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The effect of transitioning from water flooding to reduced-oxygen air flooding on oil recovery in low-permeability oil reservoirs[#]

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ABSTRACT

Reduced-oxygen air flooding can serve as an effective alternative for water injection in the development of low-permeability reservoirs. During the development process, there is a phenomenon of increased viscosity due to the mixture of crude oil oxidation and water. It is essential to clarify the impact of viscosity increase after crude oil-water mixture during low-temperature oxidation on oil recovery. This paper investigated the impact of water content on the viscosity increase of oil-water mixed fluids during air oxidation through static oxidation experiments. The results indicate that heavy components generated after crude oil oxidation can interact with water to form highly viscous fluids. As the water content increases from 0% to 70%, the viscosity of the mixed fluids initially increases and then decreases. It reaches its maximum value of 32.5 cp at a water content of 30%. The long core displacement experiment studied the impact of transitioning from water flooding to air flooding and nitrogen flooding on crude oil recovery under optimal viscosity conditions. Two sets of experiments, water flooding and gas flooding, were conducted for comparison. The results indicate that the highest oil recovery was achieved when transitioning from water flooding to air flooding. This suggests that the heavy components generated during crude oil oxidation in the air flooding process, along with the highly viscous fluid formed by interaction with water, can block high-permeability channels, exerting a localized profile modification effect. This leads to changes in gas flow channels and expands the effective gas sweep range. This leads to changes in gas flow channels and expands the effective gas sweep range.

Keywords: reduced-oxygen air flooding; low-temperature oxidation(LTO); enhance oil recovery (EOR); heavy components

NONMENCLATURE

Abbreviations	
LTO	Low-temperature Oxidation
Symbols	
PV	Pore Volume

1. INTRODUCTION

Low-permeability reservoirs in China have abundant geological reserves[1-4], but the recovery rate from water injection development is low[5-6]. As reservoirs generally enter the high water cut stage, air injection can serve as a subsequent method after water flooding development in low-permeability reservoirs[7-8]. When crude oil comes into contact with air, low-temperature oxidation occurs, producing heavier components[9-10]. These heavier components can interact with formation water under the influence of shear forces to form high-viscosity oil-water mixed fluids, which block the preferential flow paths of the gas, change the direction of the gas flow, and thus expand the sweep volume of the gas.

Researchers have conducted extensive studies on the development of light oil reservoirs using oxygen-reduced air injection. Pu Wanfen[11] and colleagues evaluated the low-temperature oxidation of light oil through oxidation tube experiments. The results showed that during the low-temperature oxidation of light oil, condensation reactions mainly occurred among light components (C5-C6) and intermediate components (C7-C17), with the addition of oxygen being the primary oxidation reaction in LTO. Qian Chuanqian[12] and others found that in the process of air injection, as the volume of injected air increased, the content of light components in the produced oil decreased, and the content of heavy components increased. Duboue[13] found that under reservoir conditions, asphaltenes in crude oil facilitated oil-water mixing, believing that water molecules diffused into the oil phase to form micro-droplets. Jia Hu[14] and colleagues proposed that injecting

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oxygen-reduced air into high water cut reservoirs could oxidize the crude oil to produce heavy components, increasing the viscosity of the crude oil, blocking high permeability channels, and enhancing the gas sweep efficiency. Song Wen[15] and others observed in a two-dimensional visual model that during low salinity water flooding, the formed mixed fluid would block high permeability channels, increasing the sweep volume of the injected fluid.

Currently, there is little literature reporting on the issue of high-viscosity oil-water mixtures formed during the low-temperature oxidation heating process in low-permeability reservoirs transitioning from water flooding to air injection. This paper uses a high-temperature and high-pressure static oxidation apparatus to conduct static oxidation experiments on crude oil under different water-cut conditions. The viscosity variation of mixed fluids formed by the interaction between crude oil and water at different water-cut levels was determined. Additionally, long core flooding experiments were conducted to identify the optimal water-cut level for viscosity enhancement and to study the effects of switching from water flooding to air injection under these conditions, clarifying the impact of low-temperature oxidation-induced fluid viscosity increase on recovery efficiency.

2. EXPERIMENTAL CONDITIONS AND METHODS

2.1 Experimental materials

The crude oil used in the experiments was sourced from a low-permeability reservoir in Xinjiang, China. The water used in the experiments was formation water from the same oil field, classified as $CaCl_2$ type with a salinity of 21,456 mg/L, with Cl^- as the predominant anion. The gas used in the experiments consisted of 5% oxygen-reduced air and N_2 with a purity of 99.9%. The experimental cores were obtained from natural cores of the oil field. The natural core was cut into cylindrical cores with a diameter of 2.5cm and a length of 30cm.

2.2 Experimental instruments

The main experimental instruments include a high-temperature high-pressure rotary reactor, flow meter, gas boosting device, chromatograph, ISCO pump, check valve, flow meter, high-temperature oven, oil-gas-water three-phase metering system, long core clamp, Brookfield viscometer, pressure detection system, data acquisition box, various glassware, etc. The isothermal oxidation experiment process is shown in Figure 1. The schematic diagram of the core displacement device is shown in Figure 2.

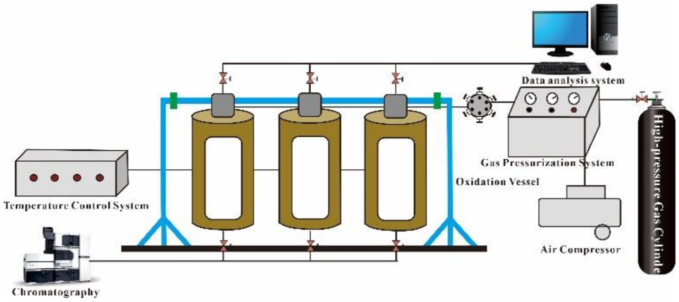

Fig 1. Flowchart of isothermal oxidation experiment

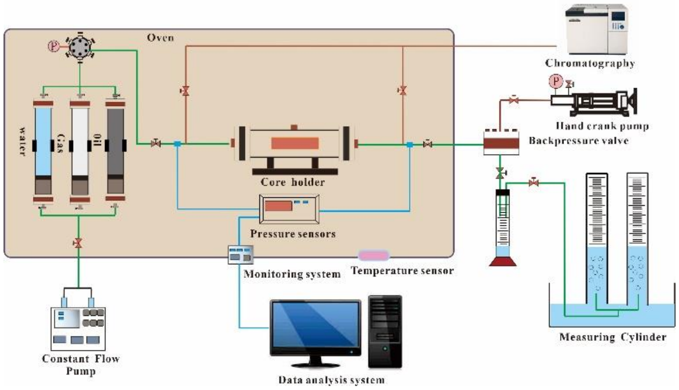

Fig 2. Gas Injection and displacement system for long core

2.3 Experimental scheme

2.3.1 Isothermal oxidation experiment

Table 1. Experimental protocol for isothermal oxidation

Experiment number	Water cut (%)	Gas	Pressure (MPa)	Temperature (℃)
①	10	Air	30	120
②	30			
③	50			
④	70			
⑤	0	N_2		
⑥	30			

We designed five isothermal oxidation experiments with different water contents ranging from 0% to 70% to investigate the effect of varying water content on the viscosity increase of mixed fluids during the oxidation process of light oil. Additionally, we established one control group without oxygen, using nitrogen gas. The experimental design is outlined in Table 1.

This section of the experiment involves the following specific steps: (1) Inject 300 mL of oil-water mixture with varying water content into the oxidation reactor separately. (2) Seal the reactor and use a vacuum pump to evacuate for 4 hours. (3) Inject compressed air until the internal pressure of the reactor reaches 30 MPa at the set constant temperature. (4)When the pressure in the reactor stabilizes, indicating the completion of low-temperature oxidation. Measure the viscosity of the liquid-phase mixture using a Brookfield viscometer, and analyze the collected gas and liquid using liquid phase analyzers for chromatographic analysis.

2.3.2 Core displacement experiment

Four displacement schemes were set up as shown in Table 2. Schemes 1 to 3 are used to compare the effect of water flooding to air injection development relative to pure water flooding and oxygen-reduced air injection development on increasing oil recovery under the condition of maximum viscosity increase. Schemes 1 and 4 are used to compare the ability to increase oil recovery with and without low-temperature oxidation. The specific experimental steps are as follows: (1) Saturation of the core with water: Weigh the dry core, then vacuum-saturate a section of the core in water. (2) Weigh the saturated core, and the difference between the wet weight and the dry weight represents the core's pore volume. (3) Measure the core's water permeability. (4) Saturation of the core with oil: Inject the experimental oil into the core at a rate of 0.1 ml/min until no water is produced at the core outlet, and calculate the oil saturation. (5) Connect the experimental apparatus and raise the pressure to 30 MPa (experimental back pressure). Start the displacement experiment according to the experimental plan, adjusting the liquid/gas injection rates. (6) Record the oil production, gas production, liquid production, and pressure difference between injection and production as a function of injection volume, and plot the development dynamic curve. (7) Change the experimental parameters and repeat steps (2)-(6).

Table 2. Protocol for long core displacement experiment

Experiment number	Injection rate (mL/min)	Displacing medium	Water content(%)
①	0.05	Water+Air	30
②		Water	0
③		Air	0
④		Water+N_2	30

3. RESULTS AND DISCUSSION

3.1 Isothermal oxidation experiment

The components of the crude oil after oxidation at different water contents are shown in Figure 3. The content of light components in the crude oil decreases, while the content of components above C10 increases. When there is no water, the content of C1-C5 decreases from 4.828% to 2.8%; the content of intermediate components C6-C10 decreases from 24.82% to 23.12%; conversely, the content of heavy components (C10+) increases from 70.35% to 74.07%. Therefore, it is clear that both light and intermediate components in the crude oil undergo oxidative condensation reactions, producing heavier components with larger molecular weights. After oxidation, the final components of the crude oil vary slightly with different water contents. As the water content increases, the decrease in light components and the increase in heavy components both decrease, indicating that the increase in water content leads to a slight reduction in the degree of oxidation of the crude oil, resulting in heavier components with higher viscosity. After full oxidation, the viscosity of the oil-water emulsion at different water contents was measured, with the results shown in Figure 4.

After low-temperature oxidation, the viscosity of fluids with water contents of 0%, 10%, 30%, 50%, and 70% are 7.62 cp, 21.31 cp, 32.53 cp, 26.46 cp, and 13.23 cp, respectively. These values are 2.31, 6.46, 9.86, 8.02, and 4.01 times the initial viscosity, respectively. The viscosity of the crude oil in the nitrogen control group is low, measuring 4.93 cp. The increase in crude oil viscosity after pure oil oxidation is mainly due to the oxidation of light components, resulting in the generation of heavier components with larger molecular weights. When water is present, not only does oxidation lead to thickening, but also the oxidized crude oil and water form a mixed fluid under shear forces, increasing the overall viscosity due to increased internal friction between the fluids. With increasing water content, the viscosity of the mixed fluid after oxidation initially increases and then decreases.

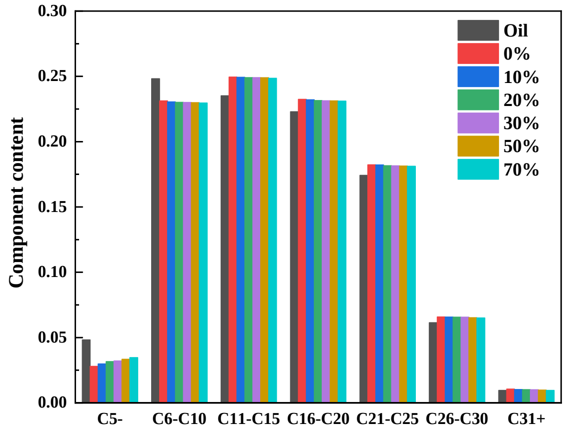

Fig. 3 Hydrocarbon distribution at water contents of 0%, 10%, 30%, 50%, and 70%

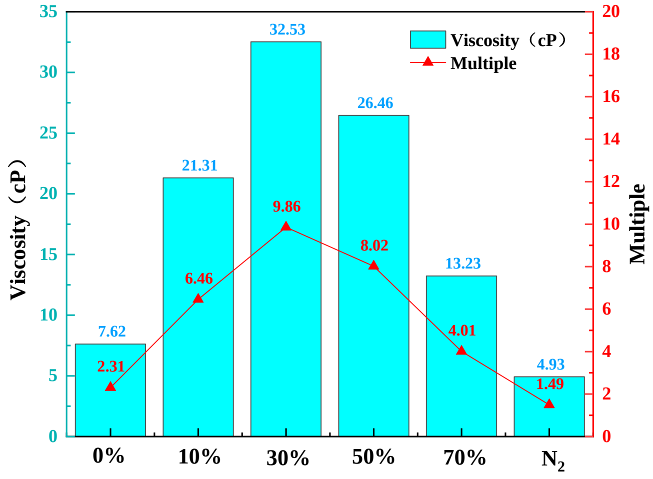

Fig. 4 Viscosity of the fluid after oxidation

（a） （b）

（c）

Fig. 5 Pictures of crude oil before and after oxidation (a) Crude oil;(b)The emulsion formed after crude oil oxidation;(c)The emulsion formed after oxidation of crude oil with 30% water content

3.2 Core displacement experiment

Through static oxidation experiments, it was confirmed that water-containing crude oil forms high-viscosity oil-water mixtures during low-temperature oxidation, especially when subjected to disturbance. Additionally, it was found that the maximum mixture viscosity could be obtained when the water content was 30%. Based on these results, core displacement experiments were conducted to investigate the impact of high-viscosity fluid formation during low-temperature oxidation on enhancing oil recovery. Figure 6 illustrates the variation of injection-production pressure difference with the volume of injected gas under different displacement methods.

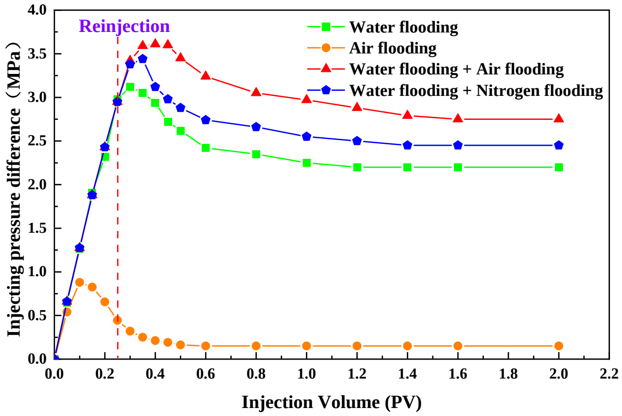

Fig. 6 Pressure differential curves under different displacement methods

The maximum injection-production pressure difference of water flooding reached 3.05 MPa. After the breakthrough of the fluid, the pressure decline trend was relatively gentle, with the injection-production pressure difference reaching 2.21 MPa at the point of water breakthrough. Compared to pure water flooding, water flooding followed by air flooding exhibited a larger injection-production pressure difference. This is because the flow pattern in the core changed from liquid flow to gas-liquid two-phase flow, and the increased viscosity of the mixed fluid of crude oil and water blocked the larger pores, resulting in greater flow resistance. During pure gas injection, the pressure first increased and then decreased as the injection volume increased, with the maximum injection-production pressure difference being 0.88 MPa. When 0.19 PV was injected, the injection pressure began to decrease rapidly, indicating gas breakthrough. After injecting 0.5 PV, gas channels were formed, and the pressure gradually stabilized. Due to the significant difference in mobility, gas easily bypassed through larger pores, resulting in a resistance factor of 0.07 during air injection. Compared to pure gas flooding, water flooding followed by air flooding exhibited a larger injection-production pressure difference. This is attributed to the presence of water, which leads to the formation of heavier components during crude oil oxidation, creating a viscous mixture that blocks pores in larger cavities, thus increasing the injection-production pressure difference by allowing gas to enter smaller pores. Compared to water flooding followed by nitrogen (N_2) flooding, water flooding followed by air flooding showed a slight increase in injection-production pressure difference. This is mainly because nitrogen cannot oxidize crude oil and only acts as a pressure boosting displacement agent. However, during the crude oil oxidation process, the presence of air leads to the formation of heavier components, resulting in localized oil-water mixtures, further increasing flow resistance, with a resistance coefficient of 1.25. The increase in injection-production pressure difference during water flooding followed by N_2 gas flooding is mainly due to the higher resistance of three-phase flow of oil, gas, and water compared to the assistance provided by two-phase flow of oil and water, resulting in a resistance factor of 1.1 at this stage.

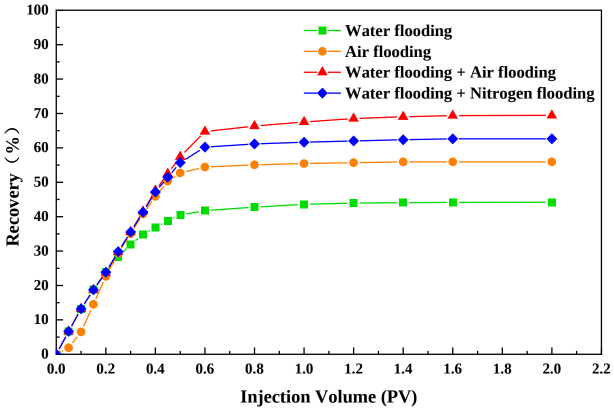

Fig. 7 Recovery rate variation curves under different displacement methods

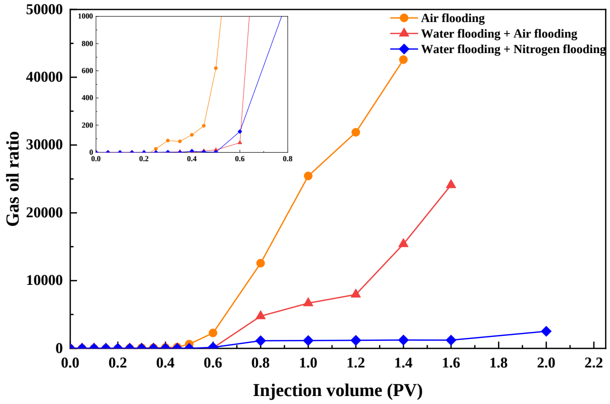

Fig. 8 Gas oil ratio curves under different displacement methods

In low-permeability reservoirs, compared to water flooding alone, subsequent air flooding allows gas to enter smaller pores, expanding the sweep volume and increasing the recovery rate by 25.25%. Air breakthrough occurs at 0.19 PV during air flooding. With increasing injection volume, the gas-oil ratio rapidly increases. Compared to pure gas flooding, water flooding followed by air flooding delays gas breakthrough due to the formation of high-viscosity fluid from crude oil and water, which blocks larger pores. This delay extends the gas sweep, enlarging its coverage and allowing for the mobilization of crude oil in smaller pores, leading to a 13.54% increase in recovery. Additionally, compared to water flooding followed by nitrogen (N_2) gas flooding, the volume of gas breakthrough changes from 0.26 PV to 0.28 PV, and the rate of increase in gas-oil ratio decreases. Injecting air after water flooding allows for low-temperature oxidation of crude oil, resulting in the formation of heavy components that interact with water to form high-viscosity fluid, which blocks larger pores and locally enhances conformance control. This delay in gas breakthrough extends the gas sweep volume.

4. CONCLUSIONS

1. In the high-temperature and high-pressure environment of the reservoir, crude oil undergoes low-temperature oxidation with air, with oxygenation reactions being predominant, resulting in the formation of heavy components that readily interact with water to form high-viscosity mixtures.

2. With increasing water content, the thickening effect exhibits a trend of initial increase followed by decrease. The viscosity of the mixed fluid is maximized at 30% water content, reaching 9.85 times the initial crude oil viscosity.

3. Following water flooding, subsequent air flooding increases the resistance factor and expands the gas

molecule sweep range. As a result, the ultimate recovery rate increases by 25.25%, 13.54%, and 6.83% compared to pure water flooding, gas flooding, and water flooding followed by nitrogen (N_2) flooding, respectively.

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