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Effect of polymer on the interaction of alkali with heavy oil and its use in improving oil recovery

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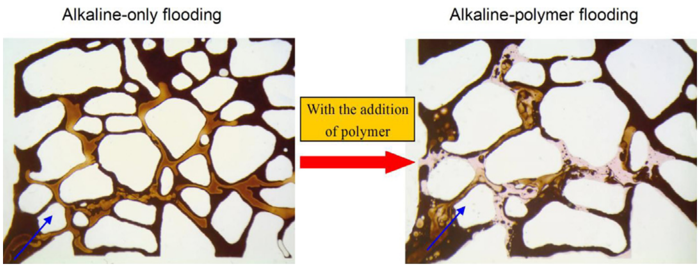
HIGHLIGHTS

- The combined alkali and polymer can maximize tertiary oil recovery for AP flooding.
- The W/O droplet flow plays major role in improving heavy oil recovery by AP flooding.
- The polymer has adverse effect on the formation of W/O droplet flow in AP flooding.
- The sequential injection of alkali slug–polymer slug is the best injection strategy.

GRAPHICAL ABSTRACT



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ABSTRACT

The main objective of this study is to experimentally investigate the effect of polymer on the interaction of alkali with heavy oil and its use in enhancing heavy oil recovery. The results of sandpack flooding tests show that the combined polymer and alkali can lead to a remarkable increment in tertiary oil recovery compared to polymer-only flooding and alkaline-only flooding. However, there is an optimum polymer concentration to maximize the incremental oil recovery for the alkaline–polymer (AP) flooding. Besides, the sequential injection of alkaline slug-polymer slug can obtain better results than the co-injection of the polymer and alkali slug with the same injection volume of chemical formula. The microscopic studies indicate that the addition of polymer has detrimental effects on the generation of water droplets inside the oil phase (W/O droplet flow) during AP flooding, which results in lower sweep efficiency than alkaline-only flooding. Therefore, the AP flooding should take full advantage of the mechanism of W/O droplet flow and avoid the detrimental effects on the generation of W/O droplet flow with the addition of polymer, and thus can lead to a significant improvement of heavy oil recovery by AP flooding.

1. Introduction

Heavy oil refers to the viscous oil with high viscosity (greater than 100 mPa s) and high gravity (10–20° API). China possesses a large proportion of heavy oil resources, especially in the Liaohe, Shengli, Xinjiang, and Henan oilfields. With the continuous depletion of the light oil reserves, the effective development of the heavy oil resources seems quite important to meet relentless demands for energy. Compared to the light oil, the primary difficulty of the recovery of heavy oil is the high oil viscosity. So thermal methods are often considered to be the most widely used effective methods for recovery of heavy oil [1]. However,

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these methods are not suitable for thin layers (<10 m) and deep reservoirs (>1000 m). For these heavy oil reservoirs, water flooding is the most commonly used secondary oil recovery technique [2]. Unfortunately, the recovery of water flooding from heavy oil reservoirs is generally quite low due to unfavorable water-oil mobility ratio between the injected water and the viscous oil, which results in the injected water fingering through the oil and leaving large quantities of reserves behind [3]. Thus, it is vital to improve the sweep efficiency for water flooded heavy oil reservoirs.

Polymer flooding is the most widely used enhanced oil recovery (EOR) methods to improve the sweep efficiency for application in light oil reservoirs [4–6]. The oil–water mobility ratio can be improved by adding polymer to the injected water, which can create a very stable displacement front. However, polymer flooding is not suggested for reservoirs with the oil viscosity greater than 200 mPa s, according to the proposed screening criteria for polymer flooding [7,8]. Due to the viscosity of the heavy oil is usually greater than 200 mPa s or even higher, very high concentrations of polymer are required to improve the oil–water mobility ratio. As a result, the increased difficulty of injection together with the cost of chemical limits the large-scale practical application of polymer flooding in heavy oil reservoirs [9].

Since heavy oil usually contains sufficient acidic components, which can react with alkali-related chemicals to produce *in situ* surfactants [10]. Extensive research during the past decades has demonstrated that the alkaline flooding could offer potential for improving waterflooded heavy oil recovery [11–15]. As early as in 1970 s, Cooke et al. [16] observed that viscous oil-external emulsions were generated when an acidic oil and alkaline solution flowed in a porous medium. These emulsions tended to block the initial water channels, diverting the water flow to un-swept regions, and a noticeable increase of pressure drop was also observed along with displacement. Dong and Liu [17] observed in micromodel flooding tests that alkaline solution could penetrate the residual oil to form water-in-oil (W/O) emulsion, which increased the resistance to water flow, and diverted the injected water to un-swept regions, leading to improved sweep efficiency greatly. More recently, Pei [18] and Ge [19] carried out a thorough study of alkaline flooding using heavy oil samples collected from several heavy oil reservoirs in Shengli oilfield in China, with viscosities ranging from 325 to 2000 mPa s, and promising results were obtained. Ding [20] and Pei [21] demonstrated that the formation of water droplets inside the oil phase (W/O droplet flow) by the penetration of alkaline solution in oil was the dominant mechanism of alkaline flooding to enhance heavy oil recovery. They found that the W/O emulsion was simply a byproduct of alkaline solution penetration rather than the basic mechanism for enhanced oil recovery by alkaline flooding.

From the above review, the polymer flooding can increase the viscosity of the injected water to improve the oil–water mobility ratio [22–24], and the W/O droplet flow in alkaline flooding can block the high-permeability water channels to improve sweep efficiency by its high viscosity and the Jamin effect [25]. Due to alkaline–polymer (AP) flooding incorporates the aforementioned two displacement mechanisms, this process might be more effective to enhance heavy oil recovery. Therefore, the primary objective of this study is to experimentally investigate the effect of polymer on the interaction of alkali with heavy oil and its use in enhanced the recovery of heavy oil with higher viscosity. And it also presents the results of a series of micromodel studies to investigate the effect of polymer on the mechanism of W/O droplet flow during AP flooding for improving heavy oil recovery.

2. Experimental

2.1. Materials

The heavy oil sample collected from the Xiaba heavy oil reservoir (Shengli Oilfield, China) has a total acid number (TAN) of 4.66 mg KOH/gram of sample. The viscosity of the heavy oil was determined to be 3950 mPa s and the density was 981.6 kg/m^3 at 55 °C. Sodium hydroxide (NaOH) was chosen as the alkaline agent. Partially hydrolyzed polyacrylamide (HPAM) with molecular weights of 10×10^6 and hydrolysis degree of 24% was provided by Beijing Hengju Oilfield Chemical Agent Co. Ltd, China. The salinity of the brine sample was analyzed to be 5000 mg/L, and the divalent-ion concentration was relatively low. Therefore, alkaline solutions with NaOH and polymer solutions at different concentrations were prepared with 0.5 wt% sodium chloride (NaCl).

2.2. Measurements of viscosity

The Brookfield Viscometer (Model DV-II+, Brookfield, USA) was used to determine the viscosities of heavy oil and polymer solutions. The instrument is equipped with a temperature control system to keep the water temperature at 55 °C. Polymer solution was prepared by slowly adding polymer into the brine that was being stirred. After that, the solution was stirred for approximately 24 h until it became completely transparent. According to the literature [27], the shear rates used in this study were set at 0.31 s^{-1} in measurements of the viscosities of polymer solutions.

2.3. Sandpack flooding tests

Sandpack flooding tests were conducted horizontally at 55 °C. A core holder with an inside diameter of 2.35 cm and a length of 19.4 cm was used sandpack. Fresh 100–200 mesh quartz sands were packed the unconsolidated core to ensure good reproducibility for each test. To prevent air bubbles from forming during the packing of the sandpack, the quartz sand was poured in the water-filled core holder at a constant rate to obtain uniform packing. The porosity of the sandpack was about 42%. The absolute permeability of the sandpack was in the range of 2.0–2.3 darcy. The sandpack was saturated with the Xiaba heavy oil until the water cut in the effluent was less than 1%. After the oil saturated, the water flooding was first performed until the oil cut in the effluent was less than 1%. Then 0.5 PV of chemical slug was injected into the sandpack, followed by extended water flooding until the oil production ceased (oil cut <1%). The produced liquids were collected continuously and the amount of oil and water in the sample were determined and recorded with time. The pressure at the inlet of the sandpack was measured by a digital pressure gauge.

2.4. Micromodel studies

Micromodel flooding tests were conducted in a glass-etched micromodel. The pore network of the micromodel was patterned on the basis of the pore structure of reservoir core. The injecting well and producing well were located on the diagonal line of the model, which resembling a quarter 5 spot well pattern. The transparent micromodel allowed the dynamic displacement process to be visually observed using a camera apparatus.

3. Results and discussion

3.1. Sandpack flooding tests

21 sandpack flooding tests were carried out to investigate the effect of polymer and alkali on the oil recovery of heavy oil. From