Study on Eliminating the Water Blocking Effect in Coal Seams Using Gas-Wetting Reversal Technology

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ABSTRACT: To eliminate or alleviate the water blocking effect (WBE) encountered while hydraulic fracturing of coal seams, the wettability of the coal body was changed, using gas-wetting reversal technology, thus improving gas drainage. After initial measurements of contact angles, surface tension, surface free energies, erosion resistance, self-absorption capacities, and self-absorption rates of coal samples, a hydrophobic and low-surface-tension gas surfactant was selected. After comparing the results of four candidate surfactants, two surfactants were selected, FC117 and FC134, which were both hydrophobic and exhibited low surface tension, to achieve the desired effect. By optimizing and evaluating gas-wetting reversal agents, our work has provided a theoretical basis and scientific guidelines for eliminating the WBE from coal seams, thereby facilitating gas drainage.

1. INTRODUCTION

The “three low and one strong” characteristics of Chinese coal seams—low pressure, low permeability, low saturation, and strong heterogeneity—make gas drainage before mining more difficult. Hydraulic fracturing,1,2 hydraulic slotting,3 hydraulic extrusion,4 or hydraulic punching5 have all been used as technical measures to increase coal seam permeability and improve its drainage effect, in most high gas outburst risk mining areas. In recent years, researchers have carried out laboratory experiments and field verification on the issue, and during this research, and the subsequent application of hydraulic measures, a water block effect, which acts to restrain coal mine gas drainage, has been found. Analysis has shown that gas-bearing coal provides natural conditions, material conditions, and pressure conditions that can accentuate this water blocking effect (WBE).6 Huang7 and Wu8 experimented with desorption times and permeability changes in coal samples with different water contents and analyzed the water block damage mechanism in coalbed methane reservoirs. Song et al.9,10 proposed adding hydrophilic surfactants to fracturing fluids to reduce the contact angle between the fracturing fluid and the coal surface, thereby reducing the capillary pressure, enhancing the drainage ability of the fracturing fluid, and hence reducing the WBE.

Reducing or eliminating the water block damage caused by capillary force has, for a while, been the focus of scholars globally, and their work has shown that addition of a surfactant to a water-based fracturing fluid is the most direct and effective method. Because the coal pore structure is difficult to change, contact angle and surface tension have been seen as realistic targets in efforts to affect capillary force. At present, most scholars use hydrophilic surfactants to reduce coal surface tension, in attempts to offset the influence caused by the decrease in contact angle, thereby reducing the overall capillary force.11 Although adding a hydrophilic surfactant can weaken or reduce the water blocking damage caused by capillary force, the surfactant cannot eliminate it, let alone transform the system to promote gas drainage. At the same time, for small and nanosized pores, the capillary force remains still large, which is not conducive to gas drainage.

In view of these facts, the authors tested hydrophobic and low-surface-tension gas-wetting reversal agents on anthracite selected from the Jincheng Yuxi coal mine as the research subject. They performed contact angle and surface tension experiments, calculated the capillary forces, and then selected the best surfactant and its best operating concentration. This work reported here has identified the mechanism through which gas-wetting reversal agents increase the production of waterproof blocks and has provided a theoretical basis and
guidelines for technology associated with enhancing permeability and promoting coal seam gas (CSG) drainage in China.

2. Wettability Reversal and Evaluation Principles

Capillary force is an important index for evaluating the degree of water blocking damage, and contact angle and surface tension are the key factors affecting its magnitude and direction. Changes in wettability can be directly shown by measuring contact angles and surface tension. Therefore, in this study, coal surface contact angles and solution surface tension were measured using the lying and suspension drop methods, respectively. Using these methods helped us to identify the surfactant able to achieve the best gas-wetting reversal.

2.1. Reversing Wettability. A process by which one fluid on a solid surface is replaced by another is called wetting. Gas wettability refers to the degree to which the solid surface is preferentially covered by gas, in a “gas—liquid—solid” system. Li, Liu, and Fahes et al. used a gas-wetting reversal agent to reduce water blocking damage in condensate gas reservoirs. In this work, core wettability inversion was achieved, and the preferential liquid moisture was changed to the preferential gas moisture, of oil drainage; permeability was thus greatly improved, which provided an important theoretical basis for improving gas well production.

Compared with the characteristics of a condensate gas reservoir, a coal seam is a porous medium, with a more complex pore structure and lower permeability. Coal is also characteristically hydrophilic, and in the process of hydraulic fracturing, water blocking damage becomes more serious once water enters the coal body. This means that using gas-wetting inversion technology to improve coal seam gas (CSG) drainage should be feasible. After being treated by a gas-wetting reversal agent, coal is preferentially covered by gas, which achieves reversion of coal wettability. Through this coal wettability reversion process, capillary force, which was originally a hindrance, could be eliminated—or even transformed into power usable in the pumping process—thus eliminating the influence of the WBE.

2.2. Contact Angle Method. Coal contact angle and surface tension are the main parameters used to evaluate coal wettability. They can be applied in the quantitative and intuitive evaluation of coal wettability before and after gas wetting reversal. To avoid the influence of water on the reversion results of a gas-wetting reversal agent, a surface active agent and deionized water were first applied to the coal, which was then dried in a 105 °C blast drying oven, for more than 24 h, until the coal sample quality did not change. The surface tension of different types and concentrations of surfactants was then measured, using the suspension drop method.

Capillary force is the key index used to evaluate the degree of water blocking damage. After a foreign fluid enters coal or other porous media, the magnitude and direction of the capillary force affect the severity of water blocking and, consequently, the difficulty of gas drainage as a backflow process. Capillary pressure may be expressed as shown in the following equation (eq 1)

\[ P_c = \frac{2\sigma \cos \theta}{r} \]  

where \( P_c \) indicates the capillary pressure (in Pa/cm), \( \sigma \) denotes surface tension (in mN/cm), \( \theta \) represents the contact angle (in degrees), and \( r \) stands for the capillary radius (in cm).

Equation 1 shows that the capillary radius (\( r \)) is difficult to change as an inherent characteristic of the coal, while coal surface tension (\( \sigma \)) and contact angle (\( \theta \)) can be changed using surfactants. Gas-wetting reversal agents embody characteristics that include hydrophobicity and low surface energy. They adhere to the coal surface through physical adsorption, reduce its surface tension, increase its contact angle to more than 90°, and change its surface characteristics. In the process of gas drainage by backflow, the capillary force changes from resistance to power, which improves gas drainage.

According to physicochemical theory applicable to surfaces, the higher the surface energy of a solid, the easier it can be wetted by a liquid. At the same time, its surface free energy amount also reflects the strength of its adsorption capacity, as a solid surface, and the higher the surface energy, the stronger the adsorption capacity of the surface. Coal, with its high surface free energy and complex porous media characteristics, is easily wetted by water and other liquids and has a strong gas adsorption capacity. Therefore, when a foreign liquid invades, it easily produces a water blocking effect, which will influence its gas pumping characteristics. Gas-wetting surfactants are used to change coal wettability, increase its contact angle, and decrease its surface tension, thereby reducing the surface free energy and gas adsorption capacity of the coal body, so as to “promote drainage and to increase production” via the gas drainage process. The Owens two-liquid method is used to calculate the surface free energy of coal, as shown in eqs 2 and 3

\[ \gamma_w(1 + \cos \theta_w) = 2(\gamma_{D}^{w} \gamma_w)^{1/2} + 2(\gamma_{P}^{w} \gamma_w)^{1/2} \]  

\[ \gamma_f(1 + \cos \theta_f) = 2(\gamma_{D}^{f} \gamma_f)^{1/2} + 2(\gamma_{P}^{f} \gamma_f)^{1/2} \]  

where \( \gamma_w \) indicates the dispersion force of water (21.8 mN/m), \( \gamma_P \) shows the polar force of water (51 mN/m), \( \gamma_D \) indicates the dispersion force of n-hexadecane (27.6mN/m), and \( \gamma_f \) denotes the polar force of n-hexadecane (0 mN/m).

Combining eqs 2 and 3 allows calculation of the coal dispersion and polar forces before and after treatment. Then, the surface free energy of coal can be represented using eq 4

\[ \gamma_s = \gamma_D + \gamma_P \]  

By measuring the contact angle and surface tension of samples treated with different types and concentrations of surfactants, surface free energy changes before and after surfactant treatment were calculated, with the results allowing us to optimize our surfactant selection process.

2.3. Coal Sample Self-Absorption Method. As a complex porous medium, coal has the dual pore characteristics of multiporosity and multiformity, consisting mainly of micropores and nanopores. When an external fluid is adsorbed onto coal surfaces, capillary force is formed at both ends of many pores, on the one hand, resulting in imbibition. On the other hand, the characteristics of high surface free energy and strong hydrophilicity provide adsorption conditions for external fluids, both on coal surfaces and in its cracks.

While imbibing, a coal body adds water through its pores and fissures. The absorbed water amount increases gradually over time, before reaching equilibrium. After being treated with different surfactants, hydrophobic surfactant molecules, with
their low surface tension and low surface energy, adsorb onto coal pores and fissure surfaces, occupying positions previously available for external water adsorption, thus inhibiting water adsorption on coal surfaces and significantly reducing the self-adsorption capacity of the coal. By observing changes in coal self-adsorption before and after treatment, the amount by which water blocking damage was mitigated could be quantified.

3. EXPERIMENTAL MATERIALS AND TREATMENTS

3.1. Experimental Reagents and Instruments. Experimental reagents included perfluoroalkyl quaternary amine iodide (FC134), acrylic acid fluorinated copolymer (FCS100), hydroxyethyl cellulose (carboxymethylcellulose, CMC), FC117 fluorocarbon surfactant (FC117), distilled water, and n-hexadecane.

The main experimental instrumentation consisted of a JMBJS20002 electronic balance, a JC2000C1 contact angle measuring instrument, a press, an electric heating blast drying oven, and a Sony Cyber-shot H50 digital camera.

3.2. Experimental Coal Samples and Treatment.

3.2.1. Coal Sample Preparation. In the field, hydraulic fracturing destroys the coal structure, resulting in broken and pulverized coal, with particle size differences of several orders of magnitude. When contact angle is used to evaluate coal wettability, briquetting and raw coal grinding methods are used in the comprehensive evaluation of coal wettability. Compared with actual contact angles, those measured when using the briquetting method can be affected by particle accumulation, and the measured contact angle can be smaller than actual contact angles. In contrast, as the raw coal grinding method still retains a complete and dense pore structure, the measured contact angles in this instance will be larger than actual contact angles, as represented by eq 5

\[ \theta_{\text{briquette}} < \theta_{\text{actual}} < \theta_{\text{raw coal}} \]  

A surface contact angle measured using the molding coal powder method will be smaller than that measured when using the raw coal grinding method, although their wettabilities remain basically the same. Actual contact angles cannot be measured directly, while the real wettability of a coal sample can be determined by measuring the contact angle differences between briquettes and raw coal. If the wettability of raw coal involves liquid wetting, the actual coal calculations must also apply to liquid wetting. This is

\[ \theta_{\text{briquette}} < \theta_{\text{actual}} < \theta_{\text{raw coal}} < 90^\circ \]  

If the wettability of the briquette corresponds to gas wetting after being treated with a gas-wetting reversal agent, the actual coal sample must belong to gas wetting. Here

\[ 90^\circ < \theta_{\text{briquette}} < \theta_{\text{actual}} < \theta_{\text{raw coal}} \]  

At the same time, compared with the molding pulverized coal method, the raw coal grinding method is faster, and the molding rate is lower. Therefore, in this study, experimentation on contact angles and on surfactant types and concentrations were conducted using the coal briquetting method, while the raw coal grinding method was used for verification, as shown in Figure 1.

3.2.1.1. Making Coal Powder Samples. Preparing coal samples involved the following steps: (1) a fresh coal sample was crushed to 80% of the sample;21 (2) 5 g of the coal sample was carefully weighed, and 0.5 g of distilled water was added and completely mixed; and (3) the sample was inserted into a pressing mold and pressed under a load of 120 kN for 30 min, making coal samples 25 mm wide and 5 mm thick.

3.2.2. Experimental Treatments.

(1) Four surfactants were used in this research: FC134, FCS100, CMC, and FC117, and each was diluted with distilled water to prepare surfactant solutions with mass concentrations of 0, 0.2, 0.5, 0.8, 1, and 1.5%.

(2) To avoid the influence of water on contact angle measurements, contact angles were measured before and after surfactant treatment. Because it was difficult to maintain briquette shapes in aqueous solutions, their

Figure 1. Process of contact angle measurement.

Figure 2. Raw coal pillar.
surfaces were treated by spraying (rather than dipping), after which the briquettes were dried in a drying oven.

3. The dried coal samples were sorted according to the type and concentration of the surfactant applied and were placed in labeled, disposable culture dishes, as shown in Figure 3.

4. The contact angles of coal samples treated with different surfactant types and concentrations were measured using the lying drop method, with distilled water and n-hexadecane used sequentially as titration liquids.

5. The surface tension of the different types and concentrations of surfactants was measured using the suspension drop method, as shown in Figure 4.

6. Contact angle and surface tension measurements were recorded and analyzed.

4. EXPERIMENTAL RESULTS AND ANALYSIS

4.1. Contact Angle Measurement and Analysis. In this study, different types and concentrations of surfactants were applied, using the spray method to treat coal samples. For analysis, dry coal samples were placed on the platform of the JC2000C1 contact angle measuring instrument, and surface contact angles of coal samples were measured using the lying drop method.

As shown in Figure 5, among the four surfactants tested, the coal sample contact angle after the FCS100 treatment with increasing concentrations decreased rather than increased. In contrast, treatment with increasing concentrations of the other three surfactants led to gradual contact angle increases and thus achieved reversal of coal surface wettability. When tested with surfactant concentrations between 0 and 0.5%, the coal surface contact angles increased faster, to the extent that, on reaching 0.5%, all three surfactants achieved a coal surface wettability change from liquid wetting to gas wetting.

Among the tested surfactants, FC117 achieved the best gas-wetting turnover effect, increasing the coal surface contact angle from 30 to 130°, which was an increase of 4.3 times. The increasing trends for FC134 and CMC were basically the same, increasing the coal surface contact angles from 30 to 90°, which represented 3-fold increases. At surfactant concentrations between 0.5 and 1.5%, the coal sample surface contact angles after the FC117 treatment decreased and tended to stabilize, while the contact angle change trends for FC134 and CMC remained the same.

It was concluded that the coal sample contact angle changes, as illustrated in Figure 5, had been mainly brought about as follows:

When the concentration of the surfactant increased from 0 to 0.5%, the contact angles of the coal surfaces treated with the three surfactants increased rapidly. At this stage, hydrophilic groups in the surfactant molecules adsorbed toward the coal surface, and the hydrophobic groups moved away from the coal surface, which inhibited adsorption of the surrounding water molecules onto the coal surface. With increased surfactant concentrations, the numbers of surfactant molecules adsorbed onto the coal surfaces gradually increased, the ability of hydrophobic groups to inhibit water molecules on the coal surface gradually improved, and the coal surface contact angles also gradually increased.

When the surfactant concentrations increased from 0.5 to 1.5%, the surface contact angle increase rate for the samples treated with the three surfactants decreased, and the contact angle decreased. At this stage, with increased surfactant concentrations, the number of surfactant molecules adsorbed onto the coal surfaces tended to become saturated, the ability of the hydrophobic groups to inhibit water molecules on the coal surface decreased, and the coal surface contact angles decreased.
coal surfaces reached its peak, and the coal surface contact angles gradually reached their maximum.

As the surfactant concentrations continued to increase, the surplus surfactant molecules and the normal adsorption in the coal surfactant molecules became disordered, and the adsorption and winding between the hydrophobic groups caused the hydrophilic groups in the excess surfactant molecules to face away from the coal surface. At this point, hydrophilic groups adsorbed water molecules onto the coal surfaces and reduced the coal surface contact angles.

4.2. Measurement and Analysis of Surface Tension. A JC2000C1 contact angle measuring instrument was used to measure contact angles and surface tension. In this study, surface tensions for different types and concentrations of surfactant solutions were measured using the suspension drop method.

As shown in Figure 6, the four surfactant solutions exhibited their ability to reduce surface tension with increased surfactant concentrations, with FC134 showing the strongest ability, followed by FCS100 and FC117, with CMC being the least effective. The change trends for surface tension, as achieved by the four surfactant solutions as their concentrations increased, were basically the same. At concentrations between 0 and 0.2%, the surface tensions decreased rapidly, with FC134 showing the strongest surface tension reduction, with a 73.8% decrease, from 72.8 to 19.07 mN/m. This was followed by FCS100 and FC117, for which it dropped to 21.37 and 23.12 mN/m, with decreases of 70.6 and 68.2%, respectively. For concentrations between 0.2 and 1.5%, the surface tensions were reduced slightly more, before tending to stabilize.

According to the definition of critical micelle concentration and surface tension, and taking account of our surface tension measurements, the critical micelle concentration for the four surfactants tested was 0.2%.

Among them, FC134 was found to be the most effective at reducing surface tension, followed by FCS100 and FC117, with CMC the least effective.

4.3. Calculation and Analysis of Coal Surface Energy. After measuring and analyzing coal surface contact angles, it was found that surfactant FCS100 did not achieve the expected effect; it had the lowest ability to reduce the surface tension and so it was excluded from further testing. Therefore, when subsequently calculating coal surface energy, water and oil phase contact angles were calculated using only FC117 and FC134, as shown in Figure 7.

It can be seen from this figure that distilled water and n-hexadecane were used to measure the contact angles of coal samples treated with different surfactant types and concentrations. The contact angle changes for FC117 and FC134 in the water and oil phases were basically the same, indicating that both surfactants were able to increase the contact angles. Under water phase conditions, the two surfactant types could change the wettability of the coal surface from liquid wetting to gas wetting, while under oil phase conditions, both surfactants exhibited the ability to drain oil, but they did not change the wettability of the coal surface from oil wetting to gas wetting. These results established that both surfactants showed strong hydrophobicity—which allowed them to achieve changes in wettability—and oil drainage capabilities.

Coal adsorption capacity mainly depends on its surface energy. After surfactant treatments, the coal sample surface free energies were reduced, the gas adsorption capacity decreased, and the gas drainage process was improved. The surface free energy of the coal body was calculated using the Owens two-liquid method, and the coal surface energy reducing effect achieved by the surfactants was quantified, as shown in Table 1.

![Figure 6. Surface tension of different types and concentrations.](image)

![Figure 7. Contact angle in the water or oil phase.](image)

| concentration (%) | dispersion energy (mN/m) | polarity energy (mN/m) | surface free energy (mN/m) |
|-------------------|--------------------------|------------------------|--------------------------|
| FC117             | FC134                    | FC117                  | FC134                    |
| 0                 | 26.86                    | 37.05                  | 63.91                    | 63.91                    |
| 0.2               | 22.06                    | 18.15                  | 40.21                    | 37.07                    |
| 0.5               | 7.52                     | 8 × 10^{-4}            | 7.5208                   | 19.36                    |
| 0.8               | 8.16                     | 12.43                  | 8.25                     | 16.77                    |
| 1.0               | 10.64                    | 11.52                  | 12.81                    | 15.49                    |
| 1.5               | 13.2                     | 12.48                  | 15.42                    | 17.56                    |

Coal dispersion force, \( \gamma_{D} \), polarity force, \( \gamma_{P} \), and surface free energy, \( \gamma_{s} \), can be calculated when affected by different surfactant types and concentrations using eqs 2–4, respectively. When calculating dispersive and polar forces, changes in their magnitude depend mainly on the contact angle, when in the water and oil phases. It can be seen from Table 1 that with increased contact angles (as represented by the increased surfactant concentrations) both dispersion and polar forces gradually decreased, with the latter changing significantly. With increasing concentration, the surface energy initially decreased.
and then increased. When the concentration reached 0.5%, the coal sample surface energy after the FC117 treatment reached its minimum, 7.5208 mN/m, and its surface energy was reduced by 88.23%; while for FC134-treated samples, the coal surface energy achieved its minimum, 15.49 mN/m, when the concentration reached 1%, and its surface energy was reduced by 75.76%.

5. EXPERIMENTAL VERIFICATION AND ANALYSIS

5.1. Erosion Resistance Testing and Analysis. Fracturing fluid flowback is an important factor in the process of hydraulic fracturing and determines whether the surfactant in the fracturing fluid continues to effectively adsorb onto the coal body during the flowback process, using its hydrophobic characteristics to inhibit water adsorption there. This characteristic allows water to be discharged from the pores and fissures in the coal body with the fracturing fluid and can effectively alleviate or even eliminate the WBE. The adsorption capacity of surfactant molecules onto coal surfaces is an important parameter for evaluating surfactant performance.

The erosion resistance test is an important means to evaluate surfactant–coal surface adsorption capacity. Determining the effective adsorption time of the surfactant is also a key factor in eliminating the WBE, as its best hydrophobic capacity can only be exerted—and the influence of water blocking damage be effectively alleviated—when the surfactant has been fully adsorbed onto the coal surface.

Outgas wetting reversal agents FC117 and FC134, and their optimal solution concentrations, were selected for this work based on the contact angle and surface tension measurements described above. Two raw coal groups were placed in 0.5% aqueous solutions of each surfactant (FC117 and FC134), using the immersion method, with a fifth group placed in distilled water, for use as a reference group. After the coal pillars had been immersed for a certain period, they were removed for drying. Among the two groups treated with each surfactant, one was washed with distilled water and then dried and the other was directly dried without treatment.

Contact angles were measured after drying, after which the samples were immersed again in the relevant solutions for further soaking. Soaking times of 12, 24, 48, 72, and 96 h were used, as shown in Figure 8.

It can be seen in this figure that with increased soaking time the contact angles for coal pillars immersed in FC117 and FC134 initially increased and then stabilized, indicating that the adsorption capacity for surfactant molecules onto coal surfaces gradually increased over time, along with the coal surface hydrophobic capacity. At the same time, regardless of whether the pillars were washed or not, there were no significant differences in the measured contact angles, indicating that the two surfactants retained their good scouring resistance, and their capacities for strong adsorption onto coal surfaces.

After soaking in a surfactant solution, the coal pillar surface contact angles gradually increased, over the period 0−24 h, and this increase then slowed, before stabilizing, over the next 24−96 h. This meant that from 0 to 24 h the surfactant molecules and water around the coal column entered the coal pores and fissures, using capillary force. At this time, there were fewer surfactant molecules adsorbed onto the coal pillar surface, the hydrophobicity was weak, and the measured coal surface contact angles were small.

With increased time, the surfactant molecules in the solution were close to the coal pillar, and the number on the coal pillar surface increased, as did the hydrophobicity and contact angles. Over the 24−96 h soaking period, more surfactant molecules reached the coal pillar surfaces and their internal pores and fissures, under the influence of diffusion. Then, as the surfactant molecules’ adsorption capacity approached saturation, the coal pillar surface contact angles slowly increased, before tending to stabilize.

5.2. Result and Analysis from Coal Sample Self-Absorption Experiments. Coal sample self-absorption testing is an important way to evaluate surfactant influence on water blocking. When an external fluid contacts a coal body, capillary force facilitates entry into the coal, through its pores and fissures. In contrast, during flowback, this same force resists the outflow of fluid, producing the WBE. This meant that by comparing the changes in coal self-absorption capacities and rates before and after surfactant treatments surfactant impact on water blocking could be assessed.

Using the erosion resistance test results, three similar quality coal pillars, with no obvious cracks, were placed in distilled water, 0.5% FC117, and 0.5% FC134 solutions, respectively. After soaking for 48 h, they were removed, wiped free from surface moisture, and dried in a 105 °C drying oven. After drying for 24 h, the coal samples were weighed, and readings $m_{11}$, $m_{12}$, and $m_{13}$ were taken; after drying for another 12 h, the samples were weighed again and readings $m_{21}$, $m_{22}$, and $m_{23}$ were taken to check whether the two sets of results were consistent. If the results were consistent, the coal pillars were completely dry, while if they were not, and the weights were lower in the second set of readings, this meant that the coal pillars were not completely dry. When this occurred, the pillars were dried again and weighed hourly until completely dried.

The qualities and treatments applicable to the three similar coal pillars, without obvious cracks, are listed in Table 2.

The electronic balance used in this experiment is illustrated in Figure 9.

Table 2. Coal Pillar Quality and Treatment

| serial number | quality (g) | treatment process |
|---------------|------------|-------------------|
| 1             | 289.5      | distilled water   |
| 2             | 290        | 0.5% FC117       |
| 3             | 290.6      | 0.5% FC134       |

![Figure 8. Contact angle under different soaking times.](https://dx.doi.org/10.1021/acsomega.0c04858)
The coal self-absorption experiment was carried out through application of coal self-wettability and capillary force. For this test, which took place wholly within the confines of the electronic balance, dried, raw coal pillar 1# was placed in a funnel, and distilled water was injected into a transparent beaker below the funnel until the raw coal pillar in the funnel contacted the water in the beaker below. At this point, weight and time were recorded.

At the start of the experiment, the coal water absorption rate and amount increased rapidly, and readings were taken every 2 h. This process was continued for 12 h until the absorption rate and amount no longer changed, at which point the 1# coal pillar self-priming experiment was deemed to be complete. The process was then repeated for coal pillars 2# and 3#.

The results showed that the amount absorbed by the coal samples increased rapidly at first, before slowing and finally stabilizing, as shown in Figures 10 and 11.

It can be seen from these figures that the results from the dry coal sample self-absorption experiment can be divided into an initial, rapid growth stage, followed by a slow-down stage in the middle, before reaching a later, stable stage. In the initial stage, when the dry coal sample was first in contact with the water, the fluid was quickly adsorbed on the surface of the coal body—due to the combined effects of its wettability and capillary force—and entered into the coal body using pores and fissures as channels. This allowed the water self-absorption amount and rate to increase in this stage. Over time, the water content in the coal pores and fissures tended toward saturation, causing the water self-absorption increase to slow, while the rate also decreased. In the final stage, the pores and fissures in the coal sample were full of water, under the action of capillary force, water adsorption on the surface of the coal sample reached saturation, the coal sample water absorption rate tended to zero, and the system stabilized.

For the dry coal samples treated with surfactants, the coal surface wettabilities changed, making them harder to wet, which made it harder for them to absorb water. The coal body surface cracks and macrospores adsorbed surfactant molecules, increasing the wetting and adsorbing difficulty.

It was considered that even when surfactant molecules have difficulty entering surface micropores they can be adsorbed into blocking positions with respect to these pores and into the throats of larger pores, achieving a water blocking and ventilation, function. In other words, the spatial distribution of surfactant molecules prevents water from entering the micropores and ensures the passage of gas to form an invisible hydrophobic film, which helps to eliminate the WBE.

Surfactant molecules cannot be adsorbed near some semiclosed or unconnected micropores; this means that wettability reversal cannot be achieved here, and water can enter such pores through capillary force—which was seen in the self-absorption tests to cause a small amount of water to enter the coal bodies. This showed that the self-absorption capacity and rate, for coal samples treated with surfactants, had been significantly reduced by 80.43 and 78.47%, for FC134 and FC117, respectively.

Through the coal sample self-priming experiment, we were able to confirm that treatment with gas-wetting reversal agents greatly reduced coal water absorption and that WBE generation and development had been greatly alleviated.

6. CONCLUSIONS AND PROSPECTS

From the initial suite of four surfactants, two were selected as being able to achieve the desired effects. Surfactants FC117 and FC134 both exhibited hydrophobicity and low surface tension characteristics. By calculating and measuring coal sample contact angles, surface tension, surface free energy, erosion resistance, water absorption, and self-absorption rates, the WBE mitigation achieved by the surfactants was quantified and evaluated.

The main conclusions and prospects derived from the work described in this paper can be summarized as follows:
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Notes
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