Experimental Study on Improving Oil Displacement Efficiency by Air Foam Flooding in Tight Oil Layer

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Abstract. The tight oil layer is poor in physical property, small pore throat radius, serious heterogeneity of reservoir, low flooding efficiency, poor water flooding efficiency and final recovery is lower than 10%. In order to further improve the oil displacement yield and simulate the conditions of oil layer, we have carried out the experiment of air foam liquid system to flooding oil, and studied the rule of improving the displacement efficiency of air tight foam reservoir. The experimental results show that the density of Gaotaizi water flooding ultimate oil displacement efficiency is 48.95% on average, after water flooding to air - foam flooding alternating final displacement efficiency is high up 79.63%, the oil displacement efficiency can be increased by 26.92%; a short alternately displacement than the big slug is better, the gas-liquid ratio is too high, the breakthrough time of change in short, flooding effect, direct air - foam liquid slug can achieve good flooding effect. That air foam flooding can improve the oil displacement efficiency of dense oil after water flooding by air - foam liquid slug, gas-liquid ratio, cycle injection parameter optimization, to further improve the dense oil displacement effect, the results of air foam flooding field test has the reference and guiding significance for the tight reservoir.

Keywords: Tight oil layer, Air foam, Slug, Oil displacement efficiency.

1. Introduction
The physical properties of tight reservoirs are poor, and the air permeability is usually less than $10^{-3}$ μm². In the development process, the output of single well is low, the output declines rapidly, the water injection effect is poor, the oil displacement efficiency is low, and the degree of water flooding is low [1-6]. A large number of CO₂ flooding, active water flooding and air foam flooding tests have been carried out for tight oil development both at home and abroad. Due to the lack of domestic CO₂ flooding gas source, high cost, and single CO₂ flooding is prone to gas channeling [7-9].

Gaotaizi reservoir in Longhupao Oilfield around Daqing belongs to ultra-low porosity and low permeability reservoir, mainly composed of siltstone, containing 20% ~ 37% of Shi Ying, 23% ~ 41% of feldspar and 14% ~ 35% of cuttings. Composition maturity and structure maturity are both low [10]. The displacement pressure of core mercury injection experiment in Gaotaizi reservoir is 10 ~ 25 MPa, and the water injection pressure is high during reservoir displacement and development, which makes it difficult to inject water. The average pore throat radius is 1.176 μm, the average pore median radius
is 0.0737 μm, and the exit efficiency is 21.5 ~ 61.6%. The pore types of Gaotaizi reservoir are mainly intergranular pores, followed by dissolution pores and a large number of micropores. The porosity of intergranular pores is 9.2%~16.8%, with an average of 11.9%, and the permeability is 0.1×10^{-3}~1×10^{-3} μm^2, with an average of 0.6×10^{-3} μm^2. The density of formation crude oil is 0.7414 g / cm^3, viscosity is 1.45 MPa · s, volume coefficient is 1.23, original gas oil ratio is 67.75 m^3 / m^3, and original saturation pressure is 8.9 MPa. Since February 1998, 300 m square well pattern and synchronous water injection have been used in the development. At the initial stage of production, the average daily oil production of a single well is 1.13 T, but the production decreases rapidly and the effect of water injection is poor. The average daily oil production of a single well decreases by 0.46 t in the fifth year and 0.32 t in the tenth year. At present, low production and low efficiency wells account for more than 80%, and shutdown wells account for more than 40%. It is predicted that the actual water flooding recovery rate is less than 12%, so new development methods are urgently needed to improve the development effect. In this paper, the air foam liquid flooding experiment was carried out in the tight oil reservoir of the high Taizi reservoir. The effects of air and foam injection volume and slug combination on the oil displacement efficiency were studied.

2. Experimental part

2.1. Materials and instruments

Crude oil is simulated oil prepared by adding kerosene after dehydration and filtration of crude oil in Gaotaizi reservoir according to the viscosity of formation oil. The foaming agent is chemical agent BH-4 provided by Daqing Oilfield. The simulated formation water is NaHCO₃ type with salinity of 5804.4 mg/L, and the water type is NaHCO₃ type. Natural core, interval 2011.5 ~ 2024.2 m, core parameters are shown in Table 1.

| Core No. | Depth/ m | Length/ cm | Diameter/cm |
|----------|----------|------------|-------------|
| 1#       | 2011.5   | 6.45       | 2.51        |
| 2#       | 2011.5   | 5.85       | 2.54        |
| 3#       | 2011.5   | 5.50       | 2.52        |
| 4#       | 2024.2   | 7.10       | 2.53        |

ISCO pump, incubator, core holder, pressure sensor, differential pressure sensor and piston container, etc.

2.2. Core displacement experiment

(1) After the natural core is extracted and dried, the permeability of the core is measured by air, and the core model is saturated with formation water to determine the porosity. (2) The irreducible water saturation is calculated by saturating the core with oil and driving water until there is no water flowing out from the core outlet. (3) After the injection pressure is adjusted to the displacement pressure, the prepared water is injected into the core by constant pressure method for water displacement experiment until no oil flows out of the core outlet. The displacement pressure difference, displacement oil and water volume and cumulative water injection volume are recorded. (4) During foam flooding, inject gas and foam liquid at a certain pressure into the core according to the designed slug for displacement until no oil flows out of the core outlet, and measure the displacement pressure difference, the oil displacement, the volume of water, and the cumulative water injection volume. And total recovery factor. The experiment temperature is 80°C. The displacement media are underground crude oil, simulated formation water, simulated surface water, and 0.5% BH-4 foam fluid prepared from simulated surface water in the Gaotaizi oil layer of Longhupao Oilfield.
Table 2. Statistical table of performance parameters of experimental displacement media

| Fluid               | Experimental temperature (°C) | Density (g/cm³) | Viscosity (mPa.S) |
|---------------------|-------------------------------|----------------|-------------------|
| Surface crude oil   | 20                            | 0.85           | 15.83             |
| Formation crude oil | 80                            | 0.741          | 1.45              |
| Simulated formation water | 80                        | 1.030          | 0.898             |
| Surface water       | 80                            | 0.997          | 0.824             |
| Foam liquid 0.5%BH-4| 80                            | 0.997          | 0.865             |

3. Results and discussion

3.1. Water flooding

It can be seen from the water flooding results of cores 1 ~ 3 (Table 3, Figure 1) that the average initial oil saturation of cores is 65.46%, the average oil displacement efficiency during waterless period is 34.69%, the average final oil displacement efficiency is 48.95%, and the residual oil saturation at the end of water flooding is between 30.55% and 34.8%, with an average of 32.18%. The oil production in waterless period accounts for 70.87% of the total oil production in water flooding, and the crude oil is mainly produced in waterless period; the water cut increases rapidly after water breakthrough in water flooding, and the oil displacement efficiency increases slowly.

Table 3. Core water flooding test results*

| Core No. | Gas permeability (10⁻³ μm²) | Core porosity (%) | Core irreducible water saturation difference MPa | Final oil displacement efficiency in waterless period (%) | Oil displacement efficiency when the water content is 98% | Injection quantity/ PV | Finally Oil displacement efficiency (%) | Injection quantity/ PV |
|----------|------------------------------|-------------------|-----------------------------------------------|--------------------------------------------------------|-------------------------------------------------------|------------------------|----------------------------------------|------------------------|
| 1#       | 0.803                        | 10.23             | 9.54                                          | 34.6                                                   | 33.26                                                 | 42.26                  | 1.42                                   | 45.00                  | 3.20                                 |
| 2#       | 0.902                        | 10.77             | 16.58                                         | 32.3                                                   | 30.55                                                 | 48.14                  | 1.65                                   | 52.33                  | 3.40                                 |
| 3#       | 0.211                        | 8.97              | 18.33                                         | 36.7                                                   | 34.80                                                 | 44.76                  | 1.05                                   | 49.52                  | 1.35                                 |

*The experimental temperature is 80°C.

Figure 1. The relationship between core water flooding oil displacement efficiency and injection volume
3.2. Foam flooding

3.2.1. Alternate displacement of oil by small slug air and foam liquid. 2# core is first displaced with water to 100% water cut, and then alternately displaced with air and foam liquid according to the ratio of gas to liquid =1:1. The displacement volume of foam liquid in each section is 0.04 PV, and when the continuous slug is alternately displaced until the water cut is stable, it turns into water flooding of about 2.5 PV. It can be seen from the data in Figure 2 and Table 4 that the ultimate oil displacement efficiency of the air-foam alternative displacement experiment is 79.63%, and the oil displacement efficiency is improved by 26.92% on the basis of water flooding.

![Figure 2](image)

**Figure 2.** The relationship between the injection volume of the small slug air-foam liquid alternate displacement and the displacement efficiency

3.2.2. Different amount of air-foam liquid slug flooding. Water flooding the 3# core to 100% water cut, and then carry out slug displacement with different amounts of air-foam liquid. In the first stage, one slug is displaced, the displacement amount is 0.16 PV air +0.08 PV foam liquid, the total amount is 0.24 PV, and then the water is floodingn to 100% water cut. In the second stage, four slugs (0.04 PV air +0.02 PV foam liquid) were displaced, with a total displacement of 0.24 PV, and water flooding was continued until the water cut was 100%. It can be seen from the data in Figure 3 and Table 4 that the oil displacement efficiency of single large slug air-foam displacement is 5.57% higher than that of water flooding. On this basis, the oil displacement efficiency is greatly improved by continuing to use the air-foam liquid displacement of small slug, which is also used to displace the 0.24 PV air-foam liquid slug, and the air-foam liquid of small slug can improve the oil displacement efficiency by 15.3%. It shows that air and foam with single large slug can't give full play to foam flooding, but the viscosity of air-foam system formed by alternate displacement with small slug decreases with the increase of shear rate, which has a high viscosity in large pores and a low viscosity in small pores, and plays the role of blocking large pores but not small ones, thus improving oil displacement efficiency.
3.2.3. **Long slug air-foam liquid slug flooding.** 1# core is water-driven to 100% water cut, then 4 slugs are displaced, and finally water injection is carried out. It can be seen from the data in Figure 4 and Table 4 that long slug air-foam displacement improves oil displacement efficiency by 19.71%, which is about 7% lower than that of short slug displacement. It is obvious that the slug is too large and the gas-liquid ratio is too high. The oil displacement effect is more close to single gas flooding and single foam flooding. It can not give full play to the role of air foam system in blocking up, blocking water and plugging oil.

**Figure 3.** The relationship between the injection volume of different amounts of air-foam liquid flooding and the oil displacement efficiency

3.2.4. **Influence of gas-liquid ratio on oil displacement efficiency.** In order to optimize the gas-liquid ratio, displacement experiments were carried out on 2# core according to the gas-liquid ratios of 1:1, 3:1 and 5:1 respectively. After the core is saturated with oil, it is floodingn by water until the water cut reaches 100%, and then it is floodingn by foam liquid-air. From the displacement effect (Figure 5), the displacement effects of three gas-liquid ratio slugs are all good, among which the displacement efficiency is slightly higher than 3:1 when the gas-liquid ratio is 1:1, and the displacement efficiency is quick when the gas-liquid ratio is 5:1. It shows that the higher the gas-liquid ratio is, the earlier the gas
channeling time is, and the oil displacement efficiency is relatively low. The lower the gas-liquid ratio is, the later the displacement effect is. In actual injection, the gas-liquid ratio should be optimized according to different reservoir structures.

3.2.5. Air-foam anhydrous hybrid flooding. While displacing air and foam to 4# core, the displacement pressure rises rapidly. Under the average displacement speed of 0.0012 mL/min, the pressure rises to 25.1 MPa after only displacing 0.13pv. Because the flooding can't continue because the pressure is too high, the air-foam slug is used for alternate flooding, and the ultimate oil displacement efficiency reaches 78.39%, which is close to the oil displacement efficiency of air-foam slug after water flooding (Table 4 and Figure 6). After air and foam liquid are mixed on the ground, the foam size is much larger than the pore size, which makes injection difficult. For ultra-low permeability reservoirs such as Gaotaizi, air-foam slug should be used for displacement, so that air and foam liquid can be mixed in the formation, and the foam has high viscosity in the high permeability layer and low viscosity in the low permeability layer, and the oil displacement effect of plugging large channels but not small channels can be exerted.

**Figure 5.** The relationship between air-foam liquid displacement efficiency and injection volume under different gas-liquid ratios

**Figure 6.** The relationship between the core ratio air-foam liquid displacement PV number and displacement efficiency
Table 4. Core air-foam fluid flooding experiment results*

| Core No. | Displacement mode | Gas permeability/Porosity / Test pressure difference/Injection velocity/ | Oil displacement efficiency/% |
|----------|-------------------|-----------------------------|-------------------------------|
|          |                   | (10-3 μm²) % pressure difference/ (mL·min⁻¹) | Water flooding Air-foam liquid floodingPromotion |
| 2#       | Alternate injection of foam liquid and air in small slug flooding | 0.902 10.77 14.66 0.035 52.71 79.63 26.92 |
| 3#       | Different air-foam liquid slug flooding | 0.211 8.97 14.31 0.008 49.60 55.17 5.57 |
| 1#       | Long slug air-foam slug flooding | 0.803 10.23 12.46 0.027 43.5 63.21 19.71 |
| 4#       | Air-foam waterless mixed flooding | 0.577 9.85 18.9 0.012 Foam flooding Air foam slug flooding 13.15 78.39 |

*The experiment temperature is 80℃.

4. Conclusions

Air-foam slug is used to displace the core of Gaotaizi tight reservoir, and the oil displacement efficiency is about 20% higher than that of water flooding. The lower the gas-liquid ratio of air-foam slug, the slower the effect, the later the gas channeling, and the higher the oil displacement efficiency. The larger the gas-liquid ratio, the faster the effect, the earlier the gas channeling, and the lower the oil displacement efficiency. The oil displacement efficiency of multi-period air-foam slug with small slug is higher than that of single air-foam slug with large slug. When driving oil with air foam, the mode of small slug and multi-slug should be adopted, the gas-liquid ratio should be controlled between 1:1 and 3:1, and the injection should be carried out in the way of "air-foam liquid-air-foam liquid" slugging alternately.

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