



Study on the variation of dynamic interfacial tension in the process of alkaline flooding for heavy oil

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HIGHLIGHTS

- ▶ The variation of dynamic IFT in process of alkaline flood for heavy oil was studied.
- ▶ The heavy oil pre-equilibrated by NaOH solution loses the interfacial activity.
- ▶ There is still interfacial activity in heavy oil pre-equilibrated by Na₂CO₃ solution.
- ▶ Interfacial reaction has more effect on interfacial property of oil with low TAN.
- ▶ The equilibrated alkaline solutions can reduce IFT to ultralow for oil with high TAN.

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ABSTRACT

Experimental investigations have been conducted to elucidate the variation of the dynamic interfacial tension (DIFT) in the process of alkaline flooding for heavy oil. The Binnan heavy oil with high TAN (Total Acid Number) and the Zhuangxi heavy oil with low TAN were pre-equilibrated by long-term contacting with NaOH and Na₂CO₃ solutions. The results show that the heavy oil pre-equilibrated by NaOH solutions almost loses the interfacial activity, and the IFT increases a lot. Although there is still interfacial activity in the heavy oil which is pre-equilibrated by Na₂CO₃ solutions, and the dynamic interfacial tension minimum (DIFT_{min}) changes a little, yet the dynamic interfacial tension equilibrium value (DIFT_{eq}) increases a lot. The effect of interfacial reaction on the interfacial property of oil with low TAN is more severe than that with high TAN. When the alkaline concentration is larger than a certain value, the IFT between the fresh oil with high TAN and the equilibrated alkaline solutions can decrease to ultralow after interfacial reaction, and the Na₂CO₃ system is superior to the NaOH system. However, the IFT between the fresh oil with low TAN and the equilibrated alkaline solutions increases after interfacial reaction. The above results can be used as guidance in the formulation design and mechanisms studies of alkaline flooding for improved heavy oil recovery.

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1. Introduction

It has long been recognized that alkaline flooding is a cost-effective enhanced oil recovery (EOR) process, particularly suitable for acidic oil reservoirs [1–3]. One of the most important phenomena in this process is the interfacial tension (IFT) reduction [4–6]. From previous reported results on dynamic IFT in crude oil or model oil/alkali systems [7–9], the following conclusions can be made: when an acidic crude oil contacts an alkali in the alkaline flooding, the organic acids in the crude oil reacts with the alkali in the flooding water to produce *in situ* surfactant which lowers

the oil–water IFT. Such surfactants accumulate at the oil–water interface and then, some of them gradually diffuse into the bulk aqueous phase and/or oil phase, depending on their affinities for the aqueous and oil phases. Thus, IFT between the oil phase and alkaline solution changes during an alkaline flooding and finally reaches an equilibrium value.

A wide range of views exists in the literature concerning which interfacial tension value would be operative in an actual field situation. The significance of the dynamic IFT minimum for reservoir situations has been discussed by some researchers [10,11]. Rubin and Radke [10] stated that the minimum interfacial tension observed using the spinning drop tensiometer is indicative of the lowest achievable reservoir equilibrium value. Later, deZabala and Radke [11] confirmed Rubin and Radke's point of view. They obtained interfacial tension data from multiple contacting of a

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fixed alkaline solution with fresh acidic oil and observed that the minima were close to those for single contacts. While others researchers [12,13] argued that equilibrium interfacial tension values are representative in the actual field. McCaffery [13] believed that the minimum interfacial tension would not be characteristic for the reservoir situation because it is attained a short time after the initial oil-caustic contact.

Currently with heavy oil, only about 5–20% of the initial oil in place (IOIP) can be recovered by water flooding [14]. Previous research has demonstrated that alkaline flooding can in fact lead to improve the recovery of heavy oil when compared to water flooding [15–19]. In the process of enhanced heavy oil recovery by alkaline injection, the injected fresh aqueous solution containing an alkaline reagent such as sodium hydroxide penetrates the reservoir rock, which contains residual oil [20]. It has been found that organic acids presenting in the oil reservoir form a reactive alkaline/acidic system with added aqueous sodium hydroxide solution. Interfacial reaction creates an *in situ* surfactant, which lowers the oil–water interfacial tension [21]. With the flow of alkaline solution in the oil reservoir, the alkaline concentration is decreasing, and the interfacial activities of the heavy oil are weakening. As the injected fresh alkaline solution has contacted fresh oil, the alkaline solution which has already contacted oil will continue to contact the fresh oil, while the oil that has not mobilized will contact the subsequent fresh alkaline solution [22]. This process will repeat in the same way, so the process of alkaline flooding for heavy oil is in fact equal to a repeated contact reaction between alkali and heavy oil [23].

Therefore, in order to facilitate the design of effective alkaline flooding for enhanced heavy oil recovery, variation of interfacial tension in the process of alkaline flooding is investigated through a series of experiments in this work. This study will not only provide an improved understanding of the interactions between the heavy oil and alkali, but also help to elucidate the mechanisms of alkaline flooding for improved heavy oil recovery and select the formula of alkaline flooding for heavy oil.

2. Materials and methods

2.1. Materials

Oil and formation brine samples were collected from the Zhuangxi and the Binnan heavy oil reservoirs in the Shengli oilfield in China. In order to remove the solids and water, these heavy oils were centrifuged at 10,000 rpm at the reservoir temperature (55 °C) for 4 h. The viscosity, density, and TAN of the oils were analyzed and are listed in Table 1. The properties of the formation brine are shown in Table 2. It can be seen that the salinity of formation brine is 0.5 wt% and the concentrations of Ca²⁺ and Mg²⁺ in

brine are relatively low. So all the solutions used in the experiments were prepared with NaCl solution with the concentration of 5000 mg/L. The alkaline agents used in this study were sodium hydroxide (NaOH) and sodium carbonate (Na₂CO₃).

2.2. Measurements of interfacial tension

The interfacial tension (IFT) between the oil and the different alkaline solution system was measured using a Texas-500 (Temco, Inc., American) spinning drop interfacial tensiometer at 55 °C. Equipped with an image-capture device and image-acquisition software, this instrument can automatically measure and record the dynamic interfacial tension. The oil–water IFT was determined according to the tensiometer's instructions.

When the length of an oil drop (L) is more than four times its diameter (D), the IFT is calculated according to the following equation:

$$\sigma = 1.2336\Delta\rho(D/n)^3\omega^2 \quad (1)$$

When the length of the oil drop (L) is less than four times its diameter (D), the IFT is calculated according to the following equation:

$$\sigma = 1.2336\Delta\rho(D/n)^3f(L/D)\omega^2 \quad (2)$$

where σ is the oil–water interfacial tension in mN/m, $\Delta\rho$ is the density difference between the oil and water phases in g/cm³, ω is the rotational velocity in rpm, D is the diameter of the oil drop in 10⁻⁴ m, L is the length of the oil drop in 10⁻⁴ m, n is the refractive index of water phase, and $f(L/D)$ is the correction factor.

2.3. Equilibrium reaction between alkali and heavy oil

Two-thirds of alkaline aqueous solution and one-third of oil by volume were added to a 100 mL separatory funnels. After the solution were shaken vigorously for about 30 min using a mechanical shaker, they were allowed to stand for about 3 weeks at 55 °C until clear mirror-like interfaces were obtained and the oil and aqueous phases became optically clear. The equilibrated oil and aqueous phases were then separated from the top and bottom of the funnel, respectively, for various physicochemical measurements.

Before pre-equilibrated, the oil phase and water phase are termed as the fresh oil and the fresh solution, and after pre-equilibrated, they are termed as the equilibrated oil and the equilibrated solution, respectively. The pH was measured using an Orion microprocessor ionalyzer/868 with a Ross combination electrode designed for low sodium error. The spinning-drop technique was used to measure the dynamic interfacial tension between oil phase and water phase. And the surface tension of

Table 1
Basic properties of the heavy oils in the Shengli oilfield.

Oils	Density @ 55 °C (kg/m ³)	Viscosity @ 55 °C (mPa s)	Total acid number ^a (mg KOH/g oil)	Resin (wt%)	Normal heptane asphaltene (wt%)
Zhuangxi	930.2	325	0.80	19.7	0.835
Binnan	947.2	2000	2.69	19.5	2.033

^a Total acid number was determined according to the GB/T18609-2001 Standard.

Table 2
The properties of formation brine from heavy oil reservoir.

Ion content (mg/L)							Total salinity (mg/L)	pH Value
K ⁺ +Na ⁺	Ca ²⁺	Mg ²⁺	SO ₄ ²⁻	CO ₃ ²⁻	HCO ₃	Cl ⁻		
1751.0	103.0	11.1	47.4	23.7	602.2	2501.0	5039	8.35

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