

Article

Study on the Effect of Sodium Dodecyl Benzene Sulfonate on Coal Moisture Imbibition and Gas Adsorption

Kaizhi Li ¹, Yanqi Chen ² , Zhaofeng Wang ^{2,3,4,*} , Ligu Wang ^{2,3,4}, Demin Chen ² , Shujun Ma ²  and Shijie Li ² 

¹ School of Civil Engineering, Henan Polytechnic University, Jiaozuo 454003, China

² College of Safety Science and Engineering, Henan Polytechnic University, Jiaozuo 454003, China; liguowang@hpu.edu.cn (L.W.); 15639142368@163.com (D.C.); mashujun@hpu.edu.cn (S.M.)

³ Collaborative Innovation Center of Coal Work Safety and Clean High Efficiency Utilization, Henan Polytechnic University, Jiaozuo 454003, China

⁴ MOE Engineering Research Center of Coal Mine Disaster Prevention and Emergency Rescue, Henan Polytechnic University, Jiaozuo 454003, China

* Correspondence: zhaofengw@hpu.edu.cn

Abstract

Coal mining has entered the stage of deep mining, and the prevention and control of gas disasters are facing significant challenges. Coal seam water injection, as an effective means of preventing and controlling gas disasters, has dual effects of pressure relief, permeability enhancement, and displacement sodium dodecyl benzene sulfonate (SDBS), as an anionic surfactant, can reduce surface tension to a certain extent in its aqueous solution and is therefore commonly used in coal seam water injection technology. In order to clarify the effect of SDBS on the water absorption capacity of coal and whether it will affect the gas adsorption capacity of coal, imbibition tests were conducted on dried coal samples in different concentrations of SDBS solutions, as well as gas adsorption tests on dried coal samples after imbibition was completed. Research shows that the key concentration range of SDBS for practical application is 0.050–0.075 wt%. When the concentration of SDBS solution is lower than 0.050 wt%, as the concentration of SDBS solution increases, the spontaneous imbibition capacity of coal increases significantly, and the adsorption capacity of coal to gas decreases significantly. When the concentration of SDBS solution is higher than 0.075 wt%, the spontaneous imbibition water capacity and gas adsorption capacity of coal hardly change significantly with the increase in solution concentration. Considering the effects of SDBS on coal water absorption and gas adsorption capacity, as well as environmental protection factors, it is recommended to use SDBS as a surfactant with a solution concentration of 0.050 wt%.

Keywords: coal seam water injection; surfactants; SDBS; imbibition; gas adsorption



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1. Introduction

As an important fossil energy and chemical raw material, coal has long occupied an important position in the global primary energy structure. It has long occupied a dominant position in China's energy structure. With the gradual depletion of shallow coal resources, coal mining countries all over the world are facing the transition to deep mining [1]. The mining depth of coal mines in China is rapidly extending downward at a speed of 10 m to 25 m per year [2,3]. With the deepening of coal mining depth, the “three highs” problem of the coal and gas storage environment [4] has become a common challenge for the safe

mining of deep coal mines in the world, and the prevention and control of coal mine gas disasters is facing severe challenges.

At present, the pre-extraction of coalbed methane is the most widely used gas control measure [5,6]. In order to increase the permeability coefficient of coal seams and achieve efficient gas extraction to the maximum extent, domestic and foreign researchers have continuously optimized coal seam water injection methods, forming a series of hydraulic measures to strengthen coal seam pressure relief, increase permeability, and promote extraction [7–10]. Research has shown that implementing hydraulic measures can not only improve coal seam permeability and gas seepage rate, but also promote the extraction of coal seam gas. At the same time, due to the stronger adsorption of water on coal than gas, after water enters the coal containing gas, it will also replace the gas in the pores and cracks of the coal, further improving the gas recovery rate. The effectiveness of water conservancy measures in controlling coalbed methane mainly depends on whether the moisture can thoroughly and uniformly wet the coal body [11]. Coal itself is a hydrophobic and oleophilic substance, so hydraulic measures for controlling coalbed methane often have a poor ability to spontaneously infiltrate and absorb water in practical applications, and even lead to water lock effects. Domestic and foreign scholars have proposed a solution to this problem by adding surfactants to external moisture, thereby improving the wetting effect of coal rock surfaces [12,13].

Sodium dodecyl benzene sulfonate (SDBS) is a widely used anionic traditional surfactant [14,15]. Domestic and foreign researchers have conducted extensive research on the application of SDBS and have achieved specific results. Meng Junqing et al. [16] used atomic force microscopy experiments to study the effect of SDBS solution concentration on the thickness of the coal surface hydration film. The study showed that the thickness of the coal surface hydration film increased first and then decreased with the increase in SDBS solution concentration; Li Shugang et al. [17] used the Wiser coal chemical structure model to investigate the adsorption phase of hydrophobic alkyl chains and hydrophilic groups in SDBS molecules. They found that the spatial distribution difference in hydrophobic alkyl chains in SDBS molecules is one of the main reasons affecting the wetting performance of coal; Xie Zhenhua et al. [18] studied composite coal dust suppressants with different mass fractions of SDBS, and found that an adequate dust suppression time had a significant effect; Luo Ruidong et al. [19] developed a new type of coal dust suppressant by adding SDBS and other agents to modified soy protein. The experiment found that the suppressant has a wide range of applicability. Cao Shuijing et al. [20] studied the wettability and wetting rate of SDBS and tetradecyltrimethylammonium bromide, and found that by using them as the primary agent in combination with coagulants and foaming agents, the inhibitory effect on coal dust was significantly changed through different formulation ratios; Dou Guolan et al. [21] studied the interaction between aqueous solutions of active surfactants such as SDBS, alkyl polyglycosides, and superabsorbent polymers; Chen Xuexue et al. [22] studied the optimal compounding of surfactants during the replacement stage of coal seam water injection shifts. The study showed that when the compounding ratio was 1:2 and the mass fraction of the compounding agent was 0.2%, the optimal effect of monomers in the contact angle experiment could be achieved. At present, domestic and foreign scholars' research on SDBS mainly focuses on reducing the surface tension of coal and suppressing dust in coal seams. Scholars' research on SDBS has made significant progress to a certain extent. Due to the limitations of test methods and equipment, the current research on SDBS still has some defects. In particular, there is a relative lack of direct research on the effect of surfactants on the migration ability of water in coal, and a small amount of research on this aspect also focuses on the effect of surfactants on the migration of pressurized water. There is a lack of direct research on the effect of surfactants

on the spontaneous imbibition water migration ability in coal and the ability of coal to adsorb gas.

In order to focus on the influence of SDBS on the spontaneous imbibition moisture migration ability and coal gas adsorption ability in coal, this study is quite different from other scholars' methods in studying the influence of SDBS on the application effect of water conservancy measures. That is, this study uses the spontaneous imbibition of different concentrations of SDBS solution by remolded coal, rather than the conventional pressurized injection of water solution into the coal. The primary purpose of using this research method is to explore the effect of the spontaneous imbibition of sodium dodecyl benzene sulfonate solution with different concentrations in micro pores, which entirely depends on capillary force, in the middle and late stages of hydraulic measures. In this study, the spontaneous imbibition process of a dry briquette in different concentrations of SDBS solution was used to simulate the spontaneous imbibition process of coal after the coal seam was injected with surfactant solution, and the effect of SDBS concentration on the spontaneous imbibition capacity of coal was reflected by monitoring the change process of coal moisture content. The briquette after imbibition and drying treatment is used to carry out a gas adsorption test to analyze the change in gas adsorption capacity of coal after the spontaneous imbibition of the surfactant solution.

2. Materials and Methods

2.1. Experimental Program

In order to simulate the changes in the ability of coal to spontaneously absorb water and adsorb gas after injecting a surfactant solution into the coal seam, this study developed a relevant experimental plan. Firstly, the collected experimental coal samples are processed to prepare a particular specification of coal sample. Then prepare SDBS solutions of different concentrations, and use the prepared coal samples to infiltrate and absorb water in these solutions spontaneously. During the imbibition process, the moisture content of coal is monitored by weighing to reflect the differences in the spontaneous water imbibition ability of coal in SDBS solutions of different concentrations. Finally, the coal samples that have reached saturation moisture content through imbibition will be dried and subjected to gas adsorption experiments under different pressure conditions using dried coal samples. The adsorption capacity of each coal sample under different adsorption equilibrium pressure conditions will be calculated to analyze the changes in gas adsorption capacity of the dried coal samples after imbibition with SDBS solutions of different concentrations.

2.2. Coal Sample Preparation

The experimental coal sample was taken from the 3002 working face of Hebi Sixth Mine of Henan Energy Group in the Hebi Mining Area, as shown in Figure 1. The mine is located in the southern part of the Hebi Mining Area, and the coal type is lean coal, which poses a risk of coal and gas outbursts. Using national standards, we experiment with the basic parameters of coal samples, including the actual density (TRD), apparent density (ARD), porosity, ash content (A_{ad}), moisture content (M_{ad}), and volatile matter (V_{ad}). The experimental values of each fundamental parameter are shown in Table 1.

Due to the high heterogeneity of raw coal (fracture, mineral distribution, pore size distribution, etc.), these factors will introduce more variables, complicating the analysis of test results. Therefore, in this study, remolded coal is selected for the test, which has the advantage of improving the homogeneity of coal samples and making the research more inclined to the role of SDBS on the coal matrix. Selecting a reasonable particle size and ratio can not only improve the strength of coal but also provide a channel for the spontaneous

imbibition of water. The particle size and ratio of 0.25–0.5 mm:0.5–1 mm = 2:1 selected in this study are optimized based on coal sample preparation in the early stage.

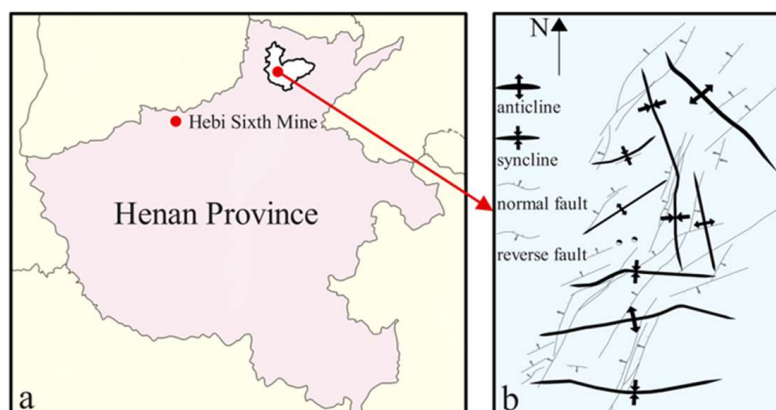


Figure 1. (a) Location of Hebi Sixth Mine; (b) outline map of Hebi Sixth Mine structure.

Table 1. Basic parameters of coal samples.

TRD (g/cm ³)	ARD (g/cm ³)	Porosity (%)	A _{ad} (%)	M _{ad} (%)	V _{ad} (%)
1.5303	1.4579	4.7	10.88	1.51	8.535

The coal sample preparation process diagram is shown in Figure 2. Firstly, crush and screen the collected block coal samples, selecting 0.25–0.5 mm and 0.5–1 mm particle coal samples; weigh approximately 270 g of coal samples with two different particle sizes in a ratio of 0.25–0.5 mm:0.5–1 mm = 2:1, and add 27 g of distilled water to mix evenly; use a coal mold and a press machine to compress cylindrical coal samples with a diameter of 50 × 100 mm under a forming pressure of 150 KN; set the drying oven temperature at 105 °C and dry the briquette sample for 12 h to complete the preparation of the coal sample for the imbibition test. For the coal sample required for the gas adsorption test, the heat shrinkable film and metal mesh pad wrapped outside the coal sample after the imbibition test shall be removed, and the wet coal sample shall be dried according to the same drying treatment method as in the previous step.



Figure 2. Flowchart of coal briquette preparation.

2.3. Imbibition Experimental Method

The imbibition test process is shown in Figure 3.



Figure 3. Imbibition experiment process.

- (1) **Reagent preparation.** Relevant studies show that the critical micelle concentration of SDBS is about 0.05–0.08 wt% [23]. Based on the core theory of Surfactant Science, this study needs to prepare 200 mL SDBS solutions with concentrations of 0.025 wt%, 0.050 wt%, 0.075 wt%, 0.100 wt%, and 0.200 wt%, respectively, and to prepare 200 mL of distilled water at the same time.
- (2) **Coal sample processing.** The pressed briquette sample is dried in a drying oven, and a Φ 50 mm metal filter screen is placed at the bottom of the dried briquette sample. A section of heat-shrinkable film is cut and sleeved on the coal sample, which is heated by a hot air gun to make its shrinkage closely fit the coal sample surface.
- (3) **Spontaneous imbibition.** Fill the drying dish with SDBS solutions of different concentrations, place the coal sample with one end of the metal filter facing downwards, and stand it vertically in the solution. The SDBS solution can only contact the coal sample through the metal filter screen, and its contact area is the end face of the briquette sample.
- (4) **Moisture content monitoring.** During the spontaneous imbibition of SDBS solution in coal samples, the coal samples are weighed at regular intervals. By comparing the quality of dry coal samples and the quality of coal samples with different imbibition times, the change in moisture content of coal samples during spontaneous imbibition is determined.

2.4. Gas Adsorption Experimental Device

To investigate the adsorption and desorption characteristics of coal samples after inhale different concentrations of surfactants, the team independently designed and developed a coal sample adsorption and desorption experimentation device, as shown in Figure 4.

- (1) **Vacuum degassing system.** The system mainly consists of a vacuum pump, a vacuum sensor, a vacuum buffer container, a drying container, and connected pipelines. Its primary function is to perform vacuum degassing of the pre-experiment inflation tank, coal sample tank, and experiment pipelines.
- (2) **Gas supply system.** The system mainly consists of high-pressure methane cylinders, high-pressure helium cylinders, pressure-reducing valves, pressure gauges, and connected pipelines. It can provide methane and helium gas supplies at different pressures according to the needs of the experiment.
- (3) **Adsorption equilibrium system.** The system is mainly composed of a reference cylinder, a special coal sample tank, valves, and connected pipelines, which can fill the coal

sample tank with quantitative methane gas to make the middling coal sample in the coal sample tank absorb and balance under a certain gas pressure.

- (4) Desorption metering system. The system mainly consists of desorption valves, free gas automatic collectors, fully automatic gas meters, and connected pipelines, which can achieve uninterrupted collection and measurement of desorbed gas throughout the entire process.
- (5) Data collection and analysis system. The system is mainly composed of a pressure sensor (measurement accuracy is ± 0.01 MPa), pressure acquisition module, temperature sensor (measurement accuracy is ± 0.5 °C), temperature acquisition module, data processing computer, and related lines. Its primary function is to collect and record the signals fed back by the sensors at various parts of the device in real time during the test.

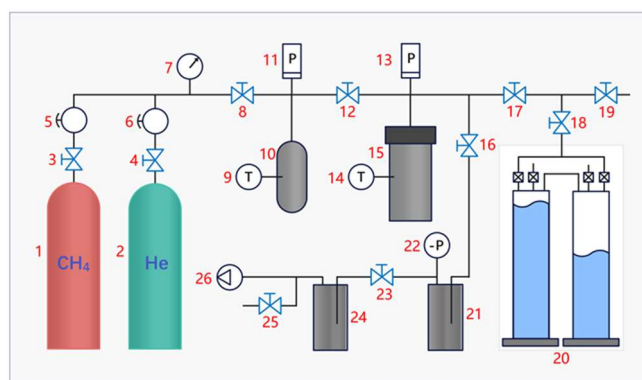


Figure 4. Schematic diagram of experimental equipment. 1. High-pressure gas cylinder; 2. high-pressure helium cylinder; 5,6. pressure-reducing valve; 7. pressure gauge; 11, 13. pressure sensor; 9, 14. temperature sensor; 10. reference cylinder; 15. coal sample tank; 20. fully automatic gas meter; 21. dry container; 22. vacuum gauge; 24. buffer container; 26. vacuum pump; 3, 4, 8, 12, 16, 17, 18, 19, 23, 25. valve.

2.5. Gas Adsorption Experimental Steps

- (1) Data recording.

Open the data collection and analysis system to collect and record real-time data throughout the entire experimental process.

- (2) Device airtightness experimentation.

Open the helium gas cylinder valve and intake valve, fill a specific volume of helium gas into the reference cylinder, then close the helium gas cylinder valve and intake valve and open the balance valve, fill helium gas into the coal sample tank, wait for the pressure in the coal sample tank and reference cylinder to stabilize, then close the balance valve and maintain it for more than 24 h, and observe whether the pressure reading changes abnormally.

- (3) Volume calibration.

Before starting all experiments, calibrate the volume of the reference cylinder, the coal sample tank, and the pipelines in the experiment. Calibrate the volume of the experimental coal sample before each experiment.

- (4) Vacuum degassing.

Open the vacuum pump and vacuum valve to degas the experimental system. When the vacuum gauge reading drops below 10 Pa, it is considered that the coal sample vacuum degassing process has been completed. After completing the vacuum pumping, close the

vacuum valve and vacuum pump in sequence, and then open the vacuum vent valve to release the negative pressure in the vacuum pumping pipeline.

(5) Inflatable adsorption equilibrium.

Open the gas cylinder valve and intake valve to allow gas to enter the reference cylinder, and gradually increase the gas pressure inside the reference cylinder by adjusting the pressure-reducing valve. Close the gas cylinder valve and intake valve, and after the pressure and temperature inside the reference cylinder stabilize, open the balance valve to allow the high-pressure gas in the reference cylinder to be filled into the coal sample tank. Then close the balance valve and wait for the coal sample to reach adsorption equilibrium. When the pressure inside the coal sample tank remains constant for 5 h, it is considered to have reached adsorption equilibrium.

3. Results

3.1. Imbibition Experimental Results

By monitoring the mass changes in coal samples during the spontaneous imbibition of SDBS solutions of different concentrations and comparing the mass changes before and after imbibition, the characteristics of moisture content changes in coal samples during imbibition can be determined. The changes in moisture content of coal samples during imbibition under different concentration conditions are shown in Figure 5.

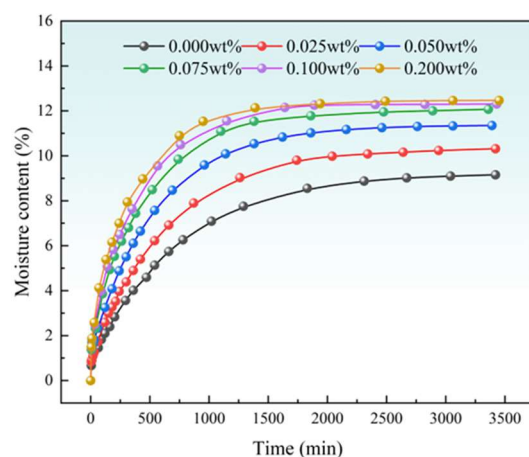


Figure 5. Water content change process of SDBS solution with different concentrations by imbibition of the coal sample.

From Figure 5, it can be seen that the change in moisture content of coal samples when imbibiting SDBS solutions of different concentrations shows a similar trend of rapid increase, slow increase, and finally stabilizing and remaining unchanged. The coal sample is still in a dry state during the initial stage of imbibition. After contacting the coal sample, water will be quickly absorbed into the interior of the coal body under the action of capillary force, mainly filling the medium and large pores inside the coal sample. At the same time, the polar groups on the surface of the coal matrix strongly adsorb water molecules through hydrogen bonding and other interactions. Therefore, in the early stage of imbibition, the moisture content of coal samples shows a rapid increasing trend. As the large pores in the coal sample are gradually filled with water, the water begins to fill the small pores inside the coal sample. Although the capillary force experienced by water in small pores is greater, the growth rate of water content in coal samples at this stage is significantly reduced due to factors such as a small pore volume, high viscous resistance, and more complex pore pathways. After a sufficient amount of time, a mechanical equilibrium is reached between the capillary force inside the coal sample and the gravity and viscous resistance of the

water content. The coal sample infiltrates and absorbs solutions of various concentrations spontaneously, and the water content gradually stabilizes.

The growth rate of moisture content and saturated moisture content of coal samples during the imbibition of SDBS solutions with different concentrations is positively correlated with the solution concentration. Due to SDBS being an anionic surfactant, its dissolution in water directly leads to a decrease in the surface tension of the solution, which in turn increases the capillary force driving the coal sample to infiltrate and absorb the solution. Therefore, the imbibition rate of coal samples is positively correlated with the concentration of SDBS solution. At the same time, due to the imbibition of SDBS solution into the coal sample, SDBS will adsorb on the surface of the coal matrix to form a monolayer with hydrophilic groups facing outward, thereby reducing the coal–water interface energy, improving the wettability of the coal sample, and promoting the diffusion of the solution into smaller pores of the coal sample. Under these conditions, there is a positive correlation between the saturated moisture content of coal samples and the concentration of solutions at different concentrations.

3.2. Adsorption Experimental Results

The volume of the reference cylinder and coal sample tank in the experimental setup is an important parameter required for later data processing. Therefore, when conducting experiments, it is necessary first to calibrate the volume of the reference cylinder and the coal sample tank. Meanwhile, due to the presence of a large amount of free gas in the coal sample tank, when the coal sample reaches gas adsorption equilibrium, the amount of gas filled into the coal sample tank is not equal to the gas adsorption capacity of the coal sample under this pressure condition. In order to determine the amount of gas adsorption when the coal sample reaches the gas adsorption balance, it is first necessary to determine the volume of the remaining space in the middling coal sample tank for each group of experiments. Therefore, the volume of the experimental coal sample needs to be calibrated before each group of experiments. This study used helium gas as the calibration gas and adopted the PVT method [24] for calibration operation. The calibration results of the reference cylinder and coal sample tank volume are shown in Table 2. The volume calibration results of the coal samples used in each group's experiment are shown in Table 3.

Table 2. Calibration results of reference cylinder and coal sample tank volume.

Calibration Frequency	Volume of Reference Cylinder $V_0(\text{cm}^3)$	Volume of Coal Sample Tank $V_d(\text{cm}^3)$
1	108.39	366.36
2	109.06	368.74
3	108.97	367.96
Average value	108.81	367.69

Table 3. Volume calibration results of experimental coal samples.

Coal Sample Number	Coal Sample Weight (g)	Coal Sample Calibration Volume (cm^3)	Coal Sample Calibration Density (cm^3/g)
1#	271.26	176.54	1.5365
2#	272.88	177.36	1.5385
3#	272.89	177.48	1.5375
4#	273.67	178.22	1.5355

Table 3. Cont.

Coal Sample Number	Coal Sample Weight (g)	Coal Sample Calibration Volume (cm ³)	Coal Sample Calibration Density (cm ³ /g)
5#	274.40	179.48	1.5288
6#	275.31	178.13	1.5455

According to the gas adsorption test steps, the gas adsorption tests of dry coal samples under different adsorption equilibrium pressures were carried out in turn. According to Formulas (1) and (2), the standard gas quantity Q_c and free standard gas quantity Q_d filled into the coal sample tank are calculated, and the methane adsorption capacity of dry coal samples treated with different concentrations of SDBS solution under different adsorption equilibrium pressures is finally obtained.

$$Q_{ci} = \left(\frac{P_{1i}}{Z_{1i}} - \frac{P_{2i}}{Z_{2i}} \right) \frac{273.15 \times V_0}{(273.15 + t) \times 0.101325} \quad (1)$$

$$Q_{di} = \frac{273.15 \times V_d \times P_i}{Z_i \times (273.15 + t) \times 0.101325} \quad (2)$$

where Q_{ci} is the standard volume of gas filled into the coal sample tank, in cm³; Q_{di} is the standard volume of free gas under the adsorption equilibrium state, in cm³; P_{1i} and P_{2i} are the absolute pressure in the reference tank before and after inflation, respectively, in MPa; T is the test temperature, in °C; Z_{1i} and Z_{2i} are the compression coefficient of gas under the pressure of P_1 and P_2 and at the temperature of T , measured in 1/MPa; V_0 is the standard volume of reference tank and connecting pipeline, in cm³; V_d is the residual volume of coal sample tank and connecting pipeline, in cm³.

The compressibility factor Z can be calculated using the R-K equation [25].

$$Z = \frac{1}{1-h} - \frac{4.934}{T_r^{1.5}} \times \frac{h}{1+h} \quad (3)$$

$$h = \frac{0.08664P_r}{Z \times T_r} \quad (4)$$

$$T_r = \frac{T}{T_C} \quad (5)$$

$$P_r = \frac{P}{P_C} \quad (6)$$

where Z is the compression coefficient of gas under a specific temperature and pressure, which is dimensionless; h is an intermediate variable; T is the temperature of the gas, in K; P is the pressure of the gas, in Pa; T_r is the contrast temperature of gas, in K; P_r is the contrast pressure of gas, in Pa; T_C is the critical temperature of gas, and the critical temperature of methane gas is 190.7 K; P_C is the critical pressure of gas, and the critical pressure of methane gas is 4,640,910 Pa.

The adsorption capacity of coal samples with different concentrations of SDBS solution after drying treatment under different adsorption equilibrium pressure conditions is shown in Figure 6.

As shown in Figure 6, with the increase in gas adsorption equilibrium pressure, the adsorption capacity of coal samples gradually increases, and the increase shows a decreasing trend. Under the same adsorption equilibrium pressure, the adsorption amount of the coal sample is negatively correlated with the concentration of the imbibition SDBS

solution. The main reasons for this phenomenon are as follows: after the solution enters the interior of the coal, the hydrophobic alkyl chains of SDBS molecules on the surface tend to strongly adsorb onto the equally hydrophobic coal surface in order to escape the water surrounding them. At the same time, the alkyl chains of SDBS molecules will be flattened or anchored on the pore surface of coal, and van der Waals forces will be generated between their long alkyl chains and the alkyl side chains and aromatic layers in the coal macromolecular structure. SDBS molecules adsorb onto the coal matrix, thus occupying a portion of the gas adsorption sites. Surfactant molecules own a specific volume and enter the coal body together with the aqueous solution through imbibition. During the drying process, water is expelled from the coal through evaporation, while gas wetting reversal agent molecules remain inside the coal, thereby reducing the adsorption space for gas molecules. The gas wetting reversal agent has the characteristic of a low surface tension, which adsorbs on the surface of pores and cracks inside coal, reducing its surface free energy and decreasing its adsorption capacity for gas molecules, thereby reducing the adsorption amount.

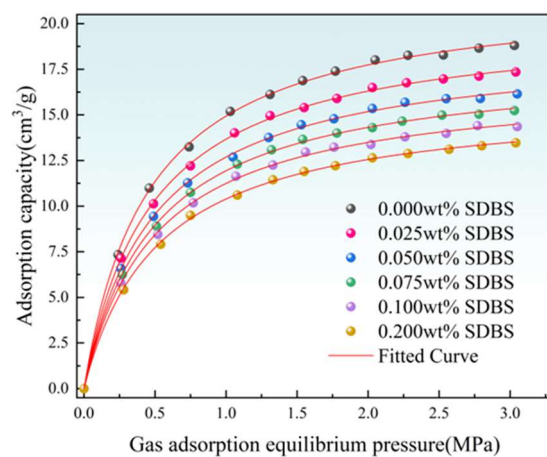


Figure 6. Adsorption capacity of dry coal samples after soaking in SDBS solutions of different concentrations.

The Langmuir curve fitting analysis was conducted based on the correlation data between adsorption capacity and pressure measured by adsorption experiments. The fitting results of the adsorption constant values of dried coal samples after imbibition treatment with SDBS solutions of different concentrations are shown in Table 4.

Table 4. Adsorption constants of dried coal samples after imbibition with SDBS solutions of different concentrations.

SDBS Solution Concentration (wt%)	a (cm ³ /g)	b (MPa ^{−1})
0.000	21.8442	2.1598
0.025	20.2061	2.0891
0.050	18.8937	2.0442
0.075	17.8843	2.0063
0.100	16.8646	1.9990
0.200	15.8651	1.8967

According to Table 4, after different concentrations of SDBS solution imbibition treatment, the adsorption constant values of dry coal samples all decreased, and the adsorption

constant values of coal samples were negatively correlated with the concentration of SDBS solution in the imbibition-treated coal samples. The adsorption constant a of coal indirectly reflects the maximum adsorption capacity of coal; that is, the larger the value of a , the greater the maximum adsorption capacity of coal. As the concentration of SDBS solution used for the imbibition treatment of coal samples increases, the adsorption constant a value of the coal sample gradually decreases. This is mainly because the active agent molecules will adhere to the pore surface of the coal sample after entering, and will even block the small pore channels, resulting in a decrease in the gas contact specific surface area of the coal sample and the occupation of gas adsorption sites. The higher the concentration of SDBS solution, the more surface active agent molecules enter the coal sample through imbibition, and the smaller the adsorption constant a value of the coal sample. The adsorption constant b of coal reflects the adsorption affinity between gas molecules and the coal surface; that is, the larger the b value, the stronger the coal's ability to adsorb gas molecules. SDBS, as an anionic surfactant, changes the wettability of coal samples from hydrophobic to hydrophilic after it enters the coal sample and adheres to the pore surface. The surface polarity of the coal sample is enhanced, which weakens the van der Waals force relied on for gas adsorption on the pore surface of the coal sample. Therefore, the higher the concentration of the SDBS solution, the weaker the adsorption ability of the coal sample for gas, and the smaller the adsorption constant b value of the coal sample.

4. Discussion

A variety of mathematical models were used to fit and analyze the moisture content change process of coal samples' imbibition with SDBS solutions of different concentrations. By comparison, it was found that exponential fitting had the best goodness of fit among all fitting models. The fitting relationship between moisture content and imbibition time in the process of coal samples' imbibition of SDBS solutions with different concentrations is shown in Figure 7, and the fitting formula and goodness of fit are shown in Table 5.

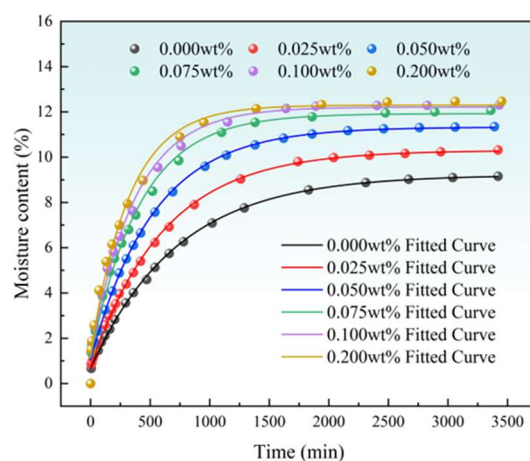


Figure 7. The fitting relationship between moisture content and time during the coal sample imbibition process.

Table 5. Relationship between moisture content and time during the imbibition of SDBS solutions in coal samples.

SDBS Solution Concentration	Fitting Formula for Changes in Moisture Content	R ²
0.000 wt%	$y = -8.56 \times \exp(-x/724.88) + 9.22$	0.99678
0.025 wt%	$y = -9.59 \times \exp(-x/613.68) + 10.31$	0.99741

Table 5. Cont.

SDBS Solution Concentration	Fitting Formula for Changes in Moisture Content	R ²
0.050 wt%	$y = -10.27 \times \exp(-x/528.83) + 11.33$	0.99597
0.075 wt%	$y = -10.79 \times \exp(-x/415.98) + 11.93$	0.99200
0.100 wt%	$y = -11.00 \times \exp(-x/371.69) + 12.21$	0.99139
0.200 wt%	$y = -11.01 \times \exp(-x/324.01) + 12.31$	0.98899

According to the analysis in Table 5, it can be seen that when the coal sample is infiltrated with different concentrations of SDBS solution for a specific period, the moisture content of the coal sample will reach its peak, that is, the coal sample infiltrates and saturates. According to the fitting formula for the variation in moisture content in coal samples, the saturated moisture content reached by the imbibition of coal samples in six different concentrations of SDBS solutions is 9.22%, 10.31%, 11.33%, 11.92%, 12.21%, and 12.31%, respectively. When the concentration of SDBS solution is lower than 0.050 wt%, the saturated moisture content of coal sample imbibition increases by 1.09% and 1.02% for every 0.025 wt% increase in concentration. The concentration of SDBS solution increased from 0.050 wt% to 0.075 wt%, and the saturated moisture content of coal sample imbibition increased by 0.59%. When the concentration of SDBS solution increases from 0.075 wt% to 0.100 wt% and from 0.100 wt% to 0.200 wt%, the saturated moisture content of coal sample imbibition increases by 0.29% and 0.10%, respectively. Therefore, 0.050–0.075 wt% is the key concentration range for the practical application of SDBS. The main reason for this may be that the critical micelle concentration of the SDBS solution is between this range under the test conditions. Before the concentration of the SDBS solution reached the critical micelle concentration, the surface tension decreased significantly with the increase in solution concentration. When the concentration of the SDBS solution is greater than the critical micelle concentration, some surfactant molecules in the solution will spontaneously gather together, and the surface tension of the solution will no longer significantly decrease with the increase in surfactant concentration. At the same time, the pore volume of coal is fixed, and there is a theoretical limit to water content. SDBS treatment helps water enter micro pores by enhancing wettability and reducing surface tension. When the imbibition process approaches this physical limit, regardless of changes in solution properties, it is challenging to improve the water content further.

By comparing and analyzing the changes in adsorption constants of dried coal samples after imbibition of SDBS solution with different concentrations, the change law of adsorption constants of coal samples is the same as that of the saturated moisture content of coal samples. When the concentration of the SDBS solution is lower than 0.05 wt%, the adsorption constant of the coal sample decreases faster with the increase in solution concentration. In comparison, when the concentration of SDBS solution is higher than 0.075 wt%, the adsorption constant of the coal sample decreases more slowly with the increase in solution concentration. The main reason for this phenomenon is that the surfactant molecules in the solution are relatively dispersed before reaching the micelle concentration. After single-layer adsorption on the pore surface of the coal sample, the surface free energy can be significantly reduced, the surface polarity of the coal sample can be enhanced, and the adsorption capacity of the coal sample for gas can be weakened. At the same time, the surfactant molecules also reduce the maximum adsorption capacity of coal to a certain extent. When the solution concentration is greater than the micelle concentration, the surfactant molecules dispersed in water reach saturation, and excess surfactant molecules form micelles in the solution. Under these conditions, the adsorption constant of coal samples

shows a slight decrease with increasing solution concentration. The main reason is that the number of surfactant molecules entering the coal sample through imbibition increases, forming multiple molecular layers on the pore surface of the coal sample, further reducing the maximum adsorption capacity of the coal and weakening its ability to adsorb gas.

The purpose of adding surfactant SDBS in coal seam water injection is to improve the efficiency of water injection, increase the moisture content of the coal body, and then improve the effect of water conservancy measures on coal seam gas control. From the test results, when SDBS is used as a surfactant, the most suitable surfactant concentration should be within the key concentration range of 0.050–0.075 wt%. However, SDBS has specific toxicity and biological persistence, which may cause pollution to groundwater. Therefore, considering issues such as application effectiveness, economic cost, and environmental sustainability, the study suggests that when using SDBS as a surfactant for coal seam water injection gas treatment, the concentration of SDBS solution should be 0.050 wt%.

5. Conclusions

The main conclusions drawn from the study on the changes in moisture content of coal samples and the gas adsorption of dried coal samples after imbibition treatment using SDBS solutions with different concentrations of coal are as follows:

- (1) SDBS, as an anionic surfactant, plays two leading roles in enhancing the effectiveness of coalbed methane treatment after its application in hydraulic measures. One approach is to enhance the efficiency of spontaneous water absorption and saturation moisture content in coal. The other involves SDBS molecules entering the coal, which can weaken its ability to adsorb gas to a certain extent.
- (2) Under the experimental conditions of this study, 0.050–0.075 wt% is the key concentration range for the practical application of SDBS. When the concentration of the SDBS solution is lower than 0.050 wt%, with the increase in the concentration of the SDBS solution, the spontaneous imbibition capacity of coal increases significantly, and the adsorption capacity of coal to gas decreases significantly. When the concentration of the SDBS solution is higher than 0.075 wt%, the spontaneous imbibition water capacity and gas adsorption capacity of coal hardly change significantly with the increase in solution concentration.
- (3) Considering the effectiveness, economical nature, and environmental sustainability of SDBS enhanced water conservancy measures for controlling coalbed methane, it is recommended that the solution concentration of SDBS used as a surfactant should be 0.050 wt%.

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