the coal matrix, a gas–liquid two-phase interaction occurs in the coal. Due to the rapid decrease in pressure in the sample cylinder during the initial stage of desorption and human reading errors, there was a significant irregular change in the desorption velocity within 1 min of desorption. Then, the desorption velocity gradually stabilized.

From Figure 5a, it can be seen that after 2 min of desorption, the desorption velocity of NH766 remains the highest. From Figure 5a, it can be seen that at 18 min, the distillation hydrolysis absorption rate exceeded that of D001. As shown in Figure 5b, at 150 min, the absorption velocity of distilled water exceeded that of G526, second only to NH766.

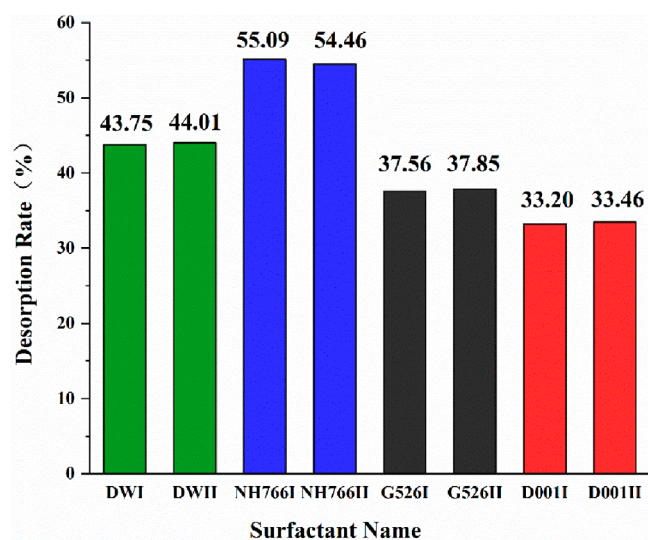


Figure 4. Methane desorption rate of coal samples treated with different surfactant fluids.

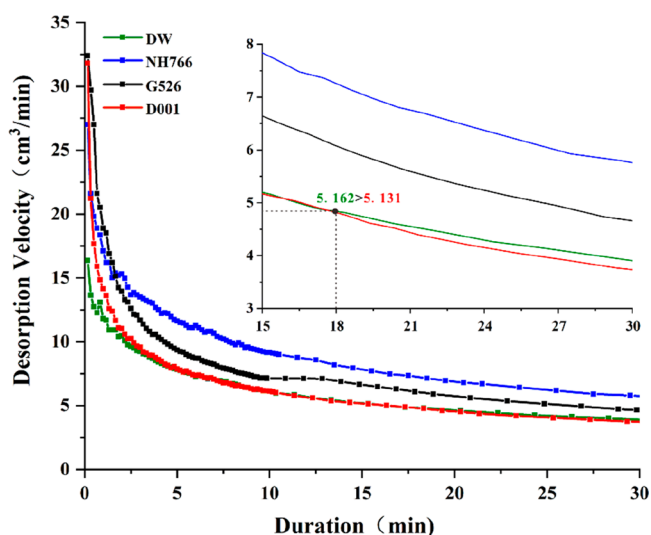
Table 5. Desorption Rate of Coal Samples Treated with Different Surfactant Fluids (for 3500 min)

solution name	group	desorption rate (%)	average desorption rate (%)
distilled water	I	43.75	43.88
	II	44.01	
NH766	I	55.09	54.77
	II	54.46	
G526	I	37.56	37.70
	II	37.85	
D001	I	33.20	33.33
	II	33.46	

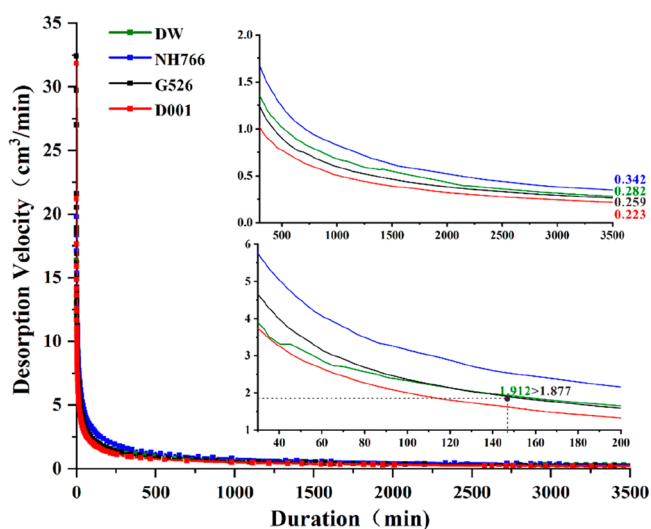
The difference in desorption velocities leads to a difference in the desorption amount. In summary, NH766 promotes methane desorption, while G526 and D001 inhibit methane desorption.

3.2. Contact Angle Variation. The contact angle test results of the four samples are listed in Table 6, and the topography photos are shown in Figure 6. The samples were treated with different surfactants under atmospheric conditions, and there is a significant difference in the contact angles of the coal sample treated with distilled water and the coal samples treated with the different surfactant fluids in Table 5. The results show that the average contact angle of the sample treated with NH766 increased by 10° compared with that of the sample treated with water, while the contact angles of the samples treated with G526 and D001 decreased by 3.1° and 5.1° , respectively. It is clear that the surfactant treatment could change the wettability of the coal samples. NH766 weakened the hydrophilicity of the coal, while G526 and D001 enhanced the hydrophilicity.

3.3. Characteristics of Changes in Oxygen-Containing Functional Groups. Since the coal sample is a fat coal with a low degree of metamorphism and a large number of oxygen-containing functional groups on the surface, this article reflects the changes in its wettability by measuring the content of oxygen-containing functional groups in the coal treated with various surfactants.^{30,31} The measured peak positions of various oxygen-containing functional groups (1000–1700



(a)



(b)

Figure 5. Desorption velocity of samples treated with different surfactant fluids.

Table 6. Contact Angle Data of the Coal Samples Treated with Different Surfactant Fluids

type of surfactant	size of contact angle (deg)					average size of contact angle (deg)
distilled water	70.6	70.3	69.6	71.0	70.2	70.34
NH766	81.6	81.2	80.3	80.2	80.4	80.74
G526	67.6	66.6	67.2	67.3	67.4	67.22
D001	65.8	65.1	64.7	65.3	65.4	65.26

cm^{-1}) are shown in Table 7, and the peak fitting results are shown in Figure 7.

Compared with the coal sample treated with distilled water, the chemical structure of the coal samples treated with the three surfactants showed the most significant changes in the content of hydrophobic $\text{C}=\text{C}$ and hydrophilic $\text{C}=\text{O}$, which is consistent with the results determined in the contact angle experiment mentioned earlier. From Figure 8, it can be seen

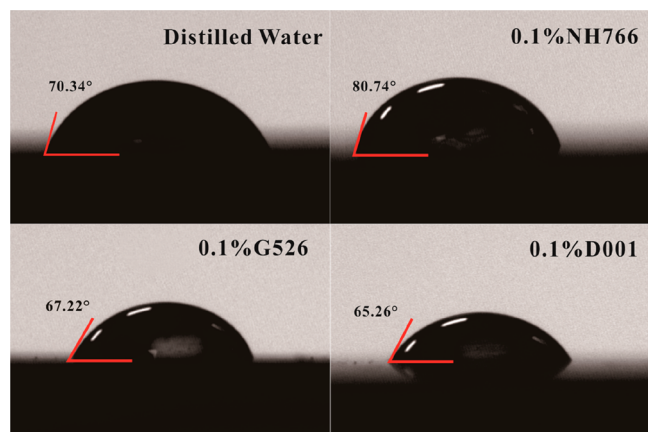


Figure 6. Photos of contact angle of coal samples treated with different surfactant fluids.

Table 7. Spectral Peak Positions of Various Oxygen-Containing Functional Groups

oxygenated functional group	functional group properties	spectral peak position (cm ⁻¹)
C–O–C	C–O–C telescopic vibration	1056
C–O	C–O tensile vibration, phenols/ethers	1119
C–O	C–O tensile vibration, phenols/ethers	1179
C–O	C–O tensile vibration, phenols/ethers	1243
C–O	C–O tensile vibration, aryl ether	1306
–CH ₃	–CH ₃ telescopic vibration	1373
–CH ₃ /–CH ₂	–CH ₂ /–CH ₃ symmetric stretching vibration	1440
C=C	C=C telescopic vibration	1517
C=O	C=O stretching vibration in carbonyl group	1595

that the C=C content in NH766 increased by 2.93%, while the C=O content decreased by 2.44%. The C=C content in G526 and D001 decreased by 0.22% and 0.87%, respectively, while the content of C=O increased by 0.53% and 1.83%, respectively. Among the four solutions, the C=C and C=O contents are in the following order: NH766 > distilled water > G526 > D001. From Table 8, it is clear that the content of oxygen-containing functional groups in the prepared coal samples significantly changed after modification with surfactants. Compared to the sample treated with distilled water, the peak area percentage of NH766 oxygen-containing functional groups decreased by 30%, while the peak area percentages of oxygen-containing functional groups in G526 and D001 increased by 5% and 16%, respectively. The relationship between the peak area of oxygen-containing functional groups is as follows: NH766 < distilled water < G526 < D001. This arrangement is completely opposite to the arrangements of methane desorption rate and contact angle. The experiment shows that all three selected surfactants can change the content of hydrophilic groups containing oxygen functional groups in coal rocks, and different surfactants have different effects on the content of oxygen-containing functional groups on the surface of coal.

4. DISCUSSION

Coal is a polymer organic compound with complexity, diversity, and heterogeneity.^{32,33} The wettability of coal is closely related to its chemical composition, structure, surface properties, and mineral composition and content.^{34–36} The coal sample contains hydrophilic and hydrophobic groups, among which the most important are fat hydrocarbons, aromatic hydrocarbons, and oxygen-containing functional groups.^{37–39} Due to the fact that different surfactants also contain different hydrophilic and hydrophobic groups, the degree of influence of different surfactants on the wettability of coal and rock varies.^{40–42} The hydrophobic groups in the nonionic surfactant NH766 are oriented and arranged on the surface of the solution under the action of hydrogen bonds, while the hydrophobic groups are closely arranged on the surface of the solution. After NH766 treatment, the hydrophobic C=C content in the oxygen-containing functional groups in the coal sample increases, while the hydrophilic C=O content decreases, resulting in enhanced hydrophobicity of the coal sample. The anionic surfactant G526 and the cationic surfactant D001 have a sparse arrangement of hydrophobic groups due to the presence of electrostatic repulsion, and the adsorption density is usually small. After treatment with G526 and D001, the hydrophobic C=C content in the oxygen-containing functional groups in the coal sample decreases, while the hydrophilic C=O content increases.

The changes in the chemical structure of coal samples treated with three types of surfactants have an impact on the wettability of the coal itself, which affects the fluidity of water in coal seams and the difficulty of reducing the pressure in coalbed methane wells. Due to the strong hydrophilicity of coal and the strong surface interaction force between water and the coal matrix, the hydrophobic effect of coal seams during drainage and pressure reduction during coalbed methane extraction is not significant, resulting in difficulty in the desorption of adsorbed methane. Therefore, by reducing the hydrophilicity of coal and rock and thus reducing the interaction force between coal and water, water can be easily discharged from the coal reservoir during the process of drainage and pressure reduction, thus reducing the water lock effect and achieving the goal of promoting methane desorption.⁴³ After the surfactant invades the coal body, there is a significant difference in the migration speed of the gas–liquid phase in the pores and fractures of the coal rock. When the liquid encounters the coal, it first migrates in the fractures and large pores. Then, the liquid generates a capillary phenomenon in the throat at the end or between the pores of the coal body, forming capillary pressure. Subsequently, the liquid enters smaller pores under the action of capillary force. However, when the gas pressure difference between the internal and external environments of the pores is insufficient to overcome the capillary resistance, it limits the outward diffusion and migration of free methane gas in coal, increases the starting pressure gradient for methane migration and production, and affects the desorption and diffusion of coalbed methane, thus affecting the desorption rate.^{44,45}

Based on the experimental results of this article, NH766 treatment increases the contact angle and hydrophobicity of the coal sample, and after high-pressure fracturing with NH766, the desorption amount increases and the desorption rate reaches its maximum. NH766 can be applied to improve the development of low-permeability coalbed methane wells.

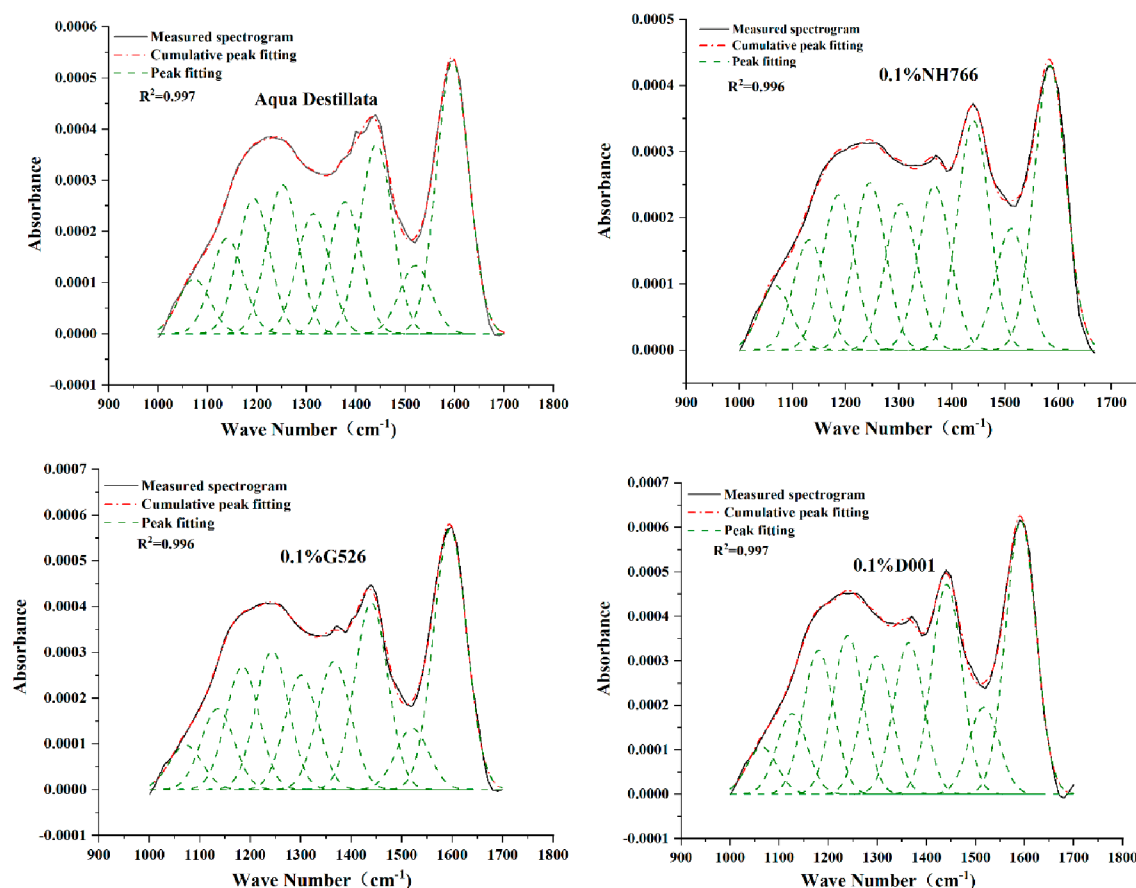


Figure 7. Oxygen-containing functional group peak fitting results.

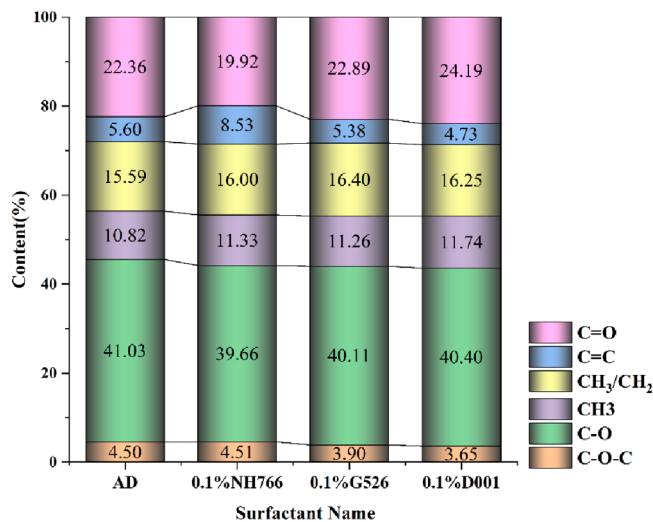


Figure 8. Histogram of the area percentage of six oxygen-containing functional groups.

Table 8. Percentage of Peak Area of Oxygen-Containing Functional Groups in Coal and Rock Treated with Different Surfactants

type of surfactant	peak area percentage (%)
distilled water	19.366
NH766	13.368
G526	20.430
D001	22.505

G526 or D001 can enhance the wettability of coal samples and reduce the level of methane desorption. The surfactants G526 and D001 can be applied to accelerate the wetting and settling of coal mine dust, reduce inhalable dust, and improve the safety of gas control.^{46,47} This paper provides the choice of surfactants for coalbed methane development and underground gas control and screens out surfactants suitable for the Baode #8 coal seam.

5. CONCLUSION

This article analyzes the methane desorption characteristics of three different surfactants after high-pressure hydraulic fracturing of fat coal at 12 MPa. Combined with the changes in coal wettability, the methane desorption characteristics and wettability changes of different surfactants on fat coal are summarized as follows:

- (1) Under the same adsorption equilibrium pressure, adsorption amount, and desorption time, the desorption rate and desorption velocity of the three surfactants and distilled water after hydraulic fracturing of coal are in the descending order of NH766 > distilled water > G526 > D001. The desorption capacity of NH766 is 24% higher than that of distillation hydrolysis, and the desorption velocity remains higher than the other three solutions after 2 min of desorption. The desorption volume of G526 is 12.5% less than that of distillation hydrolysis, and the desorption volume of D001 is 20% less than that of distillation hydrolysis. NH766 has a promoting effect on methane desorption, while G526 and D001 have an inhibitory effect on methane desorption.

- (2) After NH766 treatment, the content of hydrophobic C=C in the oxygen-containing functional groups in the coal sample increased, while the content of hydrophilic C=O decreased, resulting in a decrease of 6% in the peak area percentage of the oxygen-containing functional groups. The wettability of the coal sample treated with NH766 decreased, and the contact angle increased by 10°. After treatment with G526 and D001, the hydrophobic C=C content in the oxygen-containing functional groups in the coal samples decreased, while the hydrophilic C=O content increased; additionally, the contact angles decreased by 3.1° and 5.1°, respectively.
- (3) After NH766 treatment, the hydrophobicity of the coal is enhanced, and the methane desorption volume and velocity are increased. NH766 can be applied to surface coalbed methane well mining to improve the methane recovery rate. After treatment with G526 or D001, the hydrophilicity of coal samples is enhanced, and the methane desorption volume and velocity are reduced. G526 and D001 can be applied to underground dust control and gas outburst, improving the safety of underground coal mining.

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Author Contributions

X.C.: methodology, investigation, data analysis, and writing—original draft and editing. B.S.: methodology, experimental guidance, and writing—review and editing. Y.C.: conceptualization, project administration, funding acquisition, supervision, and writing—review and editing. P.L.: investigation and data analysis. Y.Q.: conceptualization, methodology, and data

analysis. L.L.: conceptualization, methodology, and writing and editing.

Notes

The authors declare no competing financial interest.

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