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Potential of alkaline flooding to enhance heavy oil recovery through water-in-oil emulsification

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HIGHLIGHTS

- ▶ Alkaline flooding can improve sweep efficiency through water-in-oil emulsification.
- ▶ Improvement of sweep efficiency increases with the alkaline concentration.
- ▶ There is an optimum slug size that results in the highest tertiary oil recovery.
- ▶ The injection pattern is recommended to the continuous alkaline injection.
- ▶ There is an optimum injection rate that obtains the highest tertiary oil recovery.

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ABSTRACT

Alkaline flooding has great potential for enhancing the recovery of heavy oil, especially for reservoirs in which thermal methods are not suitable. In this study, alkaline flooding tests were performed in micromodels and sandpacks to investigate the microscopic displacement mechanisms for enhancing heavy oil recovery and the effect of the injection parameters on displacement efficiency. The micromodel tests indicate that the penetration of the alkaline solution into the crude oil and the subsequent formation of a water-in-oil (W/O) emulsion reduce the mobility of the water phase and divert the injected water into the unswept region, thereby improving the sweep efficiency. The sandpack flood results show that the tertiary oil recovery can reach about 20% of the initial oil in place (IOIP) using 1.0% NaOH, and the tertiary oil recovery has been found to increase as the alkaline concentration increases. However, there is an optimum slug size and injection rate at which the highest tertiary oil recovery can be obtained during the alkaline flooding process. Continuous alkaline injection can provide a higher tertiary oil recovery compared with a cyclic alkaline injection pattern. These results show that the alkaline flooding, if properly designed and controlled, can lead to enhanced heavy oil recovery through the water-in-oil emulsification.

1. Introduction

Many countries, notably Venezuela, Canada, the United States and China, possess abundant heavy oil resources [1]. With the depletion of light oil resources and rising energy demands, the successful recovery of heavy oil is becoming increasingly important. However, the high viscosity of heavy oil makes it difficult to recover. Currently, only about 3–10% of the initial oil in place (IOIP) in heavy oil reservoirs can be recovered under primary production [2]. In order to recover additional heavy oil, different fluids usually have to be injected in order to displace the oil to the production wells. However, mobility ratio concerns dominate the displacement of viscous oil, and most EOR processes focus on reducing the oil viscosity or improving the mobility ratio [3]. Unfortunately, many heavy oil reservoirs in China are relatively thin or deep, making these reservoirs poor candidates for expensive thermal methods. Therefore, the displacement mobility ratio in these reservoirs needs to be improved using an inexpensive process [4].

Water flooding is a common and inexpensive secondary oil recovery technique for the heavy oil reservoirs with oil viscosities ranging from 100 to 10,000 mPa s. However, the incremental recoveries by water flooding are quite low, due to the poor sweep efficiencies caused by the adverse mobility ratio between oil and water [5]. As a result, most of the residual oil at the end of water flooding is bypassed, which is greatly different from that of the residual oil trapped by capillary forces in conventional oil

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reservoirs [6,7]. Therefore, the key problem in heavy oil reservoir is inefficient sweep due to low mobility of the oil, not the residual oil in the swept region [8].

Previous researches have demonstrated that alkaline flooding can potentially increase the recovery of heavy oil through the mechanism of emulsification [9–11]. However, different views on the mechanism for alkaline flooding to improve heavy oil recovery are proposed. Some researchers proposed the formation of oil-in-water (O/W) emulsions as a possible recovery mechanism [12–14]. In this application, oil is emulsified into water phase and the oil droplets either plug rock pores and give improved sweep efficiency, or are perhaps entrained along with the flowing aqueous phase. Alternatively, the formation of water-in-oil (W/O) emulsions has also been proposed as a possible recovery mechanism [15,16]. These emulsions should be more viscous than oil by itself, thus they could possibly lead to improvements in the mobility ratio and sweep efficiency of the flood [17,18]. The aforementioned researches indicate that the flow of W/O emulsion and O/W emulsion in porous media are two mechanisms of enhanced oil recovery by alkaline flooding. Generally, when alkaline concentration is low in the system with addition of surfactant, the mechanism of O/W emulsion prevails in the oil displacement process. When high alkaline concentration is applied, the mechanism of W/O emulsion is prominent. Compared with O/W emulsion, the W/O emulsion has much higher viscosity, which can effectively block water channels to improve sweep efficiency [19]. This mechanism is believed to be especially effective for heavy oil, where the sweep efficiency of water flooding is usually poor.

Although alkaline flooding has been extensively implemented in light oil reservoirs, only a few alkaline flooding studies and field tests have been conducted in heavy oil reservoirs. This is mainly ascribed to the fact that multiphase flow in heavy oil reservoir is a more complicated process than that of the light oil reservoirs. Moreover, heavy oil has higher contents of natural petroleum acids [20], which resulting in the mechanism of alkaline flooding for improving oil recovery to be more complicated. Therefore, the effect of various operating parameters on the performance of alkaline flooding in heavy oil reservoirs is not well understood.

This study is aimed at studying the potential of alkaline flooding and the microscopic displacement mechanisms for enhanced heavy oil recovery. The research is focused on the mechanism of improving the sweep efficiency through water-in-oil emulsification, and the effects of the injection parameters on the displacement efficiency are optimized by measuring the pressure drop and recovery efficiency in sandpack flood tests. The findings of this investigation can be utilized for optimizing various operational conditions, in order to maximize oil recovery, by injecting alkaline solution into the heavy oil reservoirs.

2. Experimental

2.1. Fluids and chemicals

Oil and formation brine samples were collected from the Binnan heavy oil reservoir in the Shengli oilfield in China. To remove the solids and water, the heavy oil was centrifuged at 10,000 rpm at reservoir temperature (55 °C) for 4 h. The viscosity, density, and acid number of the oil were analyzed and are listed in Table 1.

Table 1
Basic properties of the heavy oil sample.

Density @ 55 °C (kg/m^3)	Viscosity @ 55 °C (mPa s)	Acid number (mg KOH/g oil)	Resin (wt.%)	Asphaltene (wt.%)
947.2	2000	2.69	19.5	2.033

The heavy oil has a viscosity of 2000 mPa s at 55 °C. The acid number value of the oil is 2.69 mg KOH/gram of sample. The formation brine has a salinity of 0.5%, and the concentrations of Ca^{2+} and Mg^{2+} in the brine are relatively low. Thus, all of the solutions used in this study were prepared with NaCl solutions with concentrations of 5000 mg/L. The alkaline agent used in this study was sodium hydroxide (NaOH).

2.2. Measurements of interfacial tension

The interfacial tensions (IFTs) between the oil and the different alkaline solution systems were measured using a Model Texas-500 spinning drop interfacial tensiometer at 55 °C. In the cases where alkaline were added to the water phase, the rotation speed was sufficiently high that the length of the oil drop is larger than four times its diameter and the oil–water IFT was determined with an image–capture device and image-acquisition software according to the following equation:

$$\sigma = 1.2336(\rho_w - \rho_o)\omega^2\left(\frac{D}{n}\right)^3, \quad \frac{L}{D} \geqslant 4 \tag{1}$$

where σ is the oil–water interfacial tension in mN/m, ρ_w and ρ_o is the density of water phases and oil phase in g/cm^3, respectively, 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. The values of the IFT determinations were repeatable within ±0.005 mN/m.

2.3. Micromodel flood studies

A glass-etched micromodel was used to investigate the displacement mechanisms of alkaline flooding. The micromodel was constructed by etching a two-dimensional network of pores and throats on glass plates using a photochemical method. The pore network used in this study was patterned, based on the pore structure of a core obtained from the reservoir. The transparent nature of the micromodel allowed pore-scale multiphase displacements to be visually observed. To observe these phenomena easily during the flooding, 0.05% eosin was added to color the injected brine in the micromodel flood tests.

The procedure for the micromodel test was as follows: after being vacuumed, the micromodel was prepared for flooding by filling it with brine, and the brine was subsequently displaced by crude oil until no more water was produced. Because the viscosity of the crude oil was higher than the resident water, almost all of the water present in the micromodel was displaced. After the heavy oil was saturated, the model was aged for 24 h. Next, brine with the same salinity as the alkaline solution was injected into the micromodel at a constant flow rate of 0.003 mL/min. Using a video recorder and camera apparatus, the micromodel flood was visualized during the different stages of fluid injection.

2.4. Sandpack flood studies

All chemical flooding tests for heavy oil recovery were carried out using sandpacks. The sandpack used in this study was 2.35 cm in diameter and 19.4 cm in length. For each sandpack test, fresh quartz sand was wet-packed to ensure the same wettability for all the tests. The sandpack was packed as follows: fresh quartz sands with the size fractions of 80–100 and 100–200 meshes obtained from sieve screening were blended at a fixed weight ratio of 3:1. A coreholder filled with formation brine was positioned vertically, and the sand was added in several increments to fill the coreholder. In each step, the sand was shaken slightly after being poured in. During this process, the water surface was kept above