Study on air foam flooding technology to enhance oil recovery of complex fault block reservoir by water injection

Huaizhu Liu *, mingbang Tian, Baocai Xie, Renbao Chen
Jidong Oilfield, Petro China, Tangshan, Hebei, 063200, China

*Corresponding author e-mail: Huaizhu@petrochina.com.cn

Abstract. In order to solve the problem of rapid increase in water content and decrease in production after water flooding in fault block reservoirs, the air foam flooding experiments of static low temperature oxidation, single and double sand filled tube were carried out. The results showed that there was no absolute relationship between oxygen consumption and viscosity of crude oil, and there was a turning point of water saturation. The reaction rate is greatly affected by the reaction temperature. The displacement efficiency of single pipe is increased about 15%. The injection of air foam can effectively block the high permeable strip, and the middle low permeability layer is effectively utilized, and the recovery ratio is increased by about 10.9%. The plan of air foam flooding for Gao 16 block is compiled. The injection volume is 0.1PV and the gas-liquid ratio is 2:1. The recovery factor is increased by 5% and the cumulative oil increment is 22700 tons.

Key words: complex fault block reservoir; air foam; low temperature oxidation; oil displacement efficiency; enhanced oil recovery.

Jidong Oilfield is characterized by small fault block, sufficient edge and bottom water energy, high porosity and permeability, loose cementation and easy sand production during oil production. The sand bodies are distributed in "lump" and "potato" shape; the oil layers are numerous and thin, which is a typical complex fault block reservoir in Bohai Bay basin. With the development of oilfield, the water cut of the oilfield is gradually increasing, and speed of the production decline is speeding up, which brings great difficulties to increase oil production. How to further improve the recovery of this type of reservoir is facing great challenges. When air foam enters porous media, it can not only play the role of low temperature oxidation characteristics of air, but also play a dual role of flue gas drive and thermal effect to improve mobility ratio of oil - water. In addition, the Jia Min effect of foam can be used to block some large channels to increase the sweep volume of air. Low temperature oxidation characteristics of oil are used to achieve the purpose of improving reservoir recovery [1-8]. Indoor low temperature oxidation experiments and flooding experiments of single tube and double tube were carried out to study the air foam flooding enhanced oil recovery technology of complex block reservoirs.
1. Experiment

1.1. Experimental materials
The experimental oil comes from G104-5, G76 and G16 fault block. The oil sample A is ordinary heavy oil, and the oil samples B and C are light crude oil. The physical property parameters of the three oil samples are shown in Table 1. The salinity of formation water is 1647 mg / L.

| oil sample | Density (g/ml) | Temperature (℃) | freezing point (℃) | Viscosity (mPa·s) | saturated hydrocarbon content (%) | aromatic hydrocarbon content (%) | resin content (%) | asphaltene content (%) |
|------------|----------------|-----------------|-------------------|------------------|----------------------------------|-------------------------------|-------------------|---------------------|
| A          | 0.91           | 65              | -6                | 74               | 53.16                            | 27.41                        | 18.07             | 1.36                |
| B          | 0.83           | 100             | 31                | 0.5              | 77.06                            | 13.47                        | 7.73              | 1.76                |
| C          | 0.87           | 120             | 33                | 1.5              | 66.88                            | 17.6                         | 11.83             | 3.69                |

1.2. Experimental equipment
High pressure air bottle (15MPa), high pressure intermediate vessel (50MPa), ISCO pump, reactor, incubator, hand pump, sand filled pipe, and gas detector.

1.3. Experimental steps
1.3.1. Static low temperature oxidation experiment. (1) The oil sands with oil saturation of 25%, 50%, 75%, 90% and 95% are prepared with 100-120 quartz sands.
(2) After aging, these sands are loaded into the reactor.
(3) Raise the temperature to the reservoir temperature, open the air bottle, inject high-pressure air into the reactor, and observe the change of pressure with reaction time until the pressure is stable. According to the pressure drop data and the gas content data measured after the reaction, the oxygen consumption effect of crude oil can be judged. The specific experimental device is shown in Figure 1.
1.3.2. Air foam flooding experiment of single tube. (1) The 120-160 mesh quartz sand is loaded into the sand filling pipe and the gas permeability is measured;

(2) The foaming solution which its concentration was 0.5% was prepared and put into the intermediate container. The other intermediate container was filled with air which its pressure was 20MPa;

(3) Saturated water and oil with the rate of 2ml / min;

(4) Raise the temperature of the incubator to the formation temperature, set the back pressure to 20MPa, and inject high-pressure air and foaming solution (gas-liquid ratio is 2:1 under high pressure) into the sand filling pipe at the speed of 1ml / min and 0.5ml/min respectively. Record the pressure changes at the inlet and outlet ends of the sand filling pipe, the liquid production at the outlet end, and the composition changes of the produced gas to 98% water content (gas composition at the outlet end) The displacement is stopped.

1.3.3. Dual tube air foam flooding experiment. (1) The quartz sand with a certain mesh number (40-70 mesh, 120-160 mesh) is loaded into the sand filling pipe for sand filling, and the gas permeability is measured to ensure that the permeability difference between the two pipes is between 3-5;

(2) The foaming agent solution with the concentration of 0.5% was prepared and put into the intermediate container. The other intermediate container was filled with 20MPa air;

(3) Saturated water and oil at the rate of 2ml / min;

(4) The temperature of the thermostat was heated to the formation temperature, the backpressure is set to 20MPa, and the water displacement was carried out at the speed of 1mL/min. When the water cut of the outlet reached 98%, the air foam slug was injected into the sand pipe , and the high-pressure air and foaming agent solution which the ratio of gas to liquid was 2:1 were injected into the sand filling pipe at the speed of 1ml/min and 0.5ml/min respectively, and the inlet and outlet pressure of the sand pipe during the displacement process were recorded. When the water cut was 98% (the gas component at the outlet is no longer changed), the displacement was stopped.

2. Results and analysis

2.1. Static low temperature oxidation experiment

2.1.1. Modification of reaction model. The Arrhenius equation can be used to describe the low temperature oxidation reaction process, and the reaction rate expressed is mainly a function of temperature, oxygen partial pressure and oil saturation.

\[
\frac{dp_s}{dt} = k_0 e^{-\frac{E}{RT}} [P_x]^{m} [S_{oi}]^{n}
\]  

Among them, \(k_0\), E/R, m and N were reaction kinetic parameters, which were related to reservoir and fluid physical properties, \(P_x\) was oxygen partial pressure and \(S_{oi}\) was oil saturation. Ren [9] and others found that the partial pressure of oxygen had little effect on the oxidation reaction rate in the case of excessive oil saturation (> 10%), and the pressure index m was 0. The experiment of low temperature oxidation reaction under different saturations mentioned above was needed to determine the saturation index n. The logarithm of equation (1) is obtained.

\[
\ln \frac{dp_s}{dt} = \ln k_0 - \frac{E}{RT} + n \ln S_{oi}
\]
Because the experiment is carried out under the same temperature and different water saturation, for
the same kind of crude oil, the relationship between \( \frac{dp}{dt} \) and \( \ln S_{oi} \) in equation (2) was linear, and
the slope was the saturation index \( n \).

Considering the influence of low-temperature oxidation reaction on the composition of crude oil, the
contents of saturated hydrocarbon, aromatic hydrocarbon, colloid and asphaltene in three kinds of oil
samples which their water cut were 25% were measured. The results were shown in Table 2.

| Oil sample | Saturated hydrocarbon/% | Aromatic hydrocarbon/% | colloid/% | Asphaltene/% |
|------------|-------------------------|------------------------|-----------|-------------|
| A before reaction | 53.14 | 27.43 | 18.09 | 1.34 |
| A after reaction | 54.61 | 20.53 | 19.77 | 3.09 |
| B before reaction | 77.05 | 13.47 | 7.75 | 1.73 |
| B after reaction | 77.63 | 10.79 | 9.51 | 2.07 |
| C before reaction | 66.86 | 17.61 | 11.85 | 3.68 |
| C after reaction | 67.95 | 10.86 | 15.62 | 5.57 |

Table 2. Content results of oil samples before and after reaction

It can be seen from table 1 that the saturated hydrocarbon content of the crude oil after the reaction
was basically unchanged, the aromatics were reduced, the colloid and asphaltene were slightly increased,
and the aromatic hydrocarbon components in the crude oil were mainly involved in the reaction.
Therefore, the oil saturation parameter can not be simply used to measure the influence of the content
of reactants on the low-temperature oxidation reaction, so the Arrhenius equation can be improved as follows:

\[
\frac{dp}{dt} = k_0 e^{-E/RT} \left[ p_A \right]^n \left[ C_A(t)/C_f(t) \right]^n
\]

In formula (3), \( C_A(t) \) was the concentration of reactants participating in low temperature oxidation
which was mainly aromatic hydrocarbons, and \( C_f(t) \) was the concentration of reaction inhibitors
which mainly were colloids and asphaltenes.

Make \( \frac{C_A(t)}{C_f(t)} = M \), with the decrease of \( C_A(t) \) and increase of \( C_f(t) \), \( M \) was decreased. The
\( M \) values of oil samples A,B and C were respectively 0.1112, 0.1407 and 0.1621, which shown that oil
sample C had a strong ability to participate in low temperature oxidation reaction.

2.1.2. Oxygen consumption of different oil samples under conditions of different water cut. The results
of static low-temperature oxidation experiment were shown in Fig. 2-fig. 5, which shown that there was
no direct correlation between oxygen consumption and crude oil viscosity. Oil sample A with higher
viscosity had the best oxygen consumption under the condition of low water cut (less than 30%), because
of its high aromatic hydrocarbon content and high activity. However, the reservoir temperature is only
65 \(^\circ\)C. With the increase of water cut, the accelerating effect of water on low temperature oxidation
became smaller and smaller, while the cooling effect became larger and larger, and the oxygen
consumption dropped sharply. The oxygen consumption and pressure of oil sample C with moderate
aromatic hydrocarbon content and reservoir temperature which was 120 \(^\circ\)C changed gently with water
saturation, but when the water cut was higher than 75%, the oil sample can not maintain low-temperature
oxidation reaction, and the oxygen consumption effect gradually became worse. The results shown that
the oil sample B with the smallest aromatic hydrocarbon content and viscosity had the worst oxygen
consumption effect, and the pressure drop of the reactor was mainly concentrated in the early stage,
which was due to the reaction of aromatic hydrocarbons with higher activity happened in the early stage.
Fig. 2 Experimental results under different water cut conditions of oil sample A

Fig. 3 Experimental results under different water cut conditions of oil sample B

Fig. 4 Experimental results under different water cut conditions of oil sample C

Fig. 5 Relationship between oxygen consumption and water saturation of different oil samples
2.2. **Single tube air foam flooding experiment**

The results of static low-temperature oxidation experiment show that the oxidation effect of oil a and oil C is better than that of oil B. Single tube air foam flooding experiment was carried out using oil sample A and oil sample C. The experimental results were shown in Figure 6.

The experimental results of single tube air foam flooding with different oil samples were shown in Figure 6. Under the condition which water cut was 25%, the displacement efficiency of oil sample A was 40.6%, and that of oil sample C was 65.8%; under the condition which water cut was 50%, the displacement efficiency of oil sample A was 28%, and that of oil sample C was 33%. The displacement efficiency of oil sample A was obviously higher than that of oil sample C. It was the reason which oil sample A had low viscosity and high reservoir temperature, and light oil reservoir was more suitable for air foam flooding. With the increase of water cut of crude oil, the displacement efficiency of air foam flooding was decreasing. Therefore, in the process of reservoir development, under the premise of economic conditions, it was suggested that adopting air foam flooding at medium and high water cut stage could greatly improve oil displacement efficiency and raise the final recovery greatly.

![Fig. 6](image_url)

**Fig. 6** Experiment of single tube air foam flooding with different oil samples

2.3. **Double tube air foam flooding experiment**

The physical parameters of sand filling pipe used in the experiment were shown in Table 3. The experimental results of single tube air foam flooding shown that the displacement effect of light oil sample C was better than that of oil sample A. Double tube air foam flooding experiment of oil sample C was carried out. The final experimental results were shown in Figure 7.

![Fig. 7](image_url)

**Fig. 7** Experimental curves of double tube air foam flooding of oil sample C
Table 3. Physical parameters of sand filling pipe

| number | Quartz sand | Porosity (%) | Permeability (10^{-3} μm²) | Original oil saturation (%) | Irreducible water saturation (%) |
|--------|-------------|--------------|-----------------------------|-----------------------------|----------------------------------|
| G1     | 40-70       | 43.9         | 4678                        | 82.1                        | 17.9                             |
| D1     | 120-160     | 38.5         | 1642                        | 84.3                        | 15.7                             |

The pressure difference of the air foam flooding in the initial stage was larger. Oil was produced by the high and low permeability sand pipes. The liquid production rate of the high permeability sand pipe was faster than that of the low permeability sand pipe. With the water flooding, the water breakthrough channel gradually appeared, the pressure difference slowly decreased, and the liquid production of the low permeability pipe was very few. When the water cut increased to 98% (about 0.8PV), the air foam which its volume was 0.1PV was injected. The foam plugged the water breakthrough channel in the high permeability sand pipe, and the pressure difference increased. At the same time, the water cut of high permeability sand pipe was slightly reduced, which made the oil production gradually increased in the low permeability pipe. Then water flooding was carried out, and when the water cut increased to 98%, the air foam which its volume was 0.1PV was injected again, air foam slugs were repeatedly injected for third time. After injecting three slugs, the displacement efficiency of low permeability sand pipe was 28.2%, which increased by 18%. The oil displacement efficiency of high permeability sand pipe was 57.8% which increased by 4.6%, and the total oil displacement efficiency was increased by 10.9%. After three air foam slugs were injected, the displacement pressure difference increased. However, the difference of pressure difference between the second and third slugs was smaller than that of the first slug, because the plugging ability of the foam to the water breakthrough channel was gradually weakened during the injection of second and third slugs, and the increase of pressure difference was limited.

3. Conclusion

(1) In view of the complex fault block reservoir the Arrhenius correction model and the index which was reflected the continuous ability of crude oil participating in low temperature oxidation reaction were established. The index value of oil sample C was 0.1621, which shown that it had strong continuous ability to participate in low temperature oxidation reaction.

(2) There was no absolute relationship between the oxidation property of oil sample and its viscosity. The viscosity of oil sample A was larger, but it was easier to consume oxygen under the condition of low water cut; the oxygen consumption performance of oil sample C was better, and the water cut at the inflection point of oxygen consumption was 75%. When the water cut of reservoir was higher than this saturation, the oxygen consumption was poor.

(3) Under the condition of high water cut, the air foam slug could be used to plug the water breakthrough channel. The pressure difference of the sand pipe increased, the low permeability pipe was activated, the efficiency was increased, and the total oil displacement efficiency was increased by 10.9%. However, due to the existence of the gas / water breakthrough channel, the plugging capacity of the air foam was weakened, and the oil displacement of subsequent two slugs was poor.

References

[1] TERAMOTO T, UEMATSU H, TAKABAYASHI K, etal. Air-injection EOR in highly water saturated light oil reservoir [R]. SPE 100215, 2006.

[2] Shang Linlin. Experimental Study on Improving Oil Displacement Efficiency by Air Foam Flooding in Tight Oil Layer [J]. IOP Conference Series: Earth and Environmental Science, 2021, 651(3).

[3] Cheng T., Dang Y.B., Hu F.T., Jia Z.W., Niu Z., Hu B., Zhang H.L. Study on aerobic corrosion characteristics of gas injection pipe wall in oil field under dry / wet interaction condition [J]. IOP Conference Series: Earth and Environmental Science, 2021, 647(1).

[4] Li Zhaoguo, Yan Wende, Zhou Jin, Yuan Yingzhong, Zeng Shan, Fan wei. Numerical simulation
of air–foam flooding in Wuliwan District 1 of Jing’an Oilfield [J]. Journal of Petroleum Exploration and Production Technology, 2019, 9(2).

[5] Guo Donghong, Cui Xiaodong, Yang Xiaopeng. Preparation and Properties of Foaming Agent for Air Foam Flooding [J]. International Journal of Petroleum Technology, 2019.

[6] Xiaohui Qiu, Wen Zhai, Hua Ming, Yandong Chen, Hui Chen, Wanyi Lv. Exploration of Air Foam Oxygen Reduction Fracturing Technology [J]. IOP Conference Series: Earth and Environmental Science, 2018, 199(3).

[7] Zhou Jin, Yan Wende, Yu Guangming, Luo Taotao, Duan Wenbiao, Fan Wei. Study on the EOR experiment and field test of air foam flooding in Wuliwan oilfield [J]. IOP Conference Series: Earth and Environmental Science, 2018, 186(4).

[8] Shuai Hua, Yifei Liu, Qinfeng Di, Yichong Chen, Feng Ye. Experimental study of air foam flow in sand pack core for enhanced oil recovery [J]. Journal of Petroleum Science and Engineering, 2015, 135.

[9] Chunsheng Pu, Liming Zheng, Jing Liu, Jiaxiang Xu. Performance of Air Foam Flooding under Low Frequency Vibration [J]. Journal of Petroleum Science and Technology, 2015, 5(1).

[10] Jin Yang Xie, Lin Sun, Wan Fen Pu, Fa Yang Jin, Song He. Physical Simulation Experiment Research of Air Foam Flooding in Da Gang Oilfield [J]. Advanced Materials Research, 2015, 3702.

[11] Ping Yuan. Reservoir Simulation Study on Air-Foam Flooding to Enhance Oil Recovery in Waterflooding Sandstone Reservoir [J]. Advanced Materials Research, 2014, 3246.

[12] Hong Xing Xu, Chun Sheng Pu, Dao Han Shi. Research and Application of Air Foam Flooding in Longdong Jurassic Reservoir [J]. Advanced Materials Research, 2012, 1477.