Energy Proceedings
Vol 55, 2025
ISSN 2004-2965

Effects of Thermal Accumulation Along the Path of Oxygen-Reduced Air Flooding on Pore Utilization Characteristics in Low-Permeability Reservoirs

LI Qihang[1], LI Yiqiang[1], YAN Zhiqian[1], WANG Wenxu[1], CAO Jinxin[1], ZHANG Yaqian[1], TANG Xuechen[1], SONG Tao[1], LIU Zheyu[1]
(1. China University of Petroleum, a. State Key Laboratory of Petroleum Resources and Engineering;
b. School of Petroleum Engineering, Beijing 102249, China)
(LI Yiqiang: yiqiangli@cup.edu.cn)

ABSTRACT

The thermal accumulation caused by low-temperature oxidation(LTO) reactions in the formation significantly impacts the progression of these reactions. To clarify the blocking pattern of pores due to the deposition of heavy components generated by crude oil oxidation during the thermal accumulation process, this study employed serial core displacement and nuclear magnetic resonance (NMR) scanning experiments. It investigated the effect of thermal accumulation on the distribution pattern of residual oil in the core. Additionally, chromatographic experiments were used to explore the degree of crude oil oxidation and the pattern of oxygen consumption along the path under different thermal accumulation conditions. The results of the core displacement experiments show that as the temperature increases, the amount of heavy components produced by oxidation increases, and the degree of oxygen consumption per unit volume of the formation also increases. The oxygen consumption after core displacement is 16.92% at 89℃, 29.78% at 100℃, and 51.2% at 120℃. The results of NMR scanning indicate that the heavy components produced by oxidation can block the dominant airflow channels and increase the gas sweep range. The recovery rates at 89℃, 100℃, and 120℃ are 51.27%, 58.62%, and 59.37%, respectively. The recovery rates for pores smaller than 0.05μm are 0.9%, 0.95%, and 0.96%, while the recovery rates for pores larger than 0.48μm are 47.34%, 53.57%, and 54.29%, respectively. This paper can provide theoretical guidance for improving recovery efficiency through oxygen-reduced air flooding.

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

NONMENCLATURE

Abbreviations	
NMR	Nuclear Magnetic Resonance
LTO	Low-temperature Oxidation
PV	Pore Volume
Symbols	
T2	Transverse Relaxation Time

1. INTRODUCTION

Reduced-oxygen air flooding has been proven to be an effective development method for low permeability field[1-3]. Light oil in the formation undergoes LTO to produce relatively heavier components, resulting in a sealing effect on larger pores[4-6]. At the same time, LTO releases heat[7-8], creating a well-insulated environment in the formation, leading to thermal accumulation along the airflow path, further intensifying the oxidation degree of the crude oil [9-10].

Researchers have conducted extensive research on the reaction characteristics of crude oil LTO. Wang Zhengmao et al.[11] conducted a study on the oxidation characteristics of light oil throughout the entire temperature range during air flooding through simulation experiments. Qi Huan et al.[12] divided the crude oil oxidation process into four stages through static oxidation experiments: light hydrocarbon volatilization, LTO, fuel deposition, and high-temperature oxidation. Pu Wanfen et al.[13] evaluated the LTO of light oil through an oxidation tube experiment. The results showed that during the LTO process, light oil mainly undergoes condensation reactions of light components (C5-C6) and intermediate components (C7-C17), and oxygenation reaction is the main oxidation reaction of LTO. Zhao Shuai et al.[14] believe that compared to light oil, the range of LTO and the corresponding mass loss of medium oil are reduced. More oxygen-containing compounds are converted into coke material. DU Jianfen et al.[15] conducted accelerated calorimetry experiments on air oxidation of Shanshan light oil. They believe that under reservoir temperature and pressure, the oxidation of crude oil can increase the temperature by 8 to 10°C. In a well-insulated environment in actual reservoirs, more intense thermal accumulation can occur. XI Changfeng et al.[16] conducted physical and numerical simulation experiments to study the thermal oxidation front and production dynamic characteristics of light oil reservoirs injected with air. They concluded that the oxidation front of light oil can steadily advance, forming a stable displacement state of thermal oxidation under high-pressure conditions. However, there is currently limited research on the effects of thermal accumulation along the process of reduced-oxygen air flooding on the degree of crude oil oxidation. It is imperative to conduct systematic studies on the oxidation patterns along the airflow path and the utilization degree of reservoir pore spaces.

This study analyzed the impact of thermal accumulation along the reduced-oxygen air flooding process on oxygen consumption through serial core experiments. Additionally, nuclear magnetic resonance scanning experiments were conducted to analyze the sealing impact of the oxidation byproducts of crude oil on the pore spaces, providing insights into the utilization patterns of different pore levels during the thermal accumulation process of deoxygenated air displacement. The research can provide guidance for oilfield development using reduced-oxygen air flooding.

2. SERIAL CORE DISPLACEMENT EXPERIMENTS

2.1 Experimental materials

The experimental oil was taken from a low-permeability oil reservoir, with a density of 0.712g/cm³ and a viscosity of 2.6cP at 25°C, containing 2.14% of colloid and asphaltene. The experimental water was prepared as $MnCl_2$ water with a salinity of 20000mg/L. The gas used in the experiment was 5% air (field gas concentration). The experimental core samples were obtained from the natural cores of the oil field, which were fine sandstone. The natural core was cut into cylindrical cores with a diameter of 2.5cm and a length of 30cm. The core parameters are shown in Table 1.

Table 1 Serial *core displacement experiment core parameters*

Core number	Length (mm)	Diameter (mm)	Water permeability (md)	Porosity(%)	Oil saturation (%)
①	299.25	24.92	5.25	15.47	65.15
②	298.45	24.95	5.43	15.35	64.78
③	299.75	24.87	5.16	15.28	65.23

2.2 Experimental instruments

The experimental instruments include an ISCO pump, valves, flow meters, high-temperature oven, oil-gas-water metering system, long core holder, pressure detection system, data acquisition system, nuclear magnetic resonance scanner, gas chromatograph, various glassware, etc. The diameter and length of the long core displacement device are 2.5cm × 30cm, with maximum pressure and temperature limits of 50MPa and 150°C.

2.3 Experimental scheme

The long core serial experiment is designed with three holders, setting up three temperature groups to simulate the process of heat accumulation along the displacement due to the oxidation of formation crude oil. Each holder is wrapped with a heating band, and the temperatures are set to 89°C, 100°C, and 120°C respectively. Among them, 89°C represents the temperature of the oilfield formation. Considering the well-insulated environment of the formation, the temperatures after the heat release from the reaction between air and crude oil are set to 100°C and 120°C respectively. The experimental pressure is 30MPa (formation pressure). The pressure changes along the path are recorded, and component analysis of the gases and oil samples produced from the three core holders is conducted. Nuclear magnetic resonance scanning is performed before and after displacement on the three cores to record the producing of crude oil in different pores. The flowchart of the serial core displacement instruments is shown in Figure 1.

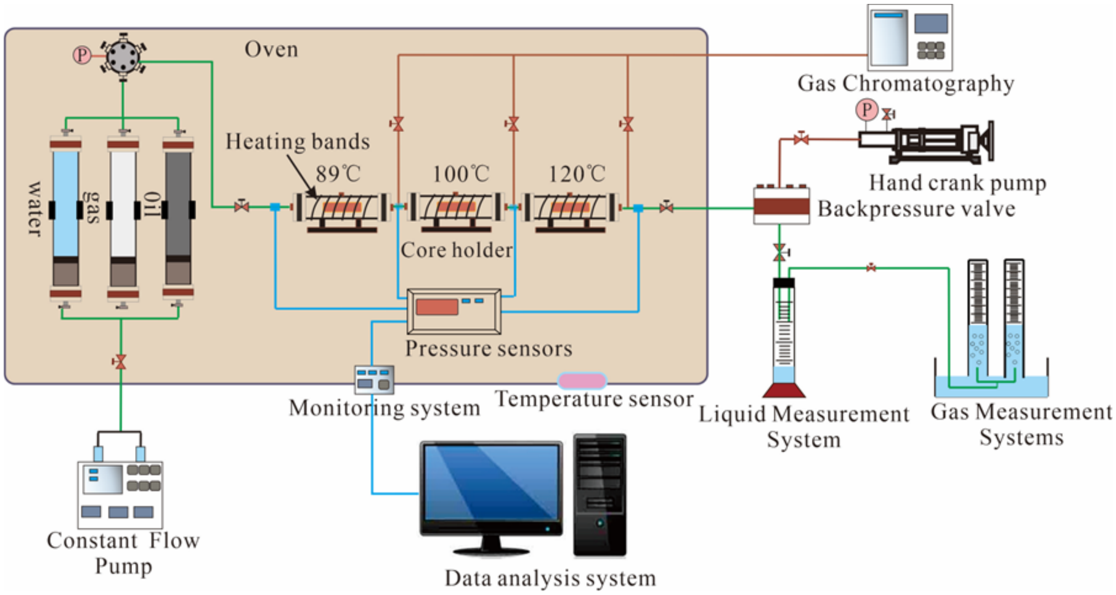


Fig. 1 Serial Core Displacement Experiment Flowchart

2.4 Experimental procedure

Connect relevant experimental equipment, and the specific experimental steps are as follows:

(1) Saturate the core with water: ① Weigh the dry weight of the core; ② Connect the other end of the core holder to the formation water for saturation; ③ Take out the rock core and weigh the wet weight. The difference between the wet weight and dry weight is the pore volume of the rock core.

(2) Measure the water permeability of the core.

(3) Saturate the core with oil and perform NMR scans on each of the three cores. Draw the NMR curves after saturation with oil.

(4) Connect the experimental apparatus and commence the displacement experiment.

(5) Record the changes in oil production, gas production, liquid production, and inlet and outlet pressure with injection volume, and collect the gas and crude oil at the outlet of the three core holders for component analysis.

(6) After the experiment, perform nuclear magnetic resonance scanning on three rock cores.

3. RESULTS AND DISCUSSION

3.1 Analysis of core displacement results

Fig. 2 shows the changes in pressure with the volume of injected gas under both original formation temperature and thermal accumulation conditions.

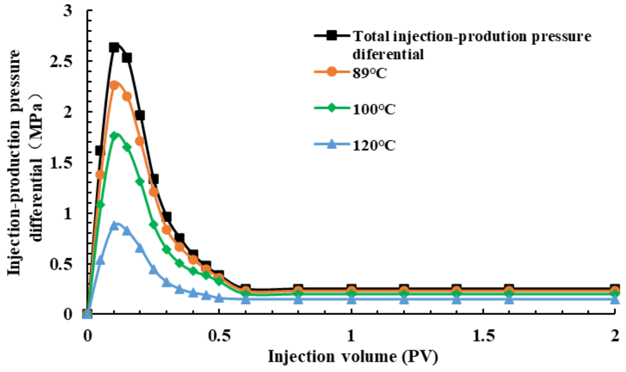


Fig. 2 Displacement pressure curves of core at 89, 100, and 120°C

At 89°C, the oxidation reaction between reduced oxygen air and crude oil is relatively slow, resulting in low oxidation levels, and the pressure difference between injection and production is mainly caused by gas displacement. As the oxidation reaction progresses, the reduced oxygen air carries the released heat towards the production well. At this point, both the gas and the crude oil carry heat, heating the formation to higher temperatures. Simultaneously, the high temperature increases the rate of oxidation reactions, leading to further deepening of the reaction. At 100°C, since the intensity of thermal accumulation is in the initial stage, oxidation reactions mainly involve oxygen addition reaction. Light components further oxidize to form heavy components, resulting in changes in the mobility of the crude oil and an increase in the displacement pressure difference. As the thermal accumulation deepens further, the formation temperature continues to rise, leading to a significant increase in reaction rate, but it still remains in the stage of LTO. At this stage, polar substances generated from crude oil are prone to aggregate and precipitate under the influence of polarity, causing blockage in dominant pores[17]. Consequently, the injection-production pressure difference further increases, mainly due to the precipitation of heavy components generated after crude oil oxidation in the pores.

The resistance factor refers to the ratio of the injection-production pressure difference established at both ends of the rock core to the pressure difference during water injection when the system reaches stability during migration in the rock core. The resistance factors at three temperatures of 89, 100, and 120°C are 0.01, 0.02, and 0.07. At high temperatures, crude oil undergoes more thorough oxidation, resulting in the generation of heavy components that are prone to aggregate and settle. This phenomenon leads to a certain degree of blockage in large pores, increasing the injection-production pressure difference. After displacement at 120°C, the resistance factor is seven times higher than that at formation temperature. This increase in resistance factor, to some extent, acts as a local profile control, making the energy propagation of displacement more uniform.

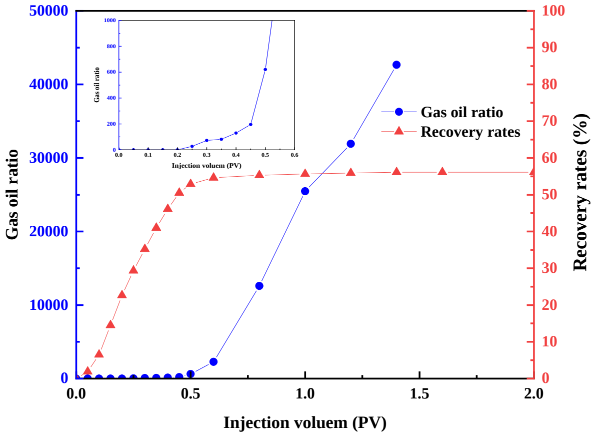


Fig. 3 Recovery rates and production gas oil ratio variation curve

The oil recovery rates and production gas oil ratio during the displacement process vary with the volume of injected gas is shown in Fig. 3. LTO is greatly affected by temperature, while high temperature is beneficial for improving oxygen utilization, strengthening flue gas and heat release. In the displacement experiment, about 0.2PV began to produce gas, at which point the recovery rates was 22.9%. The recovery rates continued to increase until 0.5PV, when the gas oil ratio increased rapidly and the recovery rates increased slowly. This mainly indicates that the reduced-oxygen air flooding process is a non-piston-like displacement. During the displacement process, LTO causes the crude oil to expand, while dissolving some gas. After the gas is produced, a stable recovery can still be maintained for a period of oil recovery stage.

3.2 Analysis of component

Considering the differences in the reaction between oxygen and crude oil in the mainstream channel of reduced-oxygen air flooding with times and positions, based on serial core displacement experiments, the influence of temperatures (89, 100, 120°C) on the efficiency of reduced-oxygen air flooding was studied. Gas samples collected at the nodes of three cores were individually analyzed for their components using a gas chromatograph. The gas composition analysis results from outlet of cores at different temperatures are shown in Fig. 4.

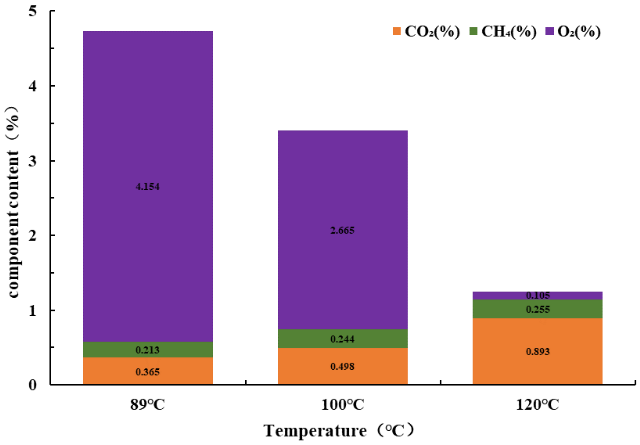
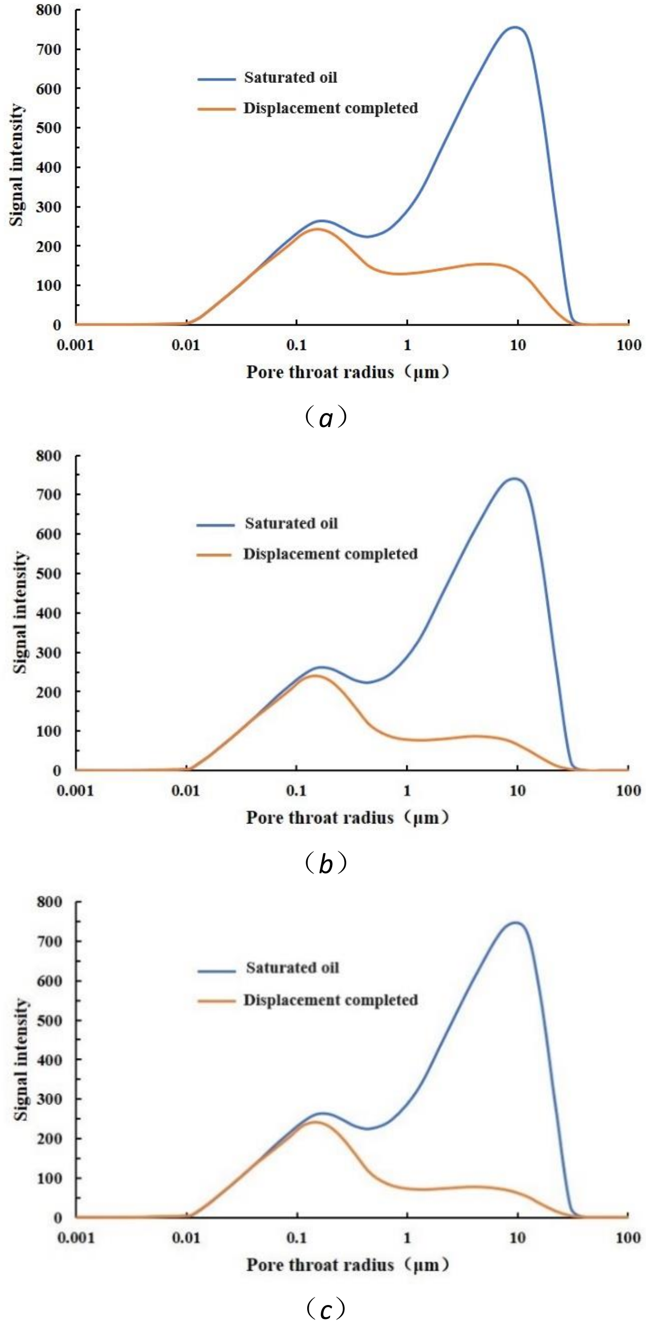


Fig. 4 Gas component content after core displacement at 89°C, 100°C, and 120°C

At 89°C, the degree of LTO is relatively weak, with oxygen consumption at 16.92%, and a small amount of CO_2 produced. The mixed gas carrying heat enters deeper layers of the formation, heating up the formation. At this point, the consumption of oxygen increases to 29.78%, indicating that higher temperatures favor LTO. As the partially oxidized mixed gas enters the 120°C core, further oxidation reactions occur at higher temperatures, deepening the oxidation degree of crude oil, with oxygen consumption reaching 51.2%. The oxygen consumption of crude oil increases with temperature increase in the same duration.

3.3 Analysis of NMR

The area covered by the T_2 curve can indicate the presence of crude oil in different pores. Crude oil mainly exists in pores with diameters ranging from 0.01 to 30μm.



（*a*）

（*b*）

（*c*）

Fig. 5 NMR T_2 spectrum before and after core displacement at 89°C(a), 100°C(b), and 120°C(c)

The decline in NMR signals varies in different pores, which reflects the mobility of crude oil in different pores. By dividing the regions where the two main peaks are located into two productivity zones, with the midpoint depression (0.48μm) as the boundary, and considering pores contributing less than 0.1% to recovery as immobile pores, the contribution of different pores to recovery can be plotted, as shown in Fig. 6. At 89°C, 100°C, and 120°C, the contribution of pores larger than 0.48μm to recovery is 47.34%, 53.57%, and 54.29%, respectively. With increasing temperature, the mobility of crude oil in large pores increases. This is because high temperatures favor deeper LTO and increase the oil swept efficiency of gas. Additionally, at higher temperatures, more heavy components are generated from crude oil oxidation, which can aggregate under polarity, blocking dominant channels and diverting gas flow, thereby increasing the producing degree of pore.

The difference in the producing degree of pore within pores smaller than 0.48μm is smaller compared to large pores. This is mainly because small pores are not the main pathways for gas flow, resulting in less contact between crude oil and oxygen in the air. As a result, the effect of LTO in small pores is minimal, and the producing degree of crude oil in these pores is mainly influenced by gas displacement. At high temperatures, the concentration of CO_2 formed is higher, enhancing the effect of flue gas, thereby increasing the producing degree of crude oil in smaller pores. When pores are smaller than 0.05μm, their contribution to the total recovery is extremely low, and they can be considered as the lower limit of the producing degree of pore for oxygen-depleted air displacement.

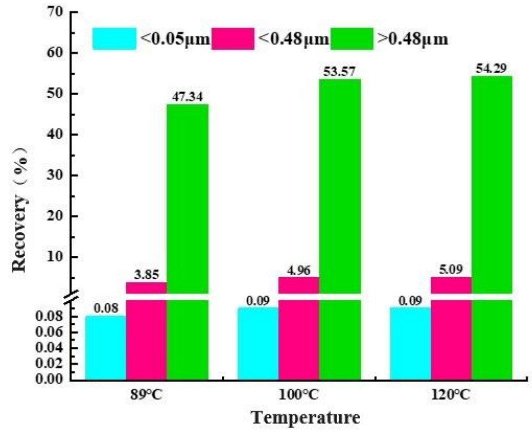


Fig. 6 Histograms of the producing degree of pore throat at different temperatures

4. CONCLUSIONS

1. As the thermal accumulation progresses during the displacement process of the reduced-oxygen air flooding, the degree of crude oil oxidation gradually deepens, leading to an increase in oil swept efficiency and an expansion of the gas coverage range, thereby gradually increasing the recovery rates.

2. As the temperature increases, the oxygen consumption per unit volume of crude oil within the formation increases. At 89°C, oxygen is consumed at a

rate of 16.92%, rising to 29.78% at 100°C, and further to 51.2% at 120°C.

3. During the reduced-oxygen air flooding, the producing degree of pores smaller than 0.05μm is less than 0.1%, while pores larger than 0.48μm contribute significantly to the recovery rates. Moreover, as the temperature increases, the producing degree of pores increases.

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