

Article

Adaptability to Enhance Heavy Oil Recovery by Combination and Foam Systems with Fine-Emulsification Properties

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Abstract: Emulsification is increasingly emphasized for heavy oil recovery through chemical flooding. However, whether systems with fine-emulsification (FE) properties significantly outperform conventional ultra-low interfacial tension (IFT) systems, especially under varying water-oil viscosity ratios, remains unclear. In this research, two FE systems and one conventional ultra-low IFT system are compared in terms of their IFTs, emulsification properties, foaming behaviors, and heavy oil recovery (in the form of combination flooding and foam flooding). The results show that FE systems 1# and 2# can generate more stable emulsions of heavy oil than the traditional ultra-low IFT variant 3#. During the first combination flooding, FE systems recover 24.5% and 27.9% of the oil after water, obviously surpassing 21.0% of the ultra-low IFT system 3#; but as this ratio increases to 0.45, those factors become very similar to ones of 33.2%, 34.5% and 32.9%, with the former no longer outperforming the latter. In the second trials of foam flooding, at a lower water-oil viscosity ratio of 0.05, FE foam 1# becomes less effective than the ultra-low IFT 3#, with oil recovery factors of 27.2% and 31.6%, respectively; but foam 2# (combining medium emulsification and ultra-low IFT) remains optimal, with the highest recovery factor of 40.0%. Again, as this ratio becomes 0.45, the advantages of FE systems over the ultra-low IFT system are almost negligible, generating similar oil recoveries of 39.2%, 41.0% and 39.4%.



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1. Introduction

As conventional light oil reservoirs approach the end of their developing life with super-high water cut, heavy oil reserves become increasingly important for oil production and supply [1,2]. Due to its high viscosity and the resulting unfavorable water-oil viscosity ratio, heavy oil recovery is only about 5–10% when using primary water flooding [1]. Enhanced oil recovery (EOR) techniques are urgently needed to recover more heavy oil. Thermal processes such as hot water flooding, steam huff-n-puff flooding, in-situ combustion, etc., [3–7] are among the commonly used methods to reduce heavy oil viscosity through heating, thus recovering more oil. Nevertheless, they simultaneously expose some deficiencies, including significant energy consumption for hot fluid preparation, large heat loss during injection, limited heating radius, steam channeling, etc. [3–7]. As a result, as oil production deteriorates year after year, we are in need of continuation technologies after these thermal processes for EOR of heavy oil. Chemical flooding, especially combination flooding, has achieved great success in the development of traditional light oil reservoirs. People are considering the application of these systems to heavy oil reservoirs to enlarge the sweep volume by increasing the viscosity of the displacing phase, enhance the oil-washing effect by reducing interfacial tension (IFT), improve the flowability of heavy oil by forming oil-in-water (O/W) emulsions, etc. [8–12].

Recently, the importance of emulsification in heavy oil recovery by chemical flooding has been increasingly emphasized, leading to the development of some FE systems. Yu [13] emulsified heavy oil into reservoir brine and found that O/W emulsions could plug any high-permeability channels to enlarge the sweep volume. Zhang [14,15] and Zhou [16] concluded that heavy oil recovery enhancement is mainly due to the plugging of water channels by emulsions. Liu [17] observed sweep coefficient improvements and heavy oil recovery enhancements by using a collaborative emulsification system. Zhao [18] found that the emulsion stability of chemical solutions plays a key role in recovering heavy oil during alkali-surfactant assisted foam flooding. Other studies have focused on the development of a new kind of amphipathic polymer to decrease heavy oil viscosity through oil-in-water emulsification, resulting in viscosity reduction rates exceeding 90% [19–23].

These studies remind us of the importance of emulsification for EOR of heavy oil [24,25]. That being the case, a natural question arises with respect to the optimization of chemical flooding systems; that is, whether FE systems are considerably better than conventional ultra-low IFT systems for replacement, or under what conditions the former would be better than the latter. Kang [26] developed a novel foam flooding agent to enhance heavy oil recovery by emphasizing ultra-low interfacial tension. In contrast, Zhang [14] emphasized that EOR is mainly due to plugging of the water channel (using polymers to increase the water-oil viscosity ratio) and not the lowering of IFT. Li [27,28] concluded that the emulsification capability of surfactants is more important for starting the oil film than achieving ultralow IFT. Guo [29] found that systems with good emulsification could achieve higher oil recovery compared to those with ultra-low IFT. Li [27] considered that a system with ultra-Low IFT leading to spontaneous emulsification is suitable for EOR. Through a series of oil floodings, Ding [11] found that the FE SP system closely performs with the ultra-low IFT in recovering heavy oil, or only slightly better than the latter. As discussed above, the focus has been on the effects of IFT and emulsification on heavy oil recovery, but the following problems still exist: (i) unified understanding is missing (some emphasize ultra-low IFT, while others believe emulsification is more critical, or emphasize both) [11,14,26–30]. Consequently, it is still unclear which mechanism is more important; (ii) existing understandings have mostly been obtained under fixed water-oil viscosity ratio conditions. As a result, it remains unclear whether these FE systems are adaptable for recovering heavy oil under different water-oil viscosity ratios and replacing the conventional ultra-low IFT systems. This is because different water-oil viscosity ratios imply varied mobility control by chemicals, thus resulting in different requirements for IFT and emulsification in EOR.

To address the issues mentioned above, two FE systems and one conventional ultra-low IFT system were compared based on aspects of IFT, emulsification properties, foaming behavior, and, finally, heavy oil recovery performance (including combination flooding and foam flooding techniques [11,14,26,30–32]). Thus, we revealed the adaptability of foam systems with FE properties for enhancing heavy oil recovery under different water-oil viscosity ratios. Our results may guide the design and selection of chemical flooding systems for EOR of heavy oil.

2. Experimental Materials and Methods

2.1. Materials

A sample of heavy oil was collected from Shengli oil field, Dongying, China, and used in all the experiments that refer to ‘oil’. Its viscosity and density were measured to be 731.0 mPa·s (by a MCR302 rheometer) and 0.98 g/cm³ at 70 °C, 0.101 MPa. A total of three anionic-nonionic surfactants with different properties were also supplied by Shengli oil field. These include surfactant 1 (S₁) with FE capacity but non- ultra-low IFT, surfactant 2 (S₂) with both medium emulsification capacity and ultra-low IFT, and surfactant 3 (S₃), characterized by ultra-low IFT but weak emulsification. A polymer of HPAM with a relative molecular weight of 2.5×10^4 was collected from Shandong Baomo Biological Chemical Co., Ltd., and used for the preparation of combination and foam systems. Viscosities of this polymer at the selected concentrations were measured using the MCR302 rheometer. The

synthetic saltwater is composed of $\text{Na}^+ + \text{K}^+$ 2299 mg/L, $\text{Mg}^{2+} + \text{Ca}^{2+}$ 184.0 mg/L, Cl^- 3435 mg/L, HCO_3^{3-} 725.0, and CO_3^{2-} 38.0 mg/L, with a total salinity of 6681 mg/L. This is used to make chemical solutions and displace heavy oil in cores during flooding tests.

2.2. Experimental Methods

2.2.1. IFT Measurements

The combination systems were first prepared for IFT measurements with heavy oil at 70 °C (representing typical temperature conditions in the Shengli oilfield), using a widely-adopted tensiometer TX-500C. The detailed composition of these systems is summarized in Table 1. Thus, whether the IFT of these chemical-heavy oil systems meets the needs of our research, can be determined.

Table 1. Composition and the measured parameters of the chemical combination systems.

System No.	Composition	Properties	
		IFT (mN/m)	Emulsion Stability
1#	0.3% S_1 + 0.17%/0.30% P	$4.5 \times 10^{-1} / 5.2 \times 10^{-1}$	Strong
2#	0.3% S_2 + 0.17%/0.30% P	$5.4 \times 10^{-3} / 5.8 \times 10^{-3}$	Medium
3#	0.3% S_3 + 0.17%/0.30% P	$2.6 \times 10^{-3} / 3.0 \times 10^{-3}$	Weak

2.2.2. Emulsification Tests

The emulsification of heavy oil using these adopted chemical solutions was studied using bottle tests. The specific procedures are described as follows: firstly, three different combination systems (1#–3#) were prepared using the polymer and surfactants S_1 , S_2 , and S_3 at concentrations of 0.17% and 0.3%, respectively. Then, 5.0 mL samples of these test solutions were put into bottles and 5.0 mL of oil was added. The bottles were then heated to a pre-specified temperature of 70 °C and shaken 30 times to mix the chemical solutions and oil, letting the former completely emulsify with the latter. After that, the unstable emulsions formed were maintained at 70 °C to allow the separation of water from them. Thus, according to the volume of separated water at different times, the water segregation rate (WSR), defined as the ratio of the volume of precipitated water to the initial amount of water (5 mL), was calculated and used as an index to evaluate the stability of the emulsion. A smaller WSR indicates a more stable emulsion. The states of emulsions formed by solutions 1#, 2# and 3# at 0 min and 90 min were also microscopically photographed using a digital camera and microscope. Subsequently, the morphologies and stabilities of the emulsions could be investigated at different times after their generation.

2.2.3. Core Flooding Tests

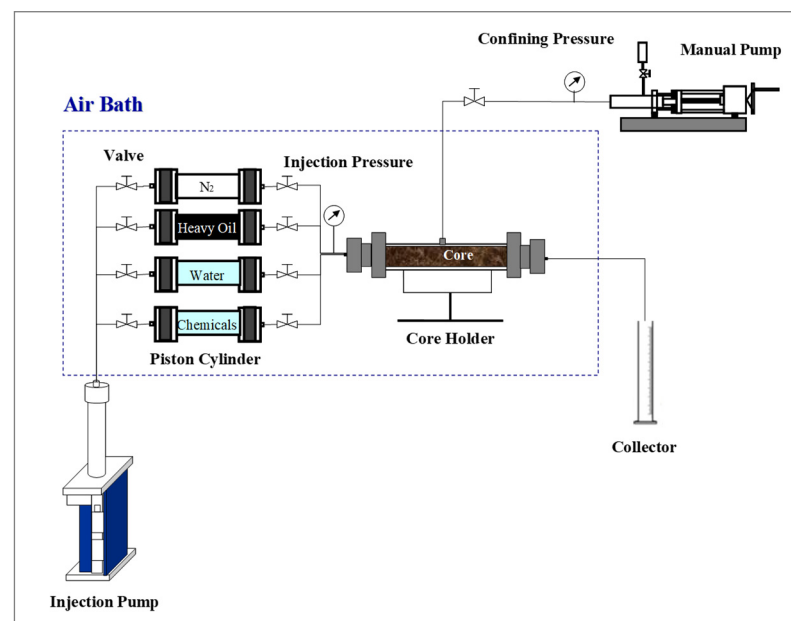
To compare the EOR performance of combination systems 1#, 2#, and 3#, with their corresponding foams at different polymer concentrations (0.17% and 0.30%) and water-oil viscosity ratios (0.05 and 0.45), a total of 12 flooding tests were conducted on cores with a diameter of 25 mm and a length of 300 mm. The specific details of the cores used and the measured oil recovery factors are displayed in Table 2.

The schematic diagram of the experimental setup for oil flooding tests is illustrated in Figure 1. A high-pressure stainless-steel core holder was used to accommodate the core sample, which was covered by a piece of rubber sleeve. Four piston cylinders were adopted to store the experimental fluids (oil, water, N_2 , and chemical solutions). An automatic pump was connected to the cylinders to inject the fluids into the core during experiments. A manual pump applied confining pressure to the rubber sleeve, making it wrap around the core, avoiding the bypassing flow of experimental fluids around the core. The produced liquids were gathered in a collector for water and oil separation and measurement. Finally, an air bath maintained the pre-specified temperature of 70 °C throughout the experiment.

Table 2. Physical properties of the cores used in the flooding tests and the corresponding oil recovery factors measured.

Flooding Pattern	System No.	Polymer Concentration (%)	Water-Oil Viscosity Ratio	K (μm^2)	Φ (%)	S_{oil} (%)	Oil Recovery Factor (%)		
							Water	Chemical	Total
Combination flooding	1#	0.17	0.05	1.3	25.2	78.4	42.4	24.5	66.9
	2#			1.2	27.9	82.9	42.3	27.9	70.2
	3#			1.2	28.0	78.0	43.1	21.0	64.1
	1#	0.30	0.45	1.2	30.6	76.6	43.6	33.2	76.8
	2#			1.1	28.5	73.8	44.5	34.5	79.0
	3#			1.2	28.9	76.5	44.1	32.9	77.0
Foam flooding	1#	0.17	0.05	1.3	26.5	79.5	43.9	27.2	71.1
	2#			1.3	30.6	80.0	44.8	40.0	84.8
	3#			1.1	32.6	75.5	43.2	31.6	74.8
	1#	0.30	0.45	1.3	30.6	80.0	42.2	39.2	81.4
	2#			1.1	30.6	73.3	41.3	41.0	82.3
	3#			1.2	33.8	78.6	43.1	39.4	82.5

Notes: K : permeability of the experimental core plugs measured by water flooding, Φ : porosity of the core plugs, S_{oil} : initial oil saturation.

**Figure 1.** Schematic of the experimental setup used in core flooding tests.

Experiments proceeded as follows: (i) core preparation: the core was saturated with synthetic saltwater after vacuumization, then it was flooded with water and its permeability was measured according to the well-known Darcy law. (ii) Oil saturation: the experimental setup and fluids were then heated to 70 °C. Crude oil was continuously injected into the core to replace the water therein until no more water was produced from the outlet of the core (the cumulative amount of oil injected was no less than 3.0 PV, pore volumes); thus, initial oil saturation and irreducible water saturation was achieved. (iii) Oil flooding: after aging for 24 h, the core was primarily flooded with water until no more oil was produced; this is called water flooding. Then, either the combination system or foam flooding was followed. The system, with a volume of 0.3 PV, was injected to displace the remaining oil, among which, foam was achieved by the alternative injection of a combination solution and N_2 with an alternating slug size of 0.1 PV. Post-water flooding was then continued until the volume of oil gathered in the collector became negligible. The dynamic oil recovery during the whole water and chemical–post water flooding was calculated according to the amount of oil collected at different injection stages. Injection pressure was also recorded.

Additionally, the injection rates for primary water, combination/foam, and post-water flooding during the whole oil recovery test were maintained at 0.10 mL/min.

3. Results and Discussion

3.1. IFT

To reduce heavy oil viscosity through oil-in-water emulsification, a new anionic-nonionic surfactant, S₁, which has an underlying strong ability to stabilize O/W emulsions, was collected. However, the IFTs of its corresponding combination system, 1#, with heavy oil are at a non-ultra-low level of 4.5×10^{-1} mN/m and 5.2×10^{-1} mN/m (Table 1), corresponding to two different polymer concentrations of 0.17% and 0.30%. A second compound surfactant, S₂, with intermediate abilities to stabilize heavy oil emulsions and an ultra-low IFT, was developed by combining S₁ with the traditional ultra-low IFT surfactant, S₃, in a ratio of 1:1. The IFTs of its combination system, 2#, with heavy oil were measured and found to be 5.4×10^{-3} mN/m and 5.8×10^{-3} mN/m (Table 1). Given the balance of its emulsification and ultra-low IFT properties, we called it a dual-effect surfactant.

We now have two FE surfactants, S₁ and S₂, with strong and intermediate capacities to stabilize heavy oil emulsions, respectively. A third surfactant, S₃, was also collected for comparison, and its related combined system has ultra-low IFTs of 2.6×10^{-3} mN/m and 3.0×10^{-3} mN/m with heavy oil (Table 1).

3.2. Emulsification Properties

To determine whether the emulsification properties of the combination systems (corresponding to surfactants S₁, S₂, and S₃) comply with our expected requirements, emulsification tests were conducted using the conventional bottle-test method. The calculated WSR and observed microscopic morphology of emulsions at different times are illustrated in Figure 2.

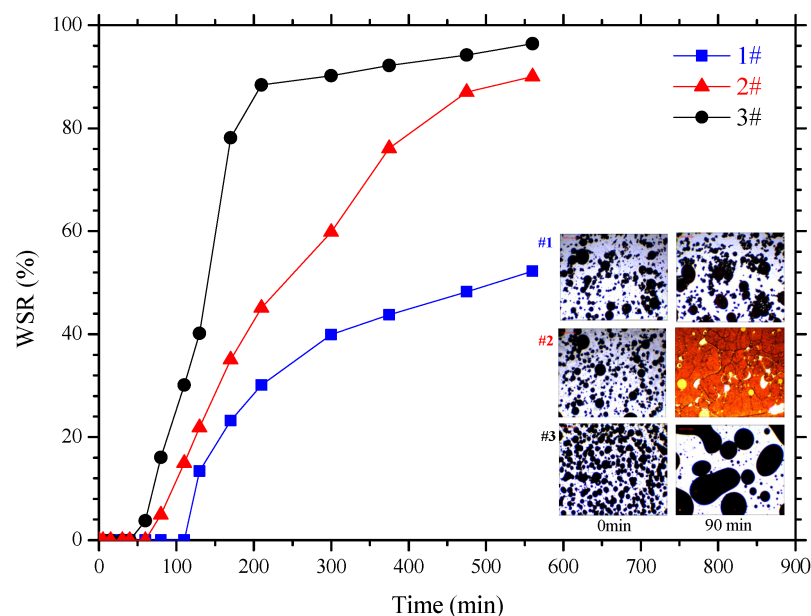


Figure 2. WSR and microscopic morphology of emulsions formed by combined systems of 1#, 2#, and 3# at different times.

As expected, system 1# performs best in stabilizing heavy oil emulsion, its mixture does not precipitate water until 130 min after generation, and the final WSR measured at 560 min is only 52.2%. System 2# behaves moderately; its mixture begins to induce water precipitation at 80 min, and the WSR increases faster than that of system 1#. Its final value, measured at 560 min, is 90.0%. The conventional ultra-low IFT system 3# has the worst performance compared to systems 1# and 2#. Its mixture with heavy oil is the first to

precipitate water at 60 min, and its WSR exhibits the fastest increase, reaching the highest final value of 96.4% at 560 min.

The microscopic pictures of emulsions (formed by 1#, 2# and 3#, attached to Figure 2) show the differences among them in emulsifying heavy oil. Clearly, all three systems can form emulsions that are well dispersed throughout the water phase after initial shaking, but the strong emulsification ability of #1 system forms a much smaller emulsion than in 2# and 3#. The average particle sizes analyzed using Image J software (V1.8.0.112) are 21.3 μm , 86.3 μm , and 98.6 μm , respectively, for these three systems. In time, the emulsion formed by the #1 system remains small at 22.5 μm , except for a few particularly large oil drops, and is well dispersed even after 90 min, demonstrating its superior ability to stabilize emulsions. The particle size of the oil droplets formed by system 2# increases to about 283.2 μm , but many oil-water interfaces remained clear within the horizon. As for the conventional system 3#, severe coalescence of the particles occurred, and very large oil droplets (measuring about 381.3 μm across) began to form and a continuous, flaky oil belt was discerned.

The measured WSR and observed microscopic images of emulsions prove that the FE systems 1# and 2# did exhibit strong and intermediate emulsification capacity, as expected, while the conventional ultra-low IFT system 3# performs worst in stabilizing heavy oil emulsions. In general, the final determined IFT and emulsification properties of the three combined systems, 1#, 2#, and 3#, are summarized in Table 1.

3.3. Combination Flooding

Given the different IFTs and emulsification behaviors observed in systems #1, #2, and #3, it would be very interesting and useful to determine which system is better at recovering heavy oil, or, in other words, whether the FE systems (#1 and #2) are good enough to replace the conventional ultra-low IFT system (3#). Therefore, a total of six combination flooding tests were conducted.

3.3.1. Oil Recovery Factor at a Low Water-Oil Viscosity Ratio of 0.05

Significant variations in the viscosities of heavy oil and combination systems usually occur in real reservoirs, which may lead to differences in mobility control by chemical systems. Therefore, the combination flooding tests were conducted in two cases: one with a low water-oil viscosity ratio of 0.05 and the other with a high water-oil viscosity ratio of 0.45. The former simulates a case where mobility control by a combination system is insufficient, while the latter imitates a relatively sufficient case.

Figure 3 and Table 2 illustrate the oil recovery factors measured at a water-oil viscosity ratio of 0.05, where the viscosities of the combination system and heavy oil are 34.0 mPa·s and 731.0 mPa·s, respectively. Injection of combination systems significantly increases the oil recovery factor after primary water flooding. The oil recovery increments generated in systems 1# and 3# are 24.5% and 21.0%, respectively. Clearly, the FE system 1# (with non-ultra-low IFT) outperforms the traditional ultra-low IFT counterpart (system 3#) by 3.4% and is a good candidate to replace the latter. This finding indicates that, in such a low water-oil viscosity ratio situation, emulsification may be more important for recovering heavy oil than ultra-low IFT, due to the well-known mechanisms, such as oil viscosity reduction, sweep volume enlargement (by the Jamin effect of emulsified oil droplets), etc. [32–35].

However, when the ultra-low IFT and intermediate emulsification properties are combined in system 2#, the highest incremental oil recovery factor is achieved at 27.9%, which is 3.4% and 6.9% greater than that of systems 1# and 3#. Therefore, upon the comparison of systems 1# and 2#, it is deemed inappropriate to overemphasize emulsification while ignoring the ultra-low IFT. The best choice is the balance between them; unfortunately, the dual-effect system 2# is very selective for crude oil, and its ultra-low IFT and medium emulsification properties may not eventuate when applied to a different type of oil. Designing such a double-effect system for a new crude oil sample is a challenging, sometimes impossible, task; if so, the FE system of 1# may be a good alternative.

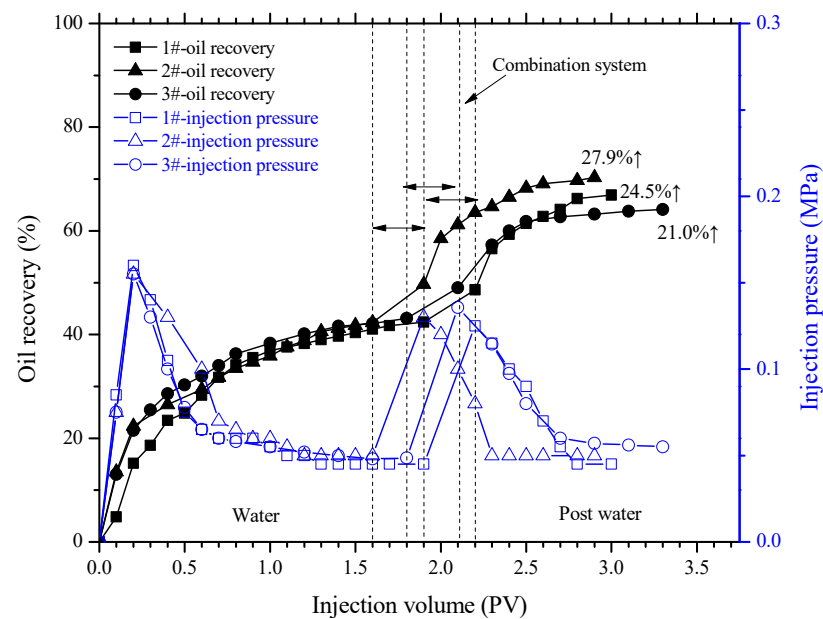


Figure 3. Oil recovery factors of different combination systems at a water-oil viscosity ratio of 0.05.

3.3.2. Oil Recovery Factor at a High Water-Oil Viscosity Ratio of 0.45

As the water-oil viscosity ratio is increased to 0.45 in Figure 4 (with viscosities of the chemical and crude oil at 331.0 mPa·s and 731.0 mPa·s), the EOR factors for combination systems 1#, 2#, and 3# are 33.2%, 34.5%, and 32.9%, respectively. These values are far beyond those obtained at the low water-oil viscosity ratio of 0.05 (Figure 3), indicating the need to increase the viscosity of the combination system to improve the water-oil mobility ratio, enlarge the sweep volume, and thus remove more heavy oil.

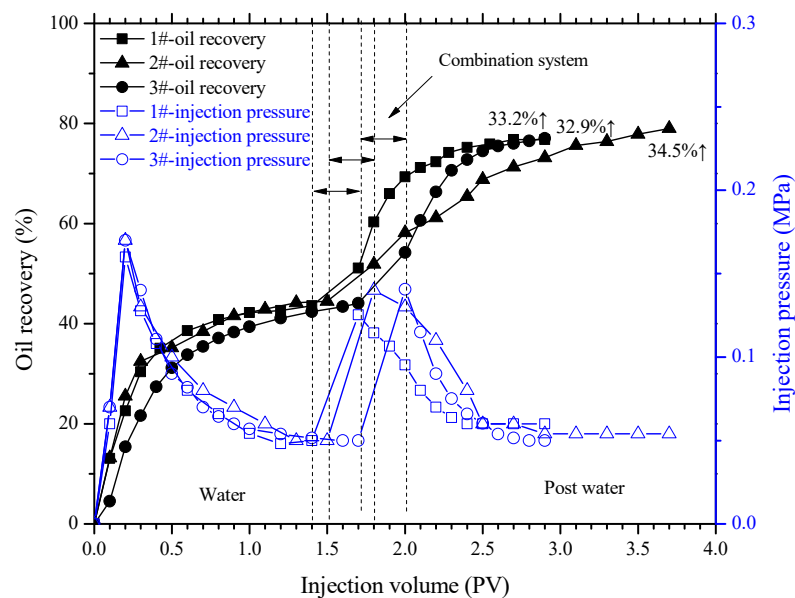


Figure 4. Oil recovery factors of different combination systems at a water-oil viscosity ratio of 0.45.

In addition, it is interesting to note that the incremental oil recovery factors of these three systems with different properties are similar, implying that under a relatively high water-oil viscosity ratio, there is no need to pursue excessive emulsification, and the traditional ultra-low IFT system 3# can meet the requirements for EOR. This can give some guidance for the choice of combination flooding systems when recovering heavy oil with different viscosities. For instance, the viscosity of combination systems used in the Shengli

oil field is generally 30–60 mPa·s. For a crude oil with a viscosity of about 67–134 mPa·s (calculated according to a water-oil viscosity ratio of 0.45), the traditional ultra-low IFT system could achieve good oil recovery, but as the crude oil becomes more viscous, the FE system may be better.

In general, when the water-oil viscosity ratio is low (0.05), the dual-effect system 2# is the best combination system for recovering heavy oil (if such a system is available for an oil sample), followed by FE system 1, then followed by the ultra-low IFT system 3#. When the water-oil viscosity ratio is relatively high (0.45), the traditional ultra-low IFT system 3# may be the best choice.

3.4. Foam Flooding

Previous studies have increasingly believed that extending the sweep volume is the premise for heavy oil EOR by chemical flooding [1,11]. Therefore, instead of increasing the polymer concentration to expand this sweep volume, it would be better to introduce a more powerful foam. Our preliminary research has also shown that foam is an excellent system for heavy oil recovery, outperforming the combined flooding pattern [11]. If enough gas is available and field injection can be achieved, foam flooding becomes another good choice for heavy oil recovery [36]. More importantly, as foam is introduced to help expand the sweep volume, it warrants further study whether the effect of emulsification on oil flooding will change or which type of system works best.

3.4.1. Foam Properties

Before conducting the oil flooding tests, the basic foam properties of the three adopted systems were investigated by the widely used Waring-Blender method [37]. 100 mL of foaming solution was stirred at a rate of 6800 rpm for 1 min; the resulting foam was transferred to a volume cylinder for volume measurement. Meanwhile, the time corresponding to the foam volume reduction to half its original volume was recorded (Figure 5).

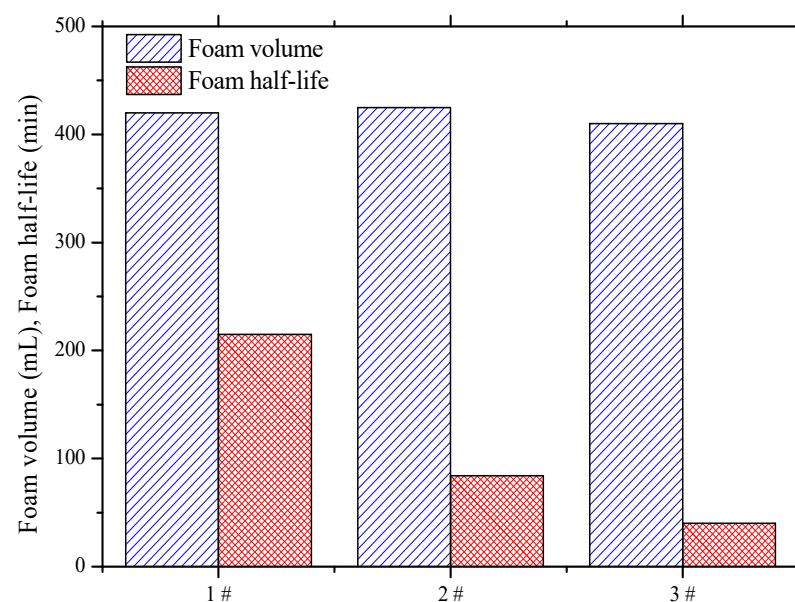


Figure 5. Properties of foams formed by combination systems 1#, 2#, and 3#.

The volume of foams formed by systems 1#, 2#, and 3# is very close, namely 420 mL, 425 mL, and 410 mL, respectively, indicating that they have a similar foaming capacity for generating bubbles. However, their stabilities differ significantly. Specifically, the foam generated by system 1# is the most stable with the longest foam half-life of 215 min. This may be due to its excellent stabilization of the air-liquid interface, given how well it can stabilize the oil-water interface (Figure 2). The 2# foam has moderate stability, with a

half-life of 84 min, while the traditional ultra-low interface tension foam 3# has the worst stability, with a half-life of 40 min.

In this way, we have three systems with significantly different emulsifications, interface tensions, and foam properties, making it necessary to determine which one performs best in recovering heavy oil at different water-oil viscosity ratios.

3.4.2. Oil Recovery Factor at a Low Water-Oil Viscosity Ratio of 0.05

The first three foam flooding tests were conducted to compare the chemicals used at a water-oil viscosity ratio of 0.05. The measured oil recovery factors are shown in Figure 6 and listed in Table 2.

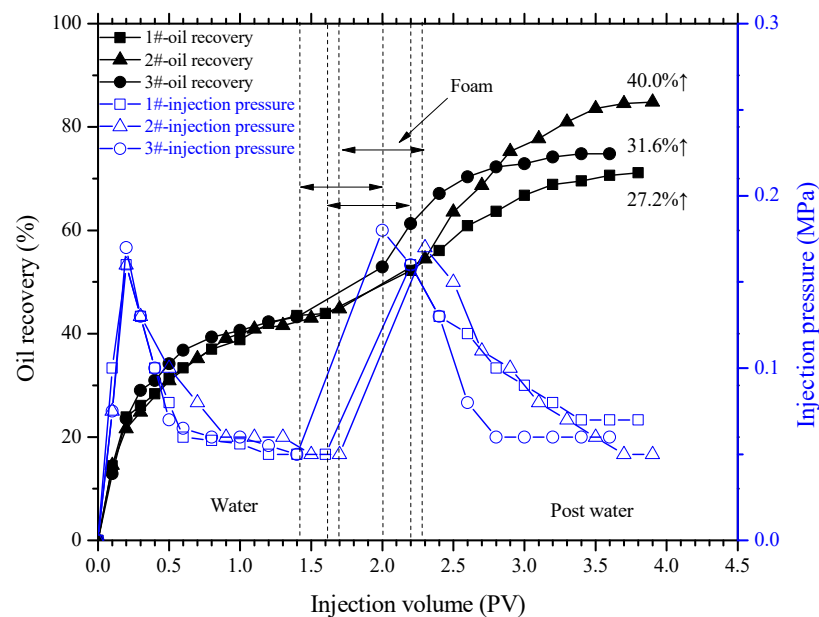


Figure 6. Oil recovery factors of different foams at a water-oil viscosity ratio of 0.05.

Figure 6 shows that foam flooding can significantly increase the oil recovery factor by 27.2%, 40.0%, and 31.6% for systems 1#, 2#, and 3#, which are far beyond those of combination flooding by 2.7%, 12.1%, and 10.4% (Figure 4), evincing the advantages of foam in developing heavy oil over the latter.

Comparing systems 1# and 3#, although the latter has poorer emulsion and foam stability (Figures 2 and 5), it outperforms the former by an additional oil recovery increment of 4.4%, indicating the priority of the ultra-low IFT mechanism over both fine emulsification and foam stability during foam flooding. As a result, the FE foam 1# is unable to replace the conventional ultra-low IFT foam 3#. This differs from the findings during combination flooding tests (Figure 4) where system 1# outperforms system 3#. This may be because, in the assistance provided by the foam in expanding the sweep volume, the reduction in oil viscosity through oil-in-water emulsification and the enlargement of the sweep volume by the Jiamin effect of emulsified oil droplets becomes less important than the oil washing improvements induced by ultra-low IFT. However, as expected, the dual-effect 2# foam is still the best system for recovering heavy oil, with the highest incremental oil recovery of 40.0%.

3.4.3. Oil Recovery Factor at a High Water-Oil Viscosity Ratio of 0.46

At the high water-oil viscosity ratio of 0.45 (Figure 7), the improved oil recovery factors by foams of 1#, 2#, and 3# become very close, namely 39.2%, 41.0%, and 39.4%, respectively, obviating the need to pursue fine emulsification again. The conventional ultra-low IFT system (3#) can meet the requirements for recovering heavy oil by foam. In general, when the water-oil viscosity ratio is low (0.05), the dual-effect system 2# is the best foam for

recovering heavy oil (if such systems are available for a new oil sample), followed by the ultra-low IFT system 3#, followed by the FE system 1#. When the water-oil viscosity ratio is relatively high (0.45), the traditional ultra-low IFT foam 3# may represent the best choice instead of the FE systems.

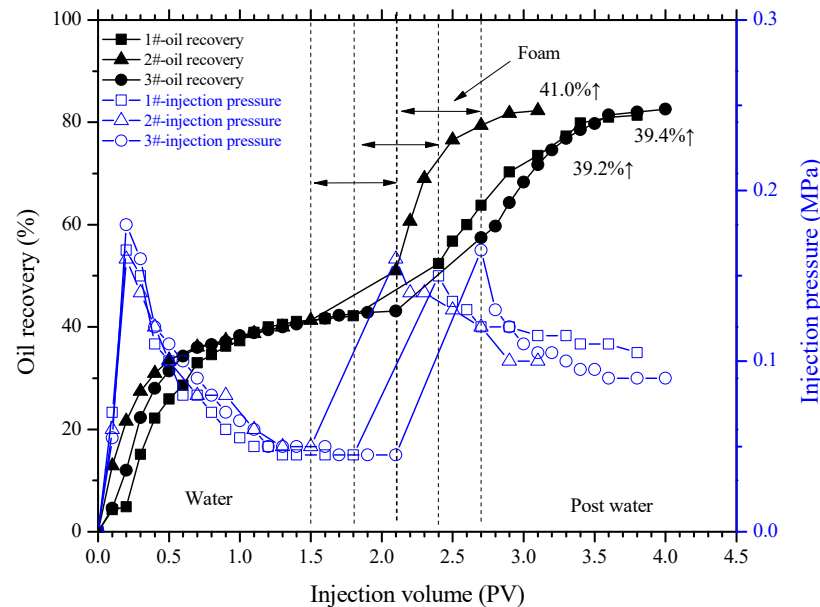


Figure 7. Oil recovery factors of different foams at a water-oil viscosity ratio of 0.45.

In conclusion, we have determined the EOR difference between the recently emphasized FE systems and the traditional ultra-low IFT system. Thus, better flooding systems under different water-oil viscosity ratios are recommended, contributing to the design and screening of chemical flooding system for enhanced heavy oil recovery. However, there are two other points worth noting: (i) these recommendations are only applicable to systems with emulsification properties similar to the FE systems used here. If significantly different systems are employed, their EOR performance and usage conditions may change, requiring further confirmation. (ii) At present, we only know that as the viscosity ratio increases from 0.45 to 0.05, the FE mechanism becomes less important in chemical flooding for heavy oil. However, it is still unclear at which specific water-oil viscosity ratio this starts. Therefore, more water-oil viscosity ratios between 0.05 and 0.45 are needed for further EOR comparisons between these FE and ultra-low IFT systems.

4. Conclusions

Two FE systems and one conventional ultra-low IFT system were compared for recovering heavy oil in the form of combination flooding and foam flooding. The main conclusions can be drawn as follows:

- (1) FE systems 1# and 2# can generate more stable heavy oil emulsions than the traditional ultra-low IFT system 3#;
- (2) The FE combination systems 1# and 2# are more powerful than the traditional ultra-low IFT system 3# in recovering heavy oil at a lower water-oil viscosity ratio of 0.05, due to their improved capacity in stabilizing heavy oil emulsion. However, as this ratio increases to 0.45, the former has almost no advantages compared to the latter.
- (3) Foam flooding significantly outperforms combination flooding in recovering heavy oil and is an excellent injection pattern for EOR by chemical methods (if the gas source and injection equipment are available).
- (4) At a water-oil viscosity ratio of 0.05, FE foam 1# no longer outperforms the traditional ultra-low IFT foam 3#, but the dual-effect foam 2# is still the best choice. As this ratio increases to 0.45 again, the advantages of FE systems over the ultra-low IFT

system are almost negligible. The conventional ultra-low IFT system 3# can meet the requirements for recovering heavy oil by foam and emulsification should not be overemphasized.

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