Experimental Study on Mechanism of Foamy Oil-Assisted Methane Foam Flooding in an Etched Glass Micromodel

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Abstract. A number of heavy oil reservoirs under cold heavy oil production with sand (CHOPS) show anomalously good primary performance due to foamy oil flow. However, as the pressure of the reservoir depletes, the foamy oil phenomenon gradually disappears and the development gradually deteriorates. In this paper, a new method named methane foam flooding is proposed as an effective enhanced heavy oil recovery process. In this paper, we take advantage of Ross miles foam equipments to select foaming agents and evaluate the foam ability, study and analyze the foam ability of different foam agent in different concentrations. and through visual microscopic model experiments to study the oil displacement mechanism and flow characteristics of methane foam flooding. The results show that foaming agent ZY-1 has excellent foam comprehensive properties, and it has the best foam stability at 1% concentration. It can be found from the micromodel flood experiments that methane foam flooding can effectively block the formation of high permeability channels, delaying the production of methane gas, emulsifying crude oil and changing the wettability of the rock to enlarge a sweeping volume and improve oil displacement efficiency.

1. Introduction
Foamy oil appears in some areas of Canada and heavy oil reservoirs in Venezuela [1]. Due to the foamy oil phenomenon, the gas fluidity in the oil phase decreases, the production gas-oil ratio increases slowly, the pressure drop rate decreases slowly, and the recovery rate is high. However, when the reservoir pressure is lower than the pseudo-bubble point pressure of crude oil, the foamy oil phenomenon disappears, and the bubbles dispersed in the oil phase eventually coalesce into a continuous free gas phase, resulting in a reservoir recovery rate of only 5-15% [2]. Follow-up technologies are needed to improve the recovery factor of foamy oil reservoirs. Based on sufficient literature research, this paper carried out a new method named methane foam flooding is proposed as an effective enhanced heavy oil recovery process [3].This article first analyzes the influence of the type and concentration of the foaming agent on the foam properties, and then selects the foaming agent with better foam properties. Micromodel were used to simulate the methane foam injection process in porous media, the pictures of injection process were collected, and the infiltrating fluid characteristics and injection process of methane foam in the pore were analyzed.
2. Experimental materials and setup

2.1. Measurements of Foam stability

The Waring Blender method was used to evaluate the foam ability (Figure 1). In order to consider the comprehensive influence of the foam quality and the half life of the foam on the foam properties, the foam stability is evaluated by the Foam Comprehensive Index [4]. The area of the shaded part in the Figure 2 can comprehensively reflect the foam ability of the system, which is the foam comprehensive index. Assuming the curve equation \( h = f(t) \), then Formula 1 is \( FCI \). For the convenience of calculation, the area of trapezoidal ABCD is approximated as S, so Formula 1 can be simplified to Formula 2

\[
FCI = S = \int_{0}^{t_{1/2}} f(t) dt
\]  
(1)

\[
FCI = S = 0.75V_{\text{max}}t_{1/2}
\]  
(2)

Where \( V_{\text{max}} \) is the maximum foam volume (ml), \( t_{1/2} \) is the half time of foam (h).

Figure 1. Installation diagram of the foaming agent select and the foam ability evaluation test

Figure 2. The relationship of foam volume and time

2.2. Micromodel flood Experiments

The crude oil samples used in the experiments were Venezuela Orinoco heavy live oil (foamy oil). The solution gas was a mixture of methane and carbon dioxide, and the molar fractions are 88.9% and 11.1% respectively. The etched glass micromodel has a porosity of 33.56%, a permeability of 16.3 D. The setup is shown schematically in Figure 3.
3. Experimental procedure

3.1. Measurements of Foam stability
The Waring Blender method is a commonly used method to evaluate foam properties. The specific experimental method is: weigh a certain amount of water, then add a certain concentration of foaming agent to the water, stir evenly, and then add 10mL of the foaming agent to be tested into the measuring cup. Use a high-speed rotating mixer to stir at a constant rate for 1 minute, then turn off the power switch, measure the volume of foam to characterize the foamability; measure the time it takes for the foam to separate out half of the liquid to characterize the stability of the foam.

3.2. Micromodel flood Experiments
All experiments were carried out at 55°C. The experiments included the following steps: 1. According to the bubble point pressure, reservoir temperature, and solution GOR, live oil was prepared in a PVT barrel; 2. Then the water was injected to saturate the micromodel at a pressure higher than the bubble point pressure of the oil; 3. Live oil was flushed through the micromodel for a sufficiently long time until the water inside the model became immobile; 4. The back-pressure was gradually reduced. The pressure depletion rate was 0.6 MPa/h. 5. Added the foaming agent to the water at the addition of 1g per 100ml and mix well. 6. Methane and foaming solution injected from the inlet of the micromodel at the same time. Using a video recorder and camera apparatus, the micromodel flood was visualized during the solution gas drive and methane foam flooding.

4. Results and analysis

4.1. Foam stability Measurements

4.1.1. Influence of type of foaming agent. Figure 4 shows at the same concentration (1%), foaming agent ZY-1 and WFS-500 generate strong foam stability. Therefore, in the process of subsequent experiments, the effect of concentration on the foam stability of the two foaming agents was compared.
Figure 4. Foam stability vs. foaming agent type

4.1.2. Influence of concentration. Figure 5 shows that the FCI increases with the increase of the concentration, and reaches the maximum value when the concentration is 1%, and then slowly decreases. The main reason is that as the concentration of the foam liquid increases, the surface tension of the system drops significantly, and the stability of the foam liquid film becomes stronger. When the concentration of the solution increases to the critical micelle concentration (CMC), the half life of the system is the longest. If the concentration continues to increase, the surface tension will no longer change significantly. And ZY-1 has better foam stability than WFS-500, so ZY-1 is selected as the foaming agent for methane foam flooding, and the preferred concentration is 1%.

Figure 5. FCI vs. foaming agent type

4.2. Micromodel flood Experiments
Two sets of micromodel flood experiments were carried out. Each set of micro-experiments has two stages: 1. Depletion drive, that is, dissolved gas flooding. The pressure is reduced from the original formation pressure of 8.45 MPa to 2 MPa through the back pressure valve. 2. After depletion drive is completed, methane is injected for displacement (Experimental Plan 1) or methane and foaming agent ZY-1 are injected for methane foam flooding (Experimental Plan 2).
Figures 6 shows microscopic images during the solution gas drive. According to the flow characteristics of the gas phase, there are three flow states exist during the solution gas drive. When the pressure was higher than the bubble point pressure, there were no gas bubble was separated from oil (Figure 6a). When the pressure was below the bubble point pressure, gas is separated from the oil in the form of small bubbles (Figure 6b). The dispersed gas bubbles flowed with the oil, thereby forming the foamy oil flow. As pressure reduced, the gas bubbles coalesced to form a continuous phase gradually (Figure 6c). The continuous gas phase moved in the micromodel, thereby forming the two-phase oil–gas flow [7].

![Figure 6](image)

**Figure 6. Different flow stages**

Methane was injected to drive after depletion drive in experiment plan 1. Figure 7 shows that methane dissolved in heavy oil, so can reduce oil viscosity and has volumetric expansion feature [8]. However, due to the relatively large difference in oil and gas viscosity, most of the injected gas quickly breaks through resulted in the development effect of methane injection gas flooding is poor.

Figure 8 shows that methane foam flooding can form stable foam, which can effectively block the formation of high permeability channels [5]. Foam can displace the crude oil in the small pores. This is because the foaming liquid gas first enters the high-permeability large pores with lower flow resistance and forms foam. The flow resistance in the large pores increases with the increase in the amount of foam. When the flow resistance increases to exceed the flow resistance in the small pores, more foam flows into the medium-permeability pores to improve macro swept volume and displacement efficiency [6].

At the same time, it can be observed in the process of methane foam flooding that under the action of surfactants, some oil droplets emulsify (Figure 9a) and disperse to form an oil-in-water emulsion. The formed emulsion has relatively low flow resistance in porous media, resulting in a relative decrease in flow resistance. Under the action of pressure difference, the emulsion carries the solubilized oil droplets and migrates to the outlet of the glass micromodel. Meanwhile, it was observed that the foam drove the residual oil in blind end. Moreover, it was observed that the foam made the oil film on the rock peeled and thinned (Figure 9b), the wettability of rock changed from oil-wet to water-wet, which can improve oil-displacement efficiency and the swept volume (Figure 9c).

![Figure 7](image)

**Figure 7. Micromodel flood was visualized during experiment plan 1**
Figure 8. Micromodel flood was visualized during experiment plan 2

Figure 9. Microscopic oil displacement mechanisms

Figure 10 shows the distribution of residual oil of experimental plan 1 and 2. Due to the rapid breakthrough of methane, the remaining oil content is high in experimental plan 1. On the contrary, due to the methane foam blocking the high-permeability channel, emulsifying crude oil, displacing the remaining oil at the blind end, and changing the wettability of the rock, the swept volume is larger and the oil displacement efficiency is higher

Figure 10. The distribution of residual oil of experimental plan 1 and 2
5. Conclusion

(1) The foam generated by ZY-1 has the strongest stability, so it is preferred as a foaming agent for methane foam flooding. Increasing the concentration of the foaming agents is beneficial to improve the stability of the foam. But when the foaming agent concentration exceeds the critical micelle concentration, continue to increase the concentration, the foam stability does not increase.

(2) There are three flow states exist during the solution gas drive: oil phase flow, foamy oil flow and two-phase oil–gas flow.

(3) Methane is easy to dissolve in heavy oil, which effectively reduces the viscosity of crude oil and improves the fluidity of crude oil.

(4) Methane foam flooding can effectively block the formation of high permeability channels, achieving the effect of simultaneous flow of high and low permeability, delaying the production of methane gas, increasing the time between methane and crude oil, and greatly reducing the viscosity of crude oil. At the same time, it has the effect of emulsifying crude oil and changing the wettability of the rock to enlarge a sweeping volume and improve oil displacement efficiency.

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