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Effect of wettability alteration on enhanced heavy oil recovery by alkaline flooding

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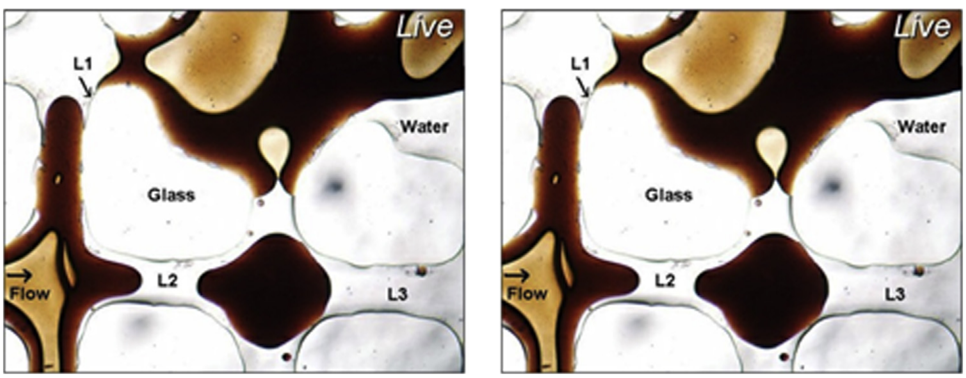
GRAPHICAL ABSTRACT



HIGHLIGHTS

- Alkaline flooding is a promising enhanced heavy oil recovery method.
- The wettability of the pore walls in the micromodel is changed.
- The contact angle can change from 24° to about 160°, under the action of alkalis.
- The wettability alteration can block the water channel and enhance the oil recovery.

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ABSTRACT

Alkaline flooding is a promising enhanced heavy oil recovery method. In this paper, this enhanced heavy oil recovery method is investigated in terms of its tertiary oil recovery potential and its effects on wettability alteration of the porous medium. Core flood tests show that the tertiary oil recovery can be greater than 10% of the initial oil in place (IOIP) by NaOH-only flooding or with NaOH and Na_2CO_3 mixed flooding systems. Micromodel experiments show that the wettability of the pore walls in the micromodel had been changed from water-wet to oil-wet, which can block water channeling and thereby improve the sweep efficiency. In order to prove the effect of wettability alteration on the enhanced heavy oil recovery, the contact angles of the heavy oil in alkaline solution on a quartz substrate have been measured. The results show that the contact angle can change from 24°, without alkali, to about 160°, under the action of NaOH or Na_2CO_3. The wettability alteration from water-wet to oil-wet can make

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the heavy oil adsorb at the rock surface and block the water channel. Therefore, the wettability alteration is one of the important mechanisms for enhanced heavy oil recovery by alkaline flooding.

1. Introduction

Alkaline flooding improves oil recovery, for conventional oils, by using an in situ surfactant generated from the reaction of alkalis and the natural organic acids in oil. The possible mechanisms of alkaline flooding for the improvement of conventional oil recovery include: (1) dispersion and entrainment of oil; (2) wettability reversal; and, (3) emulsification and entrapment of oil [1].

The in-situ surfactant can be adsorbed at the oil–water interface to reduce the interfacial tension (IFT). When the oil/water IFT is reduced to an ultralow level (less than 10^{-2} dyne/cm), residual oil can be emulsified in the reservoir, and recovery of the trapped oil is maximized [2]. If the IFT is sufficiently low, residual oil in a preferentially water-wet core can be emulsified in situ, moved downstream within the flowing alkaline solution, and entrapped again by pore throats that are too small for the oil emulsion droplets to penetrate. This reduces water mobility and improves the sweep efficiency [3]. Laboratory experimental results have shown that alkaline flooding can improve conventional oil recovery via the emulsion entrapment mechanism [4,5]. More and more attention has been paid to the recovery of heavy-oil resources because of the depletion of light oil resources [6]. Although enhanced heavy oil recovery is generally more challenging due to the oil's complex composition and high viscosity, heavy oil usually contains a high content of organic acids that can react with alkalis to form in-situ surfactants, which may help to improve oil recovery. Recent research studies have shown that waterflooding recovery of these heavy oils could be greatly improved by alkaline flooding [7–9]. Laboratory sandpack flood tests in these studies showed that a dilute chemical solution injection could cause either (1) heavy oil to be broken up into small droplets, entrained in the water phase, and carried out of the oil sands, or, (2) chemical solution in water channels with residual oil to form water-in-oil phase dispersions, thereby blocking the channels, resulting in improved sweep efficiency. If the displacement mechanisms are well understood, water flooding for these heavy oil reservoirs can be improved by applying an optimal chemical formulation to achieve the displacement process best suited to the situation.

In fact, there are two interfaces involved in the displacement process in the porous medium: the oil–water interface and the oil-solid (reservoir) interface [10,11]. The former is related to the oil–water interfacial tension and the latter is related to the reservoir wettability. The investigation of the low oil–water interfacial tension and the wettability change of the oil-solid interface are both very important for enhanced oil recovery [12–14]. Much attention has been paid to the low interfacial tension [15,16], and the formation of emulsions is related to the variation of IFT [17].

The mechanisms of enhanced heavy oil recovery by the formation of emulsions have been proposed based on IFT measurements and micromodel observations [18–20]. Dong et al. [20] have analyzed the heavy oil EOR mechanisms in alkaline flooding by observing two distinct displacement processes in micro-model tests, and found that the displacement mechanisms of alkaline flooding are in situ water-in-oil (W/O) emulsion formation. The W/O emulsion, formed during the injection of alkaline solution, plugs high permeability water channels, leading to an improvement in sweep efficiency and high tertiary oil recovery.

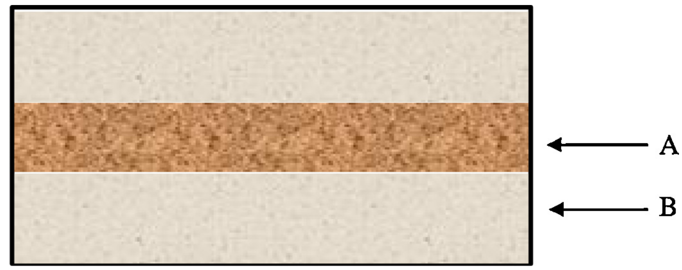

Fig. 1. Schematic diagram of the cross section of a channeled sandpack. (A) Coarse sand in the channel in the center of the holder. (B) Fine sand in the annulus.

It has also been found that good residual oil recovery can be achieved by the surface wettability changes at normal interfacial tensions (10^0 to 10^2 dyne/cm); in experiments at such conditions, no formation of emulsion was observed [21]. Wettability is one of the major factors that controls the distribution and flow of fluids in the pores of a reservoir [22–24]. The injection of an alkaline solution to improve oil recovery could reverse rock wettability from water-wet to oil-wet [25]. Cooke et al. [26] observed that, under the proper conditions of pH, salinity, and temperature, some oil reservoirs were converted from water-wet to oil-wet with the help of a NaOH solution. As a result, discontinuous, non-wetting residual oil was converted to a continuous wetting phase, which provided a flow path for what would have otherwise been trapped oil. Kowalewski et al. [27] conducted wettability tests using Berea sandstone, brine (NaCl), and *n*-decane with different concentrations of hexadecylamine. The wettability of the sandstone samples was changed from water-wet to neutral, due to the adsorption of hexadecylamine into the rock surface. Therefore, the wettability alteration caused by the adsorption of a surface-active agent on the pore surfaces of a porous rock can enhance conventional oil recovery.

The key to a non-thermal heavy oil EOR, such as alkaline flooding, is to block the water channels which have been formed during the initial waterflood. However, it has not been well understood how the injection of alkaline solution plugs the high permeability water channels by altering the wettability of pore walls, leading to an improvement in sweep efficiency and high tertiary oil recovery. In this work, channeled sandpacks were employed in flood tests to evaluate the sweep efficiency of alkaline flooding for heavy oil recovery in heterogeneous reservoirs. Glass micromodel tests and contact angle measurements of heavy oil in an alkaline solution on a quartz substrate were carried out to investigate the mechanisms of enhanced heavy oil recovery by wettability alteration.

2. Experimental

2.1. Chemicals

Heavy oil and formation brine samples were collected from the Pelican Lake reservoir, Alberta, Canada. The heavy oil sample was centrifuged at 10,000 rpm, at 35 °C, for two hours to remove water and solids from the oil. Afterwards, the oil and brine samples were analyzed for fluid characteristics at 22 °C. The oil and brine properties are listed in Table 1. As shown in the table, the heavy oil has a relatively high acid number of 1.07 mg KOH/g-oil, which is desirable for the alkaline flooding process. Meanwhile, the brine