Study on the EOR experiment and field test of air foam flooding in Wuliwan oilfield

Zhou Jin¹, Yan Wende²*, Yu Guangming¹, Luo Taotao², Duan Wenbiao¹, Fan Wei¹

¹Research Institute of Exploration and Development, Changqing Oilfield Company, Petro China, Xian 710021, Shanxi, China
²Chongqing Key Laboratory of Complex Oil & Gas Fields Exploration and Development, Chongqing University of Science & Technology, Shapingba, Chongqing 401331, China

*Corresponding Author, e-mail: yanwde@163.com

Abstract. In order to solve the problems of oil wells in ZJ53 well area of Wuliwan oilfield, such as premature water breakthrough, rapid rise in water cut, obvious plane conflict, low reserve utilization degree and the difficulty in tapping remaining oil with conventional treatment methods, the laboratory experiment and field test of air foam flooding were performed. The results of laboratory experiment of air foam flooding revealed that the crude oil in Wuliwan oilfield was able to effectively consume oxygen in low temperature oxidation reaction. When the gas/liquid ratio was 1:1~5:1, the oxidation rate was 0.5~6.252×10⁻⁵mol O₂/hr-ml[oil]. After low temperature oxidation reaction, the viscosity of crude oil and the number of long carbon chains increased, but the main peak carbon of crude oil remained unchanged, which was still C10. The foam system with foaming agent of AES and foam stabilizer of HPAM had good foam performance. In the oil displacement experiment of sand pack, when the water cut was close to 100%, the recovery factor could reach 52.8% after water flooding, then it could enhance by 7.4% and 4.9% through foam flooding and subsequent water flooding, respectively. The field test of the ZJ53 well block in Wuliwan District 1 oilfield showed that air foam flooding was able to significantly increase the water absorption thickness of single well, enhance reserve utilization degree of water flooding and improve development effect.

1. Introduction

The main development layer series of ZJ53 well area in Wuliwan District 1 of Jing’an oilfield is Triassic Chang 621. The sandbodies in this area are stably distributed and well connected. They have the typical characteristics of ultra-low permeability oil reservoirs, namely bi-directional seepage of pores and micro-fractures. Before foam flooding was performed, ZJ53 well area was at moderate water cut stage, with integral water cut of 48%, higher than that of Wuliwan District 1 (42.9%). With the extension of development time and the increase in oil recovery degree, the water cut of ZJ53 well area began to rise. In some well groups, water flooding conditions deteriorated, water flooding efficiency decreased, the contradictions between plane and vertical development became prominent and oil production rate was difficult to keep stable.

Air foam flooding technology combines the advantages of both air flooding and foam flooding. It has a wide range of gas sources and is low in cost. It fully utilizes the profile control of foam and oil
displacement of air and can effectively prevent the occurrence of water and gas breakthrough, reduce the water cut of oil wells, increase the production rate of oil wells, improve oil displacement efficiency and enhance recovery factor\textsuperscript{[1-2]}. Currently, this technology has been widely used in low-permeability oil reservoirs, tight oil reservoirs and heavy oil reservoirs\textsuperscript{[3-4]}. The air foam system can change the property of crude oil and consume the oxygen in air through low-temperature oxidation reaction of crude oil in formation. Moreover, the foam system can maintain high apparent viscosity at high temperature and salinity and increase the viscosity of injected fluids\textsuperscript{[5-6]}. For the characteristics of crude oil in Wuliwan oilfield, the properties of air oxidation and foam were evaluated, which could provide a basis for field test of air foam flooding.

2. Low temperature oxidation experiment of the light crude oil in Wuliwan oilfield

2.1 Experimental principle

When crude oil contacts with air over a wide range, if the temperature of reservoir exceeds 300°C, high temperature oxidation (HTO) reaction occurs, otherwise, low temperature oxidation (LTO) reaction occurs\textsuperscript{[7-8]}. Figure 1 shows the low temperature oxidation of the hydrocarbons in crude oil. In the process of chemical reaction, firstly, oxygenation occurs between oxygen atoms and hydrocarbon molecules. As a result, intermediate products, such as carboxylic acids, alcohols, ketones, aldehydes and peroxides are generated. Then the intermediate products are continuously oxidized into a large amount of carbon oxides and water\textsuperscript{[9]}.

\[
\begin{align*}
R + CO & \rightarrow + \frac{1}{2} O_2 \\
R\cdot CO + HO & \rightarrow + \frac{1}{2} O_2 \\
R\cdot CH_3 & \rightarrow R\cdot CH_3OH \\
R\cdot CH_3OH & \rightarrow R\cdot CHO + H_2O \\
R\cdot CO_2H & \rightarrow + \frac{1}{2} O_2 \\
ROH + CO_2 & \rightarrow R\cdot CHO + H_2O \\
\end{align*}
\]

Fig.1. Mechanism of low temperature oxidation of crude oil

2.2 Experimental methods

Firstly, a certain amount of crude oil was put into a full visual high-temperature and high-pressure PVT tester, then air was pumped into reaction vessel according to a designed gas/liquid ratio (mass ratio). The temperature began to keep constant when it increased to a designed value. The PVT volume was adjusted in order to make pressure increase to a designed value. The pressure variation was observed during reaction under the condition of constant volume. After the reaction, the property of crude oil was analyzed by gas chromatograph.

2.3 Experimental results

Under different gas/oil ratios, after 130h’s low temperature oxidation reaction, the pressure, viscosity and reaction velocity of crude oil were recorded, as shown in Table 1. The results indicated that when gas/liquid ratio was in the range of 1:1 to 5:1, oxidation rate of the crude oil in Wuliwan oilfield was 0.5–6.252×10\textsuperscript{-5}mol O2/hr-ml[oil]. With the increase of gas/oil ratio, the concentration of reactants and activated molecules increased due to the increase of oxygen content. Thereby, more and more oxidants were provided for oxidation reaction, which facilitated oxidation reaction and accelerated reaction rate. If a slow oxidation reaction occurred in the formation, with the advance of injected gas, the oxygen concentration of air gradually decreased and tended to be zero, which would prevent
oxygen breakthrough occurring in oil wells, ensure the safety of oxygen injection and avoid the risk of explosion [10]. The technology was quite safe as long as the injection pressure and volume were controlled and the gas content of oil tubing was monitored [11].

Table 1. Low-temperature oxidation experiments under different gas/oil ratios

| Experiment number | Gas/oil ratio | Pressure /MPa | Temperature /℃ | Pressure after reaction/MPa | Viscosity after reaction/ mPa.s | Reaction velocity /10^5mol O2/hr-ml[oil] |
|------------------|---------------|---------------|----------------|----------------------------|-------------------------------|---------------------------------|
| 1                | 1:1           | 12            | 60             | 11.4                       | 8.5                           | 0.500                           |
| 2                | 2:1           | 12            | 60             | 11.1                       | 8.7                           | 1.500                           |
| 3                | 3:1           | 12            | 60             | 10.8                       | 9.8                           | 3.001                           |
| 4                | 4:1           | 12            | 60             | 10.6                       | 10.4                          | 4.668                           |
| 5                | 5:1           | 12            | 60             | 10.5                       | 10.7                          | 6.252                           |

Fig. 2. Group components after crude oil reacting with air under different gas/oil ratios

Fig. 3. Total hydrocarbon gas chromatographic analysis of low temperature oxidation oil samples
After low-temperature oxidation occurred in the crude oil with different gas/oil ratios, the variation of crude oil components was analyzed using chromatographic analysis method. The results revealed that when the pressure was 12MPa and temperature was 60°C, saturated hydrocarbons and aromatics in crude oil reacted with the oxygen in air, forming oxygenated chemicals, which were part of gum or asphaltene. As a result, the content of saturated and aromatic hydrocarbon decreased but the content of gum and asphaltene increased (Figure 2).

Total hydrocarbon gas chromatography was used to analyze the change of total hydrocarbons in crude oil after low-temperature oxidation. The results indicated that because some low-carbon chains in crude oil occurred oxidation and formed long-carbon chains during low-temperature oxidation, the crude oil had lower content of light components and higher content of heavy components, compared with original oil samples (Figure 3). However, the main peak carbon of crude oil remained unchanged after reaction, which was still C10.

3. Experiment of basic foam property

3.1 Raw materials and instruments
The light crude oil was from Wuliwan District 1 of Jing’ an oilfield with viscosity of 7.69mPa.s (50°C) on the ground. The foaming agent was fatty alcohol polyoxyethylene ether sodium sulphate (AES) and the foam stabilizer was polyacrylamide (HPAM).

High-temperature and high-pressure full visual PVT tester was used as reaction vessel, gas chromatograph, Wu Yin stirrer, Brookfield viscometer and displacement device.

3.2 Experimental methods
Simulated formation water (the total salinity was 2910 mg/L and concentration of divalent cation was 275 mg/L) was used to prepare the mixed liquid of foaming agent and foam stabilizer under different concentrations. 100 ml mixed liquid was stirred for 1min at a speed of 6000 rpm/min using Wu Yin stirrer, then it was poured into a 1000ml graduated cylinder, in order to test foam property, observe foam amount and record half-life.

3.3 Experimental results
The foaming capacity and foam half-life of foaming agent are important parameters affecting foam property [12]. The fatty alcohol polyoxyethylene ether sodium sulphate (AES) was used as a foaming agent to test foam property under different concentrations (Figure 4). The experimental results showed that when the effective concentration of foaming agent was less than 0.5%, the foaming volume increased sharply with the increase of concentration of foaming agent. When the concentration was 0.5%~0.8%, the foaming volume decreased with increase of the concentration of foaming agent. When the concentration was 0.5%, the foaming ratio reached to a maximum value of 687% (Q/SY1816-2015 technical specification for the foaming agent of oil flooding required foaming ratio was $\geq 400\%$).

Liquid separation half-life of foam $t_{1/2}$ rapidly increased to a maximum value with increase of the concentration of foaming agent, then decreased slightly and tended to be stable. When the effective concentration of AES was 0.5%, liquid separation half-life of foam was 378s. When the concentration of foaming agent was more than 0.5%, liquid separation half-life of foam $t_{1/2}$ was stabilized at about 380s (Q/SY1816-2015 technical specification for the foaming agent of oil flooding required liquid separation half-life of foam was $\geq 100s$).

Polyacrylamide (HPAM) was used as a foam stabilizer and the AES with a concentration of 0.5% was used as a foaming agent in order to test foam property under different concentrations of foam stabilizer. The results were shown in Figure 5. Because foam stabilizer had a certain viscosity, the volume of foam slightly decreased with concentration increase of the foam stabilizer. When the concentration of foam stabilizer was less than 0.05%, foaming volume slightly decreased with increase of the concentration of foam stabilizer. When the concentration of foam stabilizer was 0.50%~0.1%, foaming volume dropped significantly with increase of the concentration of foam stabilizer, which was...
not advantageous to foam formation. Liquid separation half-life of foam t1/2 rapidly increased to a maximum value with increase of the concentration of foam stabilizer and tended to be stable. When the concentration of AES foaming agent was more than 0.5% and the concentration of HPAM foam stabilizer was 0.05%, liquid separation half-life of foam was stabilized at about 550s. The optimal concentration of foaming agent AES was 0.5% and the optimal concentration of foam stabilizer HPAM was 0.05%.

Fig. 4. Foam property of foaming agents at different concentrations

Fig. 5. Foam property of foam stabilizer at different concentrations

4. Experiment of air foam flooding performance

4.1 Experimental methods
Sand pack model (30mm×600mm) was made using the quartz sand with different meshes. According to experimental procedure, sand pack model was assembled at an experimental temperature of 56°C and pressure of 12.2MPa. After saturating formation water in sand pack (the total salinity was 2910 mg/L and concentration of divalent cation was 275 mg/L), the pore volume, porosity and permeability were calculated, which were 34.50%, 320×10-3um2 and 58.5%, respectively. Water flooding was performed at a certain flow velocity and it ended when integral water cut reached 98~100%. Then air
foam was injected with a slug of 0.25PV at a gas/liquid ratio of 2.5:1. Finally, subsequent water flooding was performed to record liquid volume of outlet and calculate oil recovery factor of the sand pack.

4.2 Analysis of experimental results
According to above experimental method, the relation between oil recovery degree & water cut and injection volume through water flooding, air foam flooding and subsequent water flooding was shown in Figure 6. It was shown that during the process of water flooding, water cut increased rapidly with increase of injection volume. When injection volume reached 2.5 PV, water flooding was terminated and air foam flooding was carried out. When air foam plug was 0.1PV, water cut began to drop rapidly and oil recovery degree increased significantly. After air foam flooding, subsequent water flooding was carried out. As a result, water cut gradually increased and it reached 100% when cumulative injection volume was about 4.5 PV. The recovery factor reached 52.8% at early water flooding stage. Then, it was enhanced by 7.4% through air foam flooding and 4.9% through subsequent water flooding. Therefore, the overall recovery factor could reach 65.1%.

Fig. 6. Variation regularity curve of water cut and oil recovery degree of air foam flooding with injected volume

5. Field test of air foam flooding in Wuliwan oilfield
Based on the results of laboratory experiments, air foam flooding test was performed in the ZJ53 well area of Wuliwan oilfield. In December 2009, 4 well groups in ZJ53 well area of Wuliwan District 1 were selected to implement pilot test. In 2012, the scale of test was expanded. Integral injection of 15 well groups was realized at the end of 2013. Up to 2017, a total volume of 96.4×10^4m³ was injected into test area, including 47.4×10^4m³ foam liquids and 49.0×10^4m³ air. The cumulative injected underground volume was 0.113PV, accounting for 45.15% of designed volume.

The relation curve between water cut and oil recovery degree of test area (Figure 7) indicated that before air foam flooding was performed, water cut rose rapidly, but after air foam flooding was performed, water cut rose slowly and recoverable reserves increased. In the test area, the overall utilization degree of water flooding increased from 60.0% before the test to 61.7% after the test. For the 6 comparable wells, the water absorption thickness increased. The average water absorption thickness of single well increased by 2.55m and the utilization degree of water flooding increased from 59.8% to 77.1%. The condition of water absorption profile had improved (Figure 8). The application results of field test showed that ZJ53 well area in Wuliwan oilfield represented the
characteristics of oil production rate and formation pressure increasing but water cut decreasing. The development effect had been significantly improved and pilot test of air foam flooding had obtained significant effect. For ultra-low permeability oil reservoir, air foam flooding had broad application prospects in stabilizing oil production rate, controlling water cut increasing and tapping remaining oil.

Fig. 7. The relationship curve between water cut and oil recovery degree

Fig. 8. Water absorption profile before and after air foam flooding for Well L76-60

6. Conclusions
(1) In the low-temperature oxidation reaction of crude oil in Wuliwan oilfield, with the increase of gas/oil ratio, the reaction rate was accelerated. When the gas/liquid ratio increased from 1:1 to 5:1, the oxidation rate increased from $0.5 \times 10^{-5}$mol O$_2$/hr-ml[oil] to $6.252 \times 10^{-5}$mol O$_2$/hr-ml[oil], and oxygen could be effectively consumed. After low temperature oxidation reaction, the viscosity of crude oil increased, the content of saturated and aromatic hydrocarbons decreased, the content of gum and asphaltene increased and the number of long carbon chains increased. However, the main peak carbon of crude oil remained unchanged, which was still C10.

(2) The foam system with fatty alcohol polyoxyethylene ether sodium sulphate (AES) as foaming agent (with concentration of 0.5%) and polyacrylamide (HPAM) as foam stabilizer (with concentration of 0.05%) was selected, which had the advantages of large foaming amount and long foam stabilizing time.

(3) Air foam flooding experiment was completed using sand pack physical simulation displacement device in the laboratory. Air foam plug of 0.25 PV was injected with a gas/liquid ratio of 2.5:1. Oil recovery factor could reach 52.8% at early water flooding stage, which was enhanced by 7.4% through
air foam flooding and 4.9% through subsequent water flooding. The total recovery factor reached 65.1%.

(4) Field test in ZJ53 well area of Wuliwan District 1 showed that for the 6 comparable wells, the water absorption thickness increased. The average water absorption thickness of single well increased by 2.55m and the utilization degree of water flooding increased from 59.8% before the test to 77.1% after the test. The condition of water absorption profile had improved and the development effect of test well groups was significantly improved through air foam flooding.

Acknowledgments
Authors wishing to acknowledge assistance of National Natural Science Foundation of China (51574052,51604053), Chongqing Basic Science and Advanced Technology Research Project(cstc2016jcyjA0293), Science and Technology Research Project of Chongqing Municipal Education Committee (KJ1601319), University Innovation Team Project of Chongqing Municipal(CXTDX201601033).

References
[1] Rossen W R, Van Duijn C J, Nguyen Q P et al 2010 Injection strategies to overcome gravity segregation in simultaneous gas and water injection into homogeneous reservoirs. SPE Journal 15(01): 76-90.
[2] Wang H, Chen J 2012 Enhanced flushing of polychlorinated biphenyls contaminated sands using surfactant foam: Effect of partition coefficient and sweep efficiency. Journal of Environmental Sciences 24(7): 1270-1277.
[3] Pang Z, Liu H, Zhu L 2015 A laboratory study of enhancing heavy oil recovery with steam flooding by adding nitrogen foams. Journal of Petroleum Science & Engineering 128:184-193.
[4] Liu P, Zhang X, Wu Y et al 2016 Enhanced oil recovery by air-foam flooding system in tight oil reservoirs: Study on the profile-controlling mechanisms. Journal of Petroleum Science & Engineering 150: 208-216
[5] Yu H, Yang B, Xu G, et al 2008 Air Foam Injection for IOR: from Laboratory to Field Implementation in Zhongyuan Oilfield China. SPE Symposium on Improved Oil Recovery
[6] Xu H X, Pu C S, Shi D H 2011 Research and Application of Air Foam Flooding in Longdong Jurassic Reservoir. Advanced Materials Research 347-353:1615-1620.
[7] Zhang H S, Zheng J P, Zhang L M et al 2014 A laboratory experimental study on air foam flooding in north Gaqian viscous oil reservoir. Oilfield Chemistry 31(04): 527–531
[8] Ren S R, Yu H M, Zuo J L et al 2009 EOR technology of profile control and displacement process by air foam injection in Zhongyuan oilfield. Acta Petrolei Sinica 30(3):413-416.
[9] Long L Q 2013 Experimental study on low-temperature oxidation of crude oil of Lukeqin viscous crude oil air-foam flooding. Master thesis of Chengdu University of Technology
[10] Wu F P, Liu J, Wei X M, et al 2018 A study on oxygen consumption mechanism of air-flooding in low-temperature oil reservoir. Journal of Petroleum Science & Engineering 161:368-380
[11] Lv X, Yue X A, Wu Y C et al 2005. Safety analysis of enhancing oil recovery by air-foam flooding. Petroleum Geology and Recovery Efficiency 12(5): 44-46.
[12] Yang H J, Ding Y J, Sun L et al 2012 Research on temperature resist air foam system for flooding. Journal of Southwest Petroleum University (Science & Technology Edition) 34(5): 93-98.