Research on influencing factors and remedial measures of coal seam water blocking effect

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Abstract. Coalbed methane development primarily relies on hydraulic fracturing and drainage gas extraction processes. The intrusion of external fluids and long-term drainage and extraction contribute to the water blocking effect, which becomes one of the crucial factors affecting production capacity. In this study, the coal reservoir of a certain coalbed methane in Hancheng, Shaanxi Province, was selected as the research object. The experimental method was employed to comprehensively evaluate the correlation between factors such as coal sample moisture content, permeability, porosity, properties of external liquids, and water blocking damage. The results indicated that there was a positive correlation between coal sample moisture content, liquid surface tension, and water blocking damage. On the other hand, coal sample pore permeability characteristics, liquid contact angle with rock samples, and water blocking damage showed a negative correlation. Building upon the aforementioned research, an investigation into remedial measures for water blocking damage was conducted. Additionally, a chemical treatment study using the compound surfactant system JSS-1 as a water-blocking agent was performed to manage the water blocking effect. The results demonstrated that JSS-1 as a water-blocking agent significantly reduced the surface tension of the wellbore fluid and improved its wetting behavior on the coal-rock surface. The laboratory experiments confirmed the capability of JSS-1 in managing the water blocking effect.

Keywords: Coalbed methane; water blocking effect; influencing factors; remedial measures.

1. Introduction

Coalbed methane, commonly known as "coal gas," refers to natural gas that is adsorbed in coal seams, with methane being its main component [1]. As a associated resource of coal, coalbed methane used to be a potential hazard in coal mining operations. However, with technological advancements, the large-scale development and utilization of coalbed methane have become an important aspect of unconventional natural gas research. This not only helps improve resource utilization but also provides safety assurance for coal mining operations.

China is a major producer of coal, and it also possesses a considerable amount of coalbed methane resources. According to the International Energy Agency (IEA), China's coalbed methane reserves exceed 10 trillion cubic meters, indicating promising development prospects. The National Energy Administration has set a development target in its "Coalbed Methane (Coal Mine Gas) Development and Utilization Plan" to achieve a national coalbed methane utilization volume of 10 billion cubic meters by 2025, providing policy support for the industrial development of coalbed methane. However, most of China's coalbed methane reservoirs exhibit significant characteristics of "three lows" (low porosity, low permeability, and low pressure), along with developed micro-fractures. These characteristics make it difficult for foreign fluids to be effectively displaced and expelled from the coal seams after reservoir stimulation, leading to water blocking damage. In recent years, there has been considerable research by Chinese scholars on water blocking damage and its prevention in low porosity and low permeability oil and gas reservoirs [2-4]. However, studies on water blocking damage in coalbed methane have been mainly focused on experimental attempts at remedial measures in certain blocks based on empirical knowledge [5-7]. The understanding of mechanisms is incomplete, experimental support is insufficient, and targeted remedial measures are lacking. In this study, the coal reservoir of a certain coalbed methane in Hancheng, Shaanxi Province, was selected as the research object. The correlation between external fluids and rock properties with water blocking damage in the coal body was studied. Additionally, the feasibility of water blocking remedial measures was analyzed using the JSS-1 surfactant system as an example.

2. Experimental Study on Factors Affecting Water Blocking Damage in Coal Samples

2.1 Coal Quality Characteristics and Experimental Coal Sample Preparation

The samples for this experiment were obtained from a coal mine near the coalbed methane block in Hancheng, Shaanxi Province. The sampling location corresponds to the coalbed methane reservoir, and it is approximately 700 meters away from the nearest coalbed methane production well, with a depth of around 1000 meters. According to the national standard "Classification of Coal Structures" (GB/T30050-2013), the main coal type in the experimental samples is bright coal, exhibiting a fragmented structure with clear visible bedding planes. The mechanical strength of the coal samples is relatively low to medium, with compressive strength generally below 12 MPa. Scanning electron microscopy observations and vitrinite reflectance measurements indicate a crack density of 5-12 fractures per meter and a maximum vitrinite reflectance of 2.1%-2.4%, classifying the coal as medium-rank coal. In the physical property testing, the permeability is mostly below 0.1 mD. In order to reduce experimental errors and ensure the singularity of experimental variables as much as possible, a standardization process was carried out on the coal samples, following the steps below.
(1) After processing the coal samples into standard rock samples with a diameter of 25mm and a height of 50mm, the standard rock samples were degassed using a vacuum pump. (2) The porosity φ of each coal sample was measured. (3) The initial gas permeability K0 of each coal sample was measured. (4) Each coal sample was calibrated at the inlet and outlet, and liquid was injected from the outlet in reverse (simulating the invasion of fluid during hydraulic fracturing) to establish different water saturation levels according to the subsequent experimental requirements. (5) The water block damage ratio ω was calculated.

$$\omega = \frac{K_0 - K_1}{K_0} \times 100\% \qquad (1)$$

Where: ω is the water block damage ratio, %; K_0 is the initial gas permeability, mD; K_1 represents the post-damage permeability., mD。

2.2 The water saturation level of coal samples affects the water block effect

Coal samples with similar porosity and initial permeability K0 (with a fluctuation of less than 10% based on 5% porosity and 0.1 mD permeability as references) were selected. These coal samples were subjected to incremental water saturation levels ranging from 0% to 40% using simulated formation water (with a salinity of 5000 ppm). The permeability K1 of the coal samples was tested again, and the results are shown in Table 1 and Figure 1.

Table 1: Test Results of Water Saturation and Water Block Damage Relationship in Coal Samples.

Index	Water Saturation	Porosity φ	Initial Permeability K0	Permeability after Damage K1	Water Block Damage Ratio
	%	%	mD	mD	%
01	0	5.13	0.1055	——	0
02	5	5.32	0.0972	0.0849	12.7
03	10	4.62	0.0919	0.0832	9.5
04	15	5.05	0.1034	0.0788	23.8
05	20	4.73	0.1028	0.0829	19.4
06	25	5.33	0.0921	0.0723	21.5
07	30	5.96	0.0935	0.0334	64.3
08	35	4.85	0.0981	0.0241	75.4
09	40	5.47	0.1003	0.0329	67.2

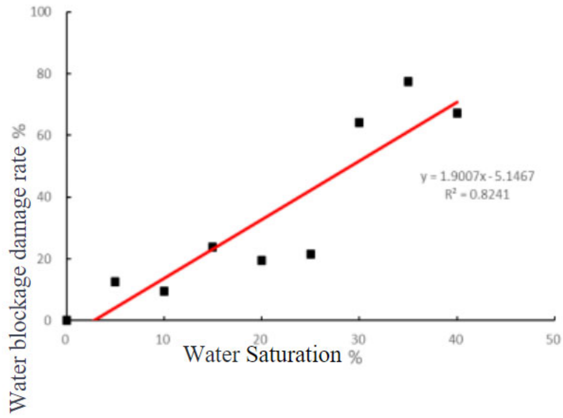

Figure 1: Relationship between Water Saturation and Water Block Damage in Coal Samples.

Based on the experimental results, as the water saturation in coal samples increases, the water block damage ratio tends to rise. When the water saturation exceeds 25%, there is a sudden increase in the water block damage ratio. Overall, there is a positive correlation between water saturation in coal samples and water block damage ratio. During coalbed methane production, as dewatering and gas extraction continue, the water saturation near the wellbore increases, and the water block effect becomes increasingly significant, leading to a gradual increase in the water saturation and its impact on production.

2.3 The impact of porosity and permeability on the water block effect

Different coal samples with varying porosity and permeability were selected. These coal samples were subjected to a 30% water saturation level using simulated formation water with a salinity of 5000 ppm. The permeability K1 of the coal samples was tested again, and the results are shown in Table 2, Figure 2, and Figure 3.

Table 2: Test Results of Porosity and Water Block Damage Relationship in Coal Samples

Index	Water Saturation	Porosity φ	Initial Permeability K0	Permeability after Damage K1	Water Block Damage Ratio
	%	%	mD	mD	%
07	30	5.46	0.0935	0.0334	64.3
10	30	2.87	0.0257	0.0000	100.0
11	30	3.11	0.0279	0.0015	94.5
12	30	3.92	0.0428	0.0049	88.5
13	30	4.33	0.0748	0.0135	81.9
14	30	5.94	0.0977	0.0222	77.3
15	30	6.19	0.1141	0.0758	33.6
16	30	8.36	0.1835	0.1251	31.8

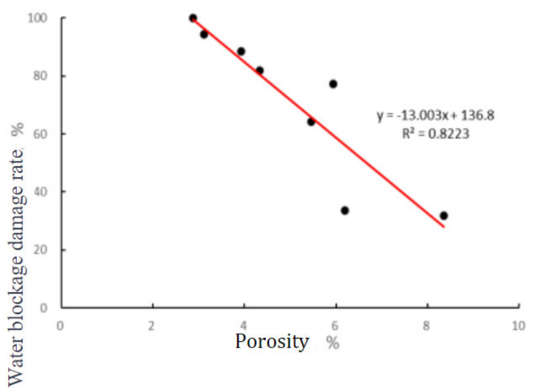

Figure 2: Relationship between Porosity of Coal Samples and and Water blockage damage

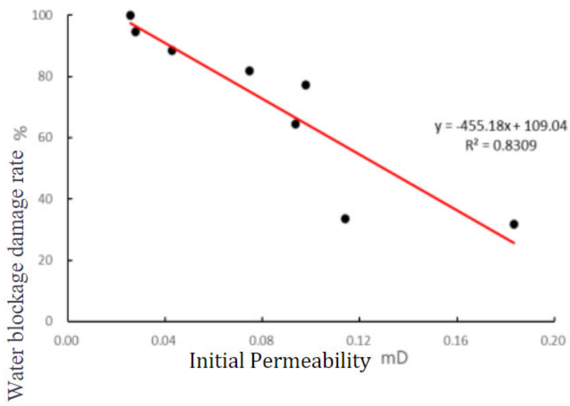

Figure 3: Relationship between Permeability of Coal Samples and Water blockage damage

According to the graph, it can be observed that the water block damage ratio decreases with increasing porosity and permeability of the rock samples. When the porosity is below 4% and the permeability is below 0.05 mD, the water block damage ratio exceeds 80%. Both porosity and permeability show a negative correlation with the water block damage ratio overall. This negative relationship is reflected in many coalbed methane wells in the Hancheng block. After hydraulic fracturing, the initial production is relatively high. However, factors such as the embedding and fragmentation of proppants gradually lead to a decrease in porosity and permeability in the treated area. This results in reduced primary fracture conductivity, hindered near-wellbore flow, and a sharp decline in production. In severe cases, the production can drop below 200m3/d or even cease completely.

2.4 The impact of surface tension and wettability on the water block effect.

Coal samples with similar porosity and initial permeability K0 (with a fluctuation of less than 10% based on 5% porosity and 0.1 mD permeability as references) were selected. Surface tension and contact angles on the coal surface were measured using water, simulated formation water, and several surfactant solutions. Subsequently, a 30% water saturation level was established in the coal samples, and the permeability K1 of the samples was tested again. The results are shown in Table 3, Figure 4, and Figure 5.

Table 3: Test Results of the Relationship between Foreign Fluid Properties and Water Block Damage in Coal Samples.

Index	Liquid Type	Surface Tension	Contact Angle	Initial Permeability K0	Permeability after Damage K1	Water Block Damage Ratio
		mN/m	°	mD	mD	%
17	Water	72.8	0.0	0.1046	0.0076	92.7
07	Simulated Formation Water	67.4	0.0	0.0935	0.0334	64.3
18	Ethanol	23.1	25.9	0.0913	0.0624	31.6
19	0.2%LAS	40.4	28.7	0.1071	0.0638	40.4
20	0.2%JFC	30.6	40.6	0.1033	0.0559	45.9
21	0.2% JSS-1	25.3	74.8	0.0974	0.0742	23.8

Note: In the table, LAS refers to the code for Sodium Dodecyl Benzene Sulfonate, JFC refers to the code for Fatty Alcohol Polyethylene Glycol Ether, and JSS-1 refers to a complex surfactant solution.

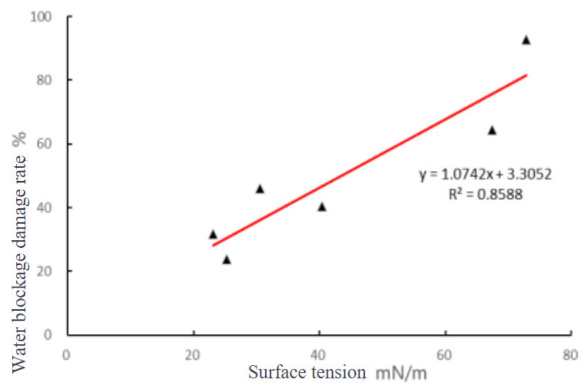

Figure 4: Relationship between Liquid Surface Tension and Water Block Damage

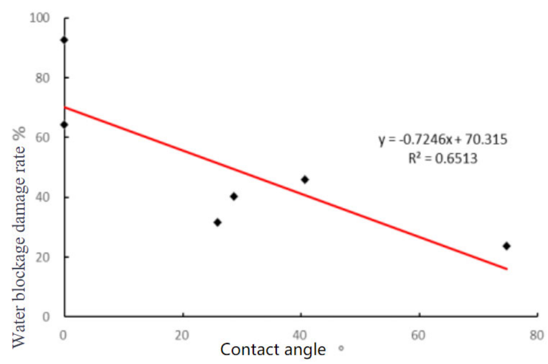

Figure 5: Relationship between Wettability and Water Block Damage

Based on the experimental results, as the liquid surface tension decreases and the contact angle increases, the water block damage tends to weaken. This indicates a positive correlation between liquid surface tension and water block damage, while a negative correlation exists between the contact angle and water block damage. According to the Laplace equation, the additional pressure formula can be derived as Equation 2. It is not difficult to observe that the trend in the experimental results is consistent with Equation 2. Currently, low surface tension and large contact angles are important assessment criteria for chemical water block prevention products.

$$\Delta P = \frac{2\sigma \cos\theta}{r} \quad (2)$$

In the equation: ΔP represents the additional pressure exerted by the liquid drainage, σ represents the liquid surface tension, r represents the pore radius.

3. Measures for mitigating water block damage.

3.1 Research status of water block damage control measures.

Currently, the methods for relieving water block damage can be mainly divided into physical methods and chemical methods.

Physical methods for relieving water blockage primarily involve two approaches. One approach is to adjust the production system and increase the bottomhole pressure difference to promote the expulsion of liquid phase trapped in the pore throats, thereby achieving the purpose of relieving water blockage. Another approach is the microwave heating method proposed by Li Gao et al., which involves targeted microwave heating in specific areas to rapidly evaporate the trapped liquid phase and expand the gas phase volume, thereby increasing the local reservoir energy. This method can also facilitate the dehydration of swelling clays, thereby improving the geometric morphology of the fractures in the treatment zone. Additionally, restimulation through re-fracturing can also help alleviate water blockage, but it is relatively costly and less commonly used, so it will not be further elaborated here.

In chemical methods for relieving water blockage, the injection of surfactant systems is the most commonly used approach. In recent years, fluorocarbon surfactants have received increasing attention due to their excellent hydrophobic properties, and they have been applied in multiple gas fields. For example, the FSSJ surfactant system used in a gas field in the Qinshui Basin of Shaanxi Province [9] and the surfactant system used in the Sulige Taohu X Block [10] have achieved good results in relieving water blockage. Both of these systems utilize fluorocarbon surfactants for formulation. Additionally, acid treatment has also been applied in some blocks to relieve water blockage. For example, the A-type acetic acid system used in the Sulige gas field [11] and the formulated acid system developed by Sun Shujuan et al. for carbonate reservoirs [12] have been used. Acid treatment can effectively improve the size and geometry of fractures and matrix flow channels, especially in the presence of solid blockage, where it has a significant unblocking effect.

Most of China's coalbed methane wells are shallowly buried and have typical low-pressure characteristics. Some production wells have casing pressures even below 1 MPa, making it difficult to relieve water blockage by increasing the pressure difference. The microwave heating method is currently not mature and has high costs, making it challenging to scale up its application in coalbed methane wells. Therefore, physical methods for relieving water blockage are difficult to widely apply in coalbed methane wells.

Among the chemical methods, the addition of surfactants does not require specialized equipment and has lower costs, making it the most suitable for application in coalbed methane wells. Since fluorocarbon surfactants are generally priced higher, it is possible to consider using a combination of anionic and nonionic surfactants to form a system that achieves the purpose of relieving water blockage. Following this approach, the feasibility of using the JSS-1 conventional surfactant system in contact with coalbed water blockage was tested.

3.2 Experimental Study on Water Blockage Remediation Using JSS-1 Surfactant System

Based on the previous experimental results, a water blockage remediation experiment was conducted using a 0.3% JSS-1 surfactant system. The liquid data are as follows:

Table 4: Liquid Test Results

Index	water saturation	surface tension	contact angle	Initial Permeability K0	Permeability after Damage K1	Water Block Damage Ratio
	%	mN/m	°	mD	mD	%
22	10	21.5	76.9	0.1053	0.0954	9.4
23	20			0.0922	0.0807	12.5
24	30			0.0985	0.0904	8.2
25	40			0.0904	0.0730	19.3

According to the method described in section 2.2, experiments were conducted using JSS-1 solution to establish saturation. The results showed that the water blockage rate was generally below 20% after using JSS-1, indicating a significant decrease in damage compared to the simulated formation water.

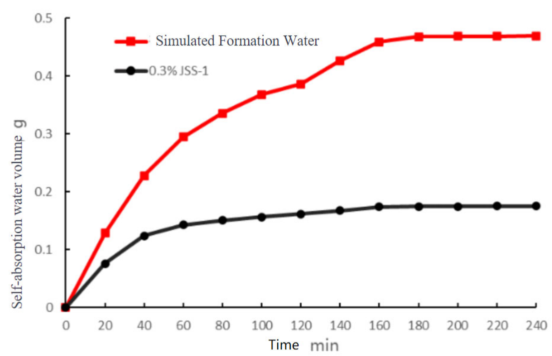

Figure 6: Results of self-imbibition test.

According to Figure 6, within a certain time range, the imbibition capacity of 0.3% JSS-1 solution in the coal sample is much lower than that of the simulated formation water, demonstrating its excellent water blockage removal characteristics.

4. Conclusion and Recommendations

(1) According to the evaluation experiments, there is a positive correlation between coal sample water saturation, liquid surface tension, and water lock damage. On the other hand, there is a negative correlation between coal sample pore-permeability characteristics, liquid-coal contact angle, and water lock damage.
(2) Surface-active agents are suitable for mitigating water lock in coal seam gas wells, and the conventional surface-active agent system JSS-1 has shown promising application results in laboratory experiments. It is recommended to optimize the formulation based on specific field requirements before applying it in practice.

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