MICROMODEL STUDY OF THE DISPLACEMENT MECHANISMS OF ENHANCED HEAVY OIL RECOVERY BY ALKALINE FLOODING

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ABSTRACT
In this study, the displacement mechanisms of alkaline flooding in enhanced heavy oil recovery (EOR) are investigated by using a micromodel. It has been observed that two mechanisms govern the EOR process. One is a novel mechanism ─ *in situ* water-in-oil (W/O) emulsion and partial wettability alteration. The W/O emulsion formed in the injection of alkaline solution blocks the high permeability zone and the pore walls are altered to partially oil-wet, leading to an increase in pressure drop and high tertiary oil recovery. The other mechanism is formation of an oil-in-water (O/W) emulsion. Heavy oil is emulsified in brine by an alkaline plus very dilute surfactant formula and then entrained in the water phase and produced out of the model.

INTODUCTION
Alkaline flooding improves oil recovery by using *in situ* surfactants produced from the reaction of alkali and the natural organic acids. Johnson (1976) summarized the three possible mechanisms of alkaline flooding to improve oil recovery. These include (1) dispersion and entrainment of oil, (2) wettability reversal, and (3) emulsification and entrapment of oil. Johnson (1976) also pointed out that each mechanism worked under different injection conditions with respect to oil, formation rock, and injection water properties, and, therefore, each process should be designed to improve oil recovery in a somewhat different manner. Alkaline flooding has been extensively studied in EOR for conventional oils, including numerous laboratory experiments and some field tests. For heavy oils, the investigations on EOR by alkaline flooding are very limited due to the adverse mobility ratio between the water and oil phases. Compared with the conventional oils, Western Canadian heavy oils are more viscous (usually with viscosities ranging from 1,000 to more than 10,000 mPa.s). The results of sandpack flood tests (Liu, 2006; Liu et al., 2006; 2007; Ma et al., 2007) showed that waterflood recovery of these heavy oils could be improved greatly by alkaline flooding. If the mechanism of oil displacement

is elucidated, the oil displacement process can be optimized to maximize oil recovery. The heavy oil used in the reference by Ma et al. (2007) was used in this study to unravel the EOR mechanisms by observing the alkaline flood process in micromodel tests.

EXPERIMENTAL

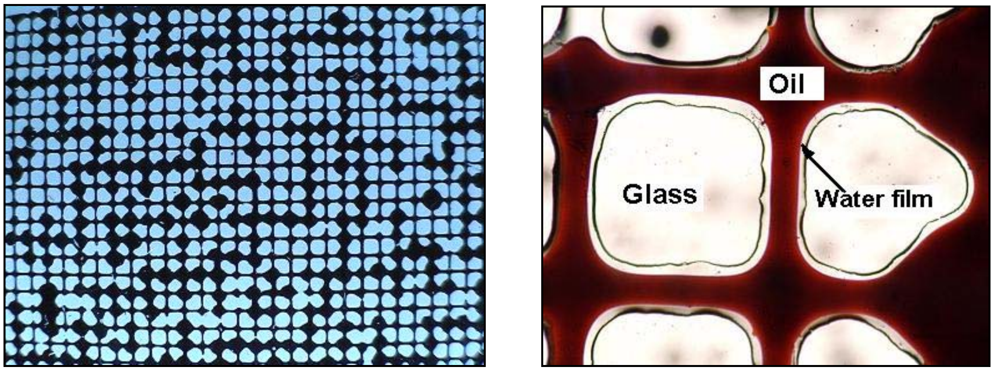
The glass micromodel was cleaned first with Varsol (commercial paint thinner) and then with ethanol to remove any oil left in the model after the previous displacement test. The model was blown by air to remove the residual solvent. To keep it strongly water-wet, the model was heated in a muffle furnace at 400°C for one hour to remove trace organic compounds adsorbed on the pore surface. The displacement procedure for a micromodel test is as follows: 1) saturate the micromodel with water phase; 2) inject the heavy oil at 60°C; 3) conduct waterflood for 2 pore volumes (PV) at 60°C; 4) conduct alkaline flood at ambient temperature. In Step 2, a higher temperature is applied to obtain relatively high water saturation (thicker water film); in Step 3, the mobility of heavy oil was increased at 60°C so that there was a better sweep efficiency for water flooding. The chemical agents used in this study included NaOH, Na_2CO_3, and surfactant Stepanol Me Dry (sodium lauryl sulfate from Stepan, Canada).

RESULTS AND DISCUSSION

Two EOR Mechanisms of Alkaline Flooding

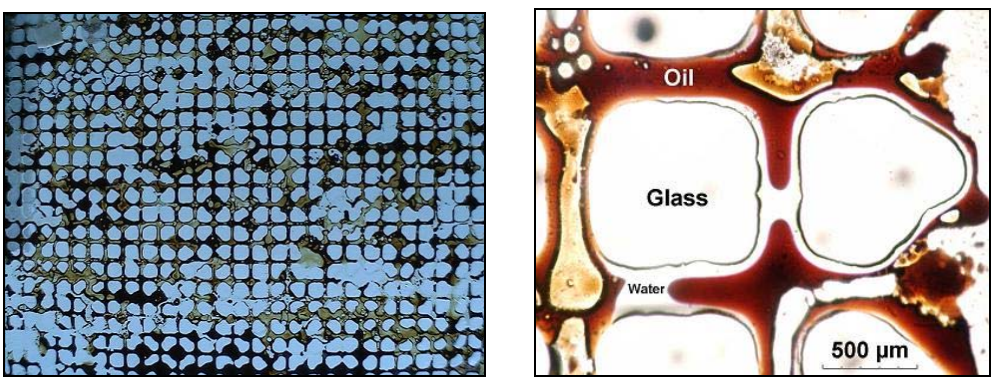
In micromodel tests, the oil and water distribution after the model was saturated with oil and connate water is shown in Figure 1. Figure 1A is a picture of the micromodel containing heavy oil and irreducible water at the end of oil injection. Figure 1B is an image of pore-level oil and water distribution. This image shows water films surrounding the solid boundaries and the continuous oil phase staying in the central portion of pores and throats of the pore network. The image also illustrates that the micromodel is water-wet.

Two EOR mechanisms were observed in micromodel tests: one is W/O emulsion and partial wettability alteration; the other is emulsification and entrainment of heavy oil in water phase. Figure 2 shows the picture of the micromodel network with an injection of a chemical slug consisting of 0.40 wt% NaOH + 0.20 wt% Na_2CO_3. In alkaline injection, the injected water phase penetrated into the residual oil phase and created some discontinuous water ganglia inside the oil channels to form W/O emulsion. The viscosity of W/O emulsion is much higher than that of the crude oil. Therefore, the oil was displaced in the form of W/O emulsion with little fingering effect. Some oil also touched the pore walls, indicating that the pore wall became partially oil-wet. The wettability alteration also aided in blocking the water flow in those channels. The improvement in oil displacement efficiency is verified in many sandpack flood tests for other heavy oils (Liu, 2006; Liu et al., 2007). Figure 3 shows the pressure drop curve for the micromodel test of alkaline flooding. When the pressure drop declined to a certain low value (at 100 minutes) during waterflood, chemical slug injection was initiated. As shown in Figure 3, the pressure drop increased continuously up to 12.4 kPa because of the the formation of W/O emulsions which had a higher viscosity than the oil. At the time of 256 minute a rapid decrease in pressure drop was observed because the alkaline solution broke through the model outlet. After that no further oil was recovered.



(A) Portion of micromodel (B) pore-level image

Figure 1. Micromodel with heavy oil and irreducible water saturation.



(A) Portion of micromodel (B) pore-level image

Figure 2. Formation of W/O emulsion in alkaline injection.

In micromodel tests, the O/W emulsion mechanism dominated the displacement in EOR by injecting an alkaline/surfactant (A/S) formula (0.20 wt% NaOH + 0.40 wt% Na_2CO_3 + 450 mg/L surfactant). Figure 4 shows the emulsification and entrainment of the heavy oil in the water phase in the injection of an A/S slug. Because of the use of the surfactant, the interfacial tension between oil and water was lowered to 10^{-3} dyne/cm. The oil was emulsified and entrained into the water phase. The emulsion flow in porous media also led to a build up of the pressure drop and improvement in oil recovery in sandpack flood tests. However, the increase in pressure drop in this process is not as evident as in the W/O emulsion process.

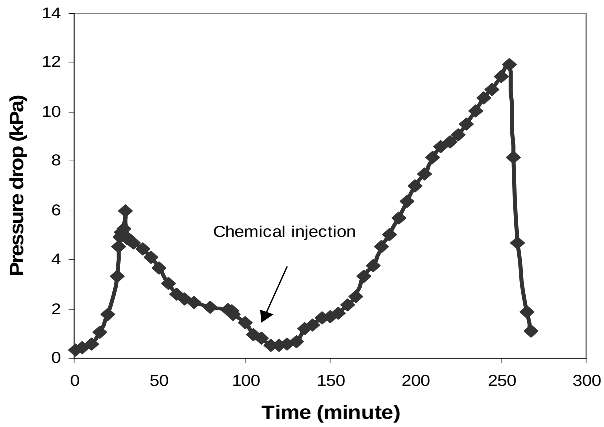
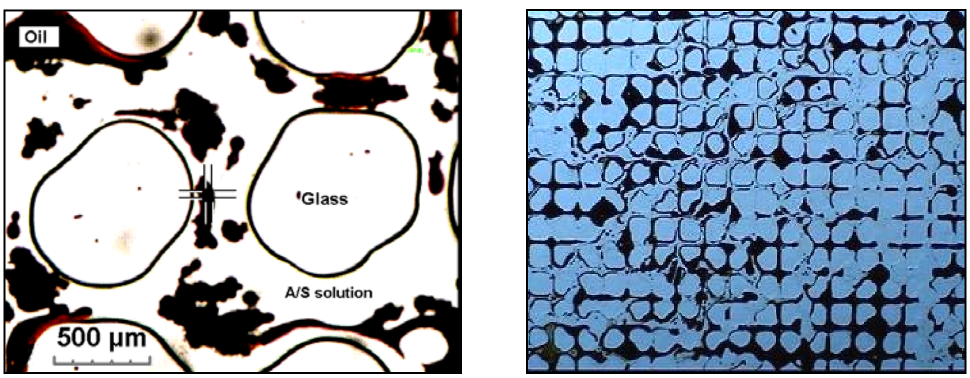


Figure 3. Pressure drop in water and alkaline flooding in a micromodel test.

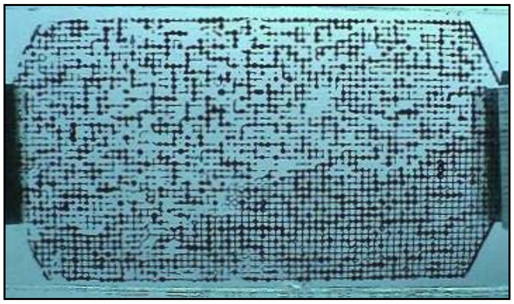


(A) (B)

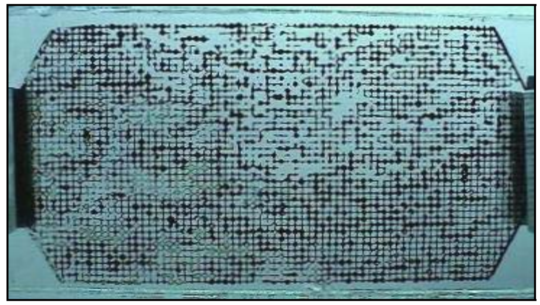
Figure 4. Emulsification and entrainment of heavy oil in water phase in micromodel test. A) pore-level image, B) image of micromodel during oil displacement.

Comparison of Sweep Efficiency of Two EOR Processes

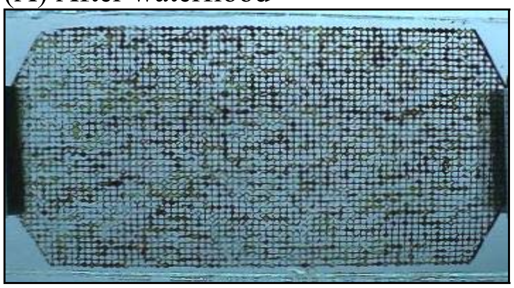
The two EOR processes resulted in different displacement efficiencies which can be visualized in micromodel tests. Figure 5 shows the pictures of the whole micromodel at different stages of alkaline flooding with an alkaline slug. Figure 5A was taken after the initial waterflood, showing that some water channels (light colored) were created. When the alkaline solution was injected, as shown in Figure 5B, the water channels were eliminated by re-mobilized residual oil, and the area behind the displacement front became relatively uniform. It is the blocking of water channels that diverted the injected alkaline solution phase to the un-swept region of the model to improve the sweep efficiency. Figure 5C shows the micromodel when the alkaline slug front reached its



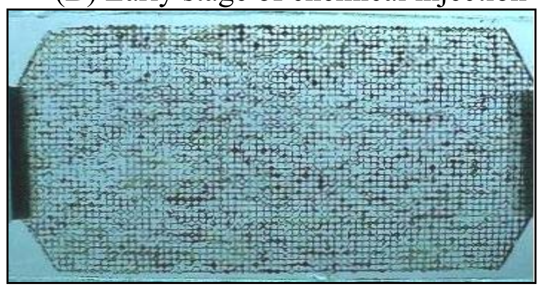
(A) After waterflood



(B) Early stage of chemical injection

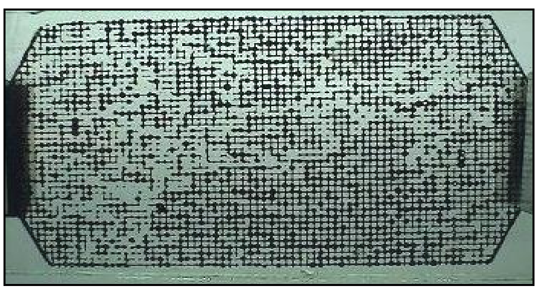


(C) Chemical slug reached production end

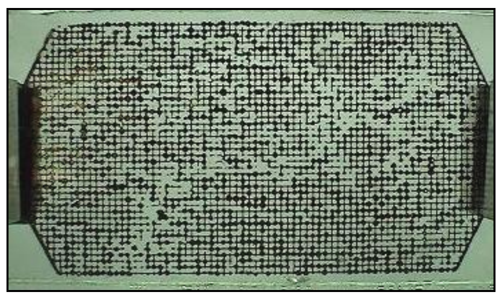


(D) At 1.0 PV chemical injection

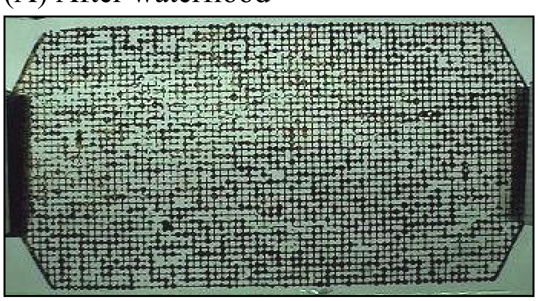
Figure 5. Pictures of micromodel test with alkaline injection.



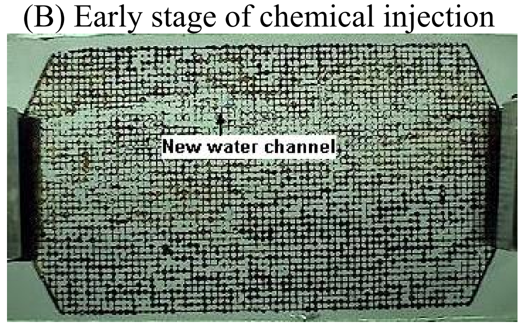
(A) After waterflood



(B) Early stage of chemical injection



(C) Chemical slug reached production end



(D) At 1.0 PV chemical injection

Figure 6. Photos of micromodel test with alkaline/surfactant injection.

outlet, displaying a relatively uniform oil saturation distribution over the entire model. Figure 5D shows the model after approximately one pore volume of alkaline solution injection. From the color of the model, it is seen that the oil saturation was greatly reduced, compared with the model in Figure 5C, and was still uniform.

Figure 6 shows the pictures of the whole micromodel at different stages of A/S injection (0.20 wt% NaOH + 0.40 wt% Na_2CO_3 + 450 mg/L surfactant). Figure 6A shows the oil saturation distribution after waterflood with some water channels. In the early stage of chemical injection, as shown in Figure 6B and 6C, sweep efficiency was improved by the injection of A/S solution. The water channels disappeared in the region behind the displacement front. By injecting an A/S slug, O/W emulsion was formed in the pores and the residual oil was mobilized by O/W emulsion flow. After the injection of 1 PV of chemical solution, as shown in Figure 6D, some new water channels were created. In this situation, the oil production declined rapidly and the further injection of A/S solution had poor sweep efficiency.

CONCLUSIONS

Alkaline solution can penetrate into heavy oil in porous media, forming W/O emulsions. Due to the very high viscosity of the W/O emulsion, the resistance to water flow in high water saturation zone can be increased to improve sweep efficiency. When an alkaline/surfactant formula is used to create ultralow IFT and O/W emulsion for a heavy, the oil can be produced by the mechanism of O/W emulsion flow. The pressure drop along the model is much lower for this mechanism compared with that of the mechanism of W/O emulsion. The two displacement mechanisms can be applied individually or in combination for improving waterflooding of heavy oils.

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