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Research Article

Influence of Oil Viscosity on Alkaline Flooding for Enhanced Heavy Oil Recovery

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Oil viscosity was studied as an important factor for alkaline flooding based on the mechanism of "water drops" flow. Alkaline flooding for two oil samples with different viscosities but similar acid numbers was compared. Besides, series flooding tests for the same oil sample were conducted at different temperatures and permeabilities. The results of flooding tests indicated that a high tertiary oil recovery could be achieved only in the low-permeability (approximately 500 mD) sandpacks for the low-viscosity heavy oil (Zhuangxi, 390 mPa·s); however, the high-viscosity heavy oil (Chenzhuang, 3450 mPa·s) performed well in both the low- and medium-permeability (approximately 1000 mD) sandpacks. In addition, the results of flooding tests for the same oil at different temperatures also indicated that the oil viscosity put a similar effect on alkaline flooding. Therefore, oil with a high-viscosity is favorable for alkaline flooding. The microscopic flooding test indicated that the water drops produced during alkaline flooding for oils with different viscosities differed significantly in their sizes, which might influence the flow behaviors and therefore the sweep efficiencies of alkaline fluids. This study provides an evidence for the feasibility of the development of high-viscosity heavy oil using alkaline flooding.

1. Introduction

Thermal methods are the primary ways to develop heavy oil reservoirs. However, severe heat losses reduce the effectiveness of thermal processes in deep or thin heavy oil reservoirs and increase the production cost. Inexpensive alkaline reagents can react with the organic acids in heavy oil and form massive amounts of surfactant *in situ* at the oil/water interface, by which the interface tension (IFT) can be reduced greatly [1–5]. In recent years, a new mechanism proposed by Ding et al. [6] has attracted the attention of researchers. He described the interfacial reaction between the oil phase and the alkaline solution in detail and proposed two stages related to the reaction during the alkaline flooding process. The first stage was the occurrence of water columns that resulted from the penetration of the alkaline solution into the crude oil. The second stage was the division of these water columns into small discontinuous water droplets due to the nonuniform enrichment of surfactants at the oil/water interface. The viscous fingering effect was significantly reduced by the presence of water drops inside the oil phase. In contrast, the water in oil (W/O) emulsion was simply a byproduct of alkaline liquid penetration rather than the basic mechanism of enhanced oil recovery (EOR) during alkaline flooding. They also observed differences of water breakthrough and alkaline breakthrough. In water flooding, after water breaks through, several connected water channels are created diagonally and little oil can be recovered by continued water flooding. Consequently, most of the oil is bypassed, due to the viscous fingering caused by the adverse mobility ratio between the oil and the water. In alkaline flooding, after alkaline breaks through, it can be seen that relatively uniform degree oil saturation is distributed over the entire model. Oil is subsequently displaced in the form of the "water drop" with little viscous fingering. Therefore, it is the "water drop" mechanism that reduces the mobility of water phase and diverts the injected alkaline solution to the unswept region of micromodel to improve the sweep efficiency.

The mechanism of "water drops" flow allowed the successful interpretation to some phenomena in alkaline flooding.

Many factors influence the performance of alkaline flooding. Arhuoma et al. [7] investigated the influence of alkaline concentration on the alkaline flooding for Alberta heavy oil through sandpack flooding tests using NaOH as the alkaline reagent. Their results indicated that the recovery initially increased with the increase of alkaline concentration; afterwards, the variation became very slight or even decreased, which suggests that an optimum concentration exists for enhancing the oil recovery. Almalik et al. [8] have studied the influence of the alkaline type and the injection mode on oil recovery. They observed that NaOH performed better than $Na_3PO_4{\cdot}12H_2O$ and KOH under identical conditions, and the continuous alkaline flooding yielded a higher recovery than when slugs were used. Previous research has been primarily focused on these dynamic injection conditions. However, a few static reservoir conditions have been also studied in some reports. Chiwetelu et al. [9] and Trujillo [10] have investigated the influence of reservoir temperature on alkaline flooding, the results showed that about 12% more oil was recovered at 65°C than at 25°C, and the IFT values were significantly greater at higher temperatures which was considered as the main reason for the change regulation.

The static conditions of heavy oil reservoirs are complicated and different with each other, which can also influence the effectiveness of alkaline flooding significantly. Among these static conditions, oil viscosity may exhibit the largest variation range in heavy oil reservoirs. However, the previous study about this aspect is insufficient to satisfy the requirement to design a good EOR plan. Therefore, the influence of oil viscosity on alkaline flooding in heavy oil reservoirs is investigated here by sandpack flooding experiments.

2. Experimental

2.1. Fluids and Chemicals. Oil samples were collected from the heavy oil reservoirs of Zhuangxi, Chenzhuang, Xia-8 and Binnan in Shengli Oilfield; their viscosities were measured by a rotary viscometer, and the viscosity-temperature properties are shown in Figure 1. The acid-number of these four oil samples were measured by potentiometric titration method, and the results are listed in Table 1. All the aqueous phase was brine that contained 0.5 wt% NaCl. Chemicals used in this study, such as NaOH and NaCl, were all analytical-grade reagents supplied by Sinopharm.

2.2. IFT Measurements. The dynamic IFT values between heavy oil and alkaline solutions were measured at 50°C using an American Texas-500 spinning drop tensiometer according to the following:

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

where σ is the interfacial tension (mN/m), ρ_w is the density of the water phase (g/cm^3), ρ_o is the density of the oil phase (g/cm^3), ω is the rotational velocity (rpm), D is the measured drop width (mm), L is the length of the oil drop (mm), and n is the refractive index of the water phase.

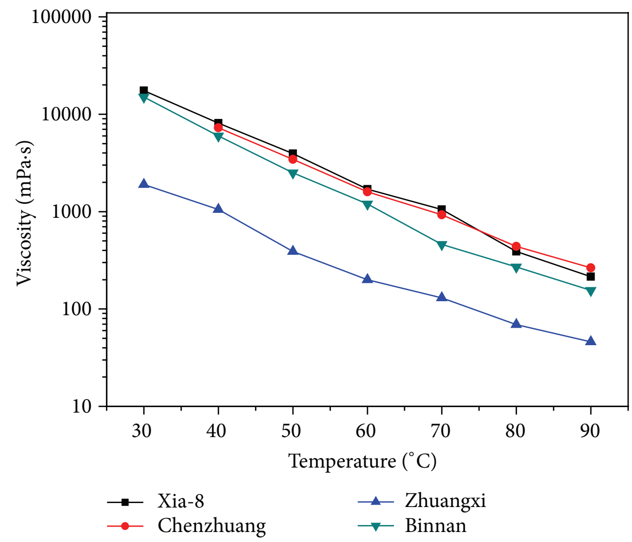


Figure 1: Viscosity-temperature curves of four types of heavy oil.

2.3. Microscopic Flooding Tests. The glass-etched micromodel was used to investigate the displacement mechanisms of alkaline flooding. The micromodel was made by the two same glass plates which were impacted tightly, and the pore throats were etched on the interface by special corrosive substances. The procedure of the microscopic flooding test was described as follows: the micromodel was first saturated with brine after being vacuumed, and it was subsequently displaced by heavy oil until no more brine was produced. The alkaline solution was then injected at a constant flow rate of 0.003 mL/min. The flooding tests can be visualized using a video recorder and camera apparatus.

2.4. Sandpack Flooding Tests. The sandpacks used in this study were 30 cm in length and 2.45 cm in diameter. They were wet-packed as follows: first, fresh quartz sand with 100–200 and 80–100 mesh sizes was blended at a weight ratio of 3 : 1. The sandpack was positioned vertically, and the sand was then added into the sandpack filled with brine water in several increments. In each step, the sand in the sandpack was shaken slightly after being added. The water surface was kept above the sand surface to avoid the intrusion of air.

The sandpack displacement was conducted at 50°C using the following procedure: first, the sandpack was saturated with brine solution, and then the permeability was measured and the porosity was calculated. Afterward, the sandpack was subsequently saturated with the heavy oil until no more water was produced (the water cut was less than approximately 1 vol%). After the oil injection, water flooding was conducted until the oil cut was less than 1 vol%, and then a chemical slug of 0.3 pore volume (PV) was injected. The injection of the chemical slug was followed by an extended period of water flooding until the oil production became negligible (oil cut

Table 1: Basic properties of four types of heavy oil.

Heavy oil	Density at 50°C (g/cm^3)	Viscosity at 50°C (mPa·s)	Acid number (mg KOH per g sample)
Zhuangxi	0.9302	390	1.85
Chenzhuang	0.9778	3450	2.02
Binnan	0.9632	2500	3.85
Xia-8	0.9712	3950	4.66

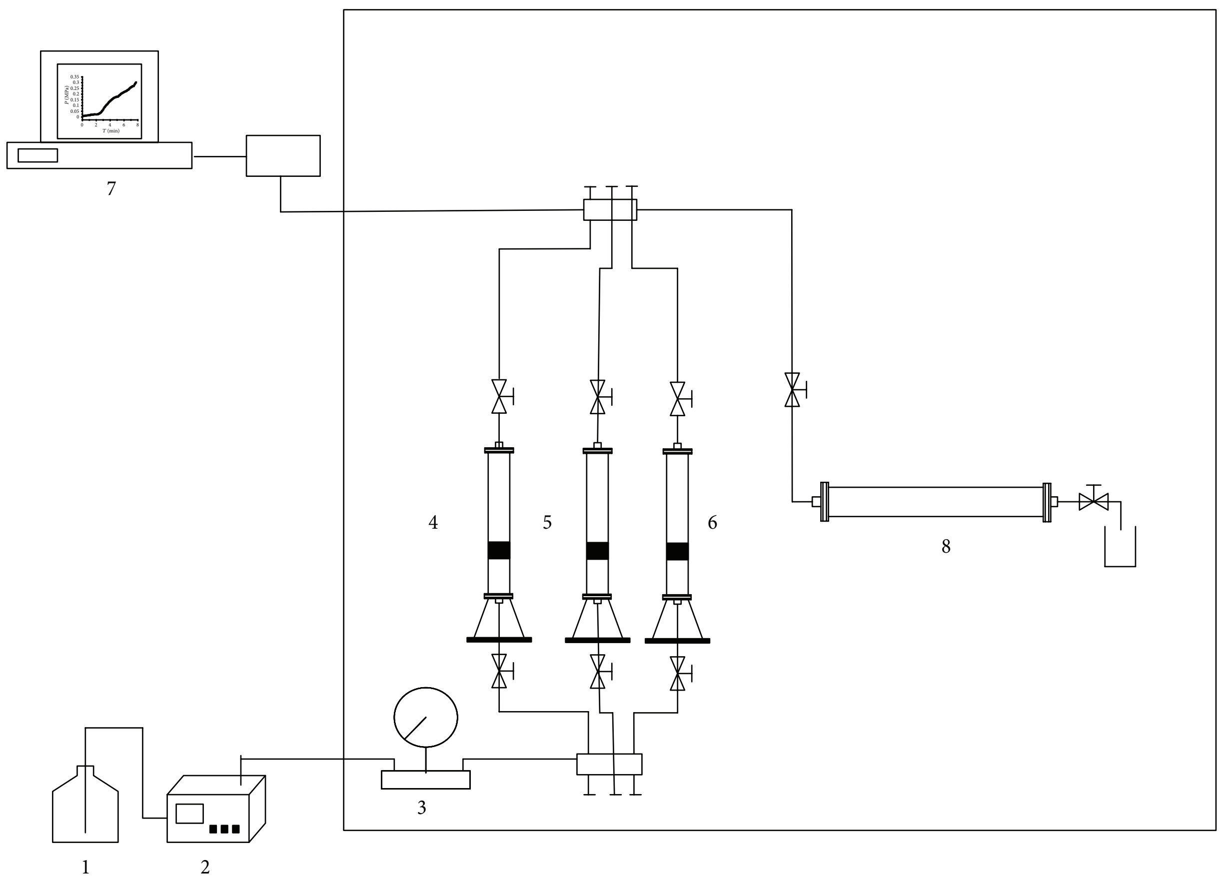


Figure 2: The equipment for sandpack flooding. 1, distilled water; 2, pump; 3, pressure meter; 4, brine water container; 5, crude oil container; 6, alkaline solution container; 7, pressure collection system; 8, Sandpack model.

< 1 vol%). The injection rate of the brine solution and the chemical slug was set at 0.5 mL/min.

The equipment for the sandpack flooding is shown in Figure 2.

3. Results and Discussion

3.1. Performance of Alkaline Flooding for Oils with Different Viscosities. To investigate the influence of oil viscosity on the performance of alkaline flooding, alkaline flooding for two oil samples with different viscosities, and similar acid numbers were compared. Then, series flooding tests for the same oil sample were conducted at different temperatures.

Zhuangxi and Chenzhuang heavy oil were selected for their similar acid numbers and different viscosities, as shown in Figure 1 and Table 1. 18 alkaline flooding tests (Runs 1 ~ 18) were conducted in sandpacks with three levels of permeability: low-permeability (approximately 500 mD), medium-permeability (approximately 1000 mD), and high-permeability (approximately 2000 mD). Three alkaline concentrations were investigated at each permeability level. The parameters of the sandpacks, the chemical formulas, and the flood results are summarized in Table 2.

The alkaline flooding performances of these two oil samples were significantly different, as shown in Figures 3 and 4. The correspondingly dynamic recovery with the production is shown in Figure 5. For the Zhuangxi heavy oil with a relative low-viscosity, the incremental oil recovery was greater than 20% when the sandpack permeability was approximately 500 mD; however, it declined significantly as the permeability increased, and the tertiary oil recovery was only 5 ~ 10% in the high-permeability sandpacks. For the Chenzhuang heavy oil, which exhibits a higher

Table 2: Summary of sandpack flooding tests for different heavy oils.

Run no.	Heavy oil	Permeability (mD)	Initial oil saturation (%)	Chemical formula	Equilibrium IFT (mN/m)	Recovery (%)		
						Water flooding	Alkaline flooding	Total
1	Zhuangxi	570	90.0	0.25% NaOH + 0.5% NaCl	0.600	29.0	22.9	51.9
2	Zhuangxi	488	82.4	0.5% NaOH + 0.5% NaCl	0.064	36.7	26.7	63.4
3	Zhuangxi	570	84.9	1% NaOH + 0.5% NaCl	0.200	23.1	29.7	52.8
4	Zhuangxi	1120	83.7	0.25% NaOH + 0.5% NaCl	0.600	36.7	7.2	43.9
5	Zhuangxi	985	88.1	0.5% NaOH + 0.5% NaCl	0.064	37.5	12.4	49.9
6	Zhuangxi	1075	84.5	1% NaOH + 0.5% NaCl	0.200	35.5	16.5	52.0
7	Zhuangxi	1875	88.0	0.25% NaOH + 0.5% NaCl	0.600	39.4	5.6	45.0
8	Zhuangxi	2080	87.4	0.5% NaOH + 0.5% NaCl	0.064	39.9	9.3	49.2
9	Zhuangxi	2125	89.5	1% NaOH + 0.5% NaCl	0.200	40.6	10.4	51.0
10	Chenzhuang	558	85.1	0.25% NaOH + 0.5% NaCl	0.122	31.8	14.7	46.5
11	Chenzhuang	577	82.6	0.5% NaOH + 0.5% NaCl	0.096	33.2	20.1	53.3
12	Chenzhuang	543	86.3	1% NaOH + 0.5% NaCl	0.180	35.3	21.3	56.6
13	Chenzhuang	1025	84.4	0.25% NaOH + 0.5% NaCl	0.122	35.8	15.3	51.1
14	Chenzhuang	1180	85.7	0.5% NaOH + 0.5% NaCl	0.096	37.3	21.4	58.7
15	Chenzhuang	1065	84.2	1% NaOH + 0.5% NaCl	0.180	37.8	23.9	61.7
16	Chenzhuang	2135	89.1	0.25% NaOH + 0.5% NaCl	0.122	40.2	8.6	48.8
17	Chenzhuang	2110	86.1	0.5% NaOH + 0.5% NaCl	0.096	39.8	12.9	52.7
18	Chenzhuang	2240	88.5	1% NaOH + 0.5% NaCl	0.180	40.2	13.5	53.7

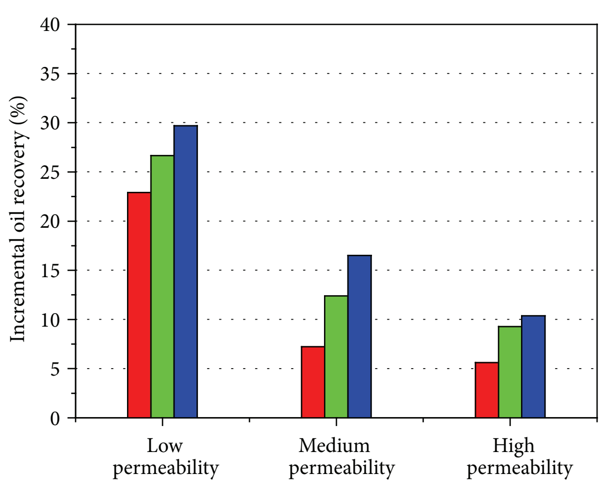


Figure 3: Alkaline flooding performance of Zhuangxi heavy oil.

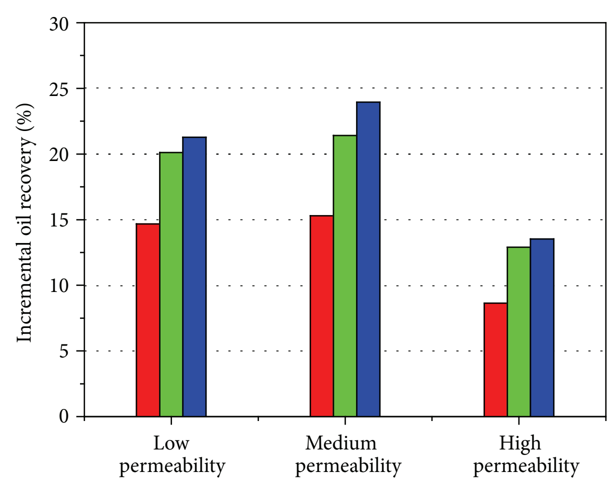


Figure 4: Alkaline flooding performance of Chenzhuang heavy oil.

viscosity, the tertiary oil recovery was as high as 20% at both low- and medium-permeabilities, but it also decreased when the permeability was approximately 2000 mD. These results demonstrate that oil with a higher viscosity exhibits a wider range of applicable permeability and that only in the low-permeability sandpacks can the low-viscosity heavy oil such as Zhuangxi oil achieve a high tertiary oil recovery.

Subsequently, temperature was changed to achieve different oil viscosities for the same oil sample. Xia-8 and Binnan heavy oil were selected for these tests, and their basic properties are also shown in Table 1.

For the Xia-8 heavy oil, the sandpack flooding tests were conducted at viscosity values of 18,235 mPa·s (30°C), 3950 mPa·s (50°C), and 1083 mPa·s (70°C). Similarly, the tests were performed at viscosity values of 15,030 mPa·s (30°C),

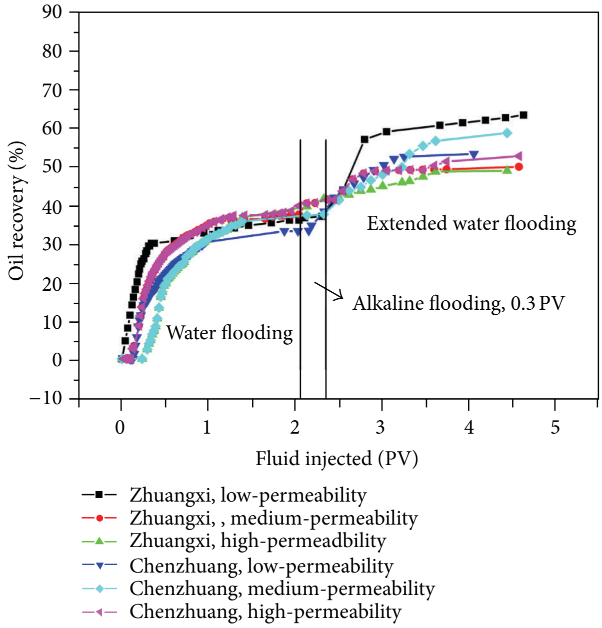


FIGURE 5: Oil recovery curves for different permeability sandpacks (alkaline concentration = 0.5 wt%).

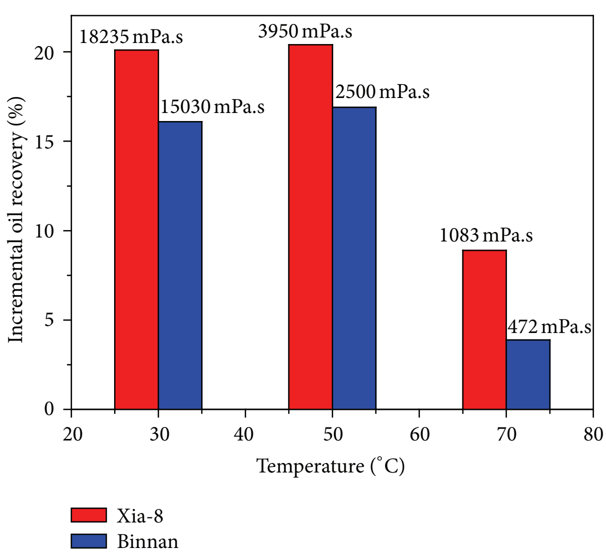


FIGURE 6: Influence of oil viscosity on the alkaline flooding efficiency.

2500 mPa·s (50°C), and 472 mPa·s (70°C) for the Binnan heavy oil. The chemical formula of 0.5% NaOH + 0.5% NaCl was used for all of the sandpack flooding tests. The test parameters and flood results are summarized in Table 3.

The incremental oil recoveries of the sandpack flooding tests are shown in Figure 6. The results lead to the conclusion that the behaviors of tertiary oil recovery for the two oil samples are similar with the variation of oil viscosity. The incremental oil recovery reached 20% at 30°C and 50°C for the oil with high-viscosity, and it declined intensively at 70°C for the oil with low-viscosity.

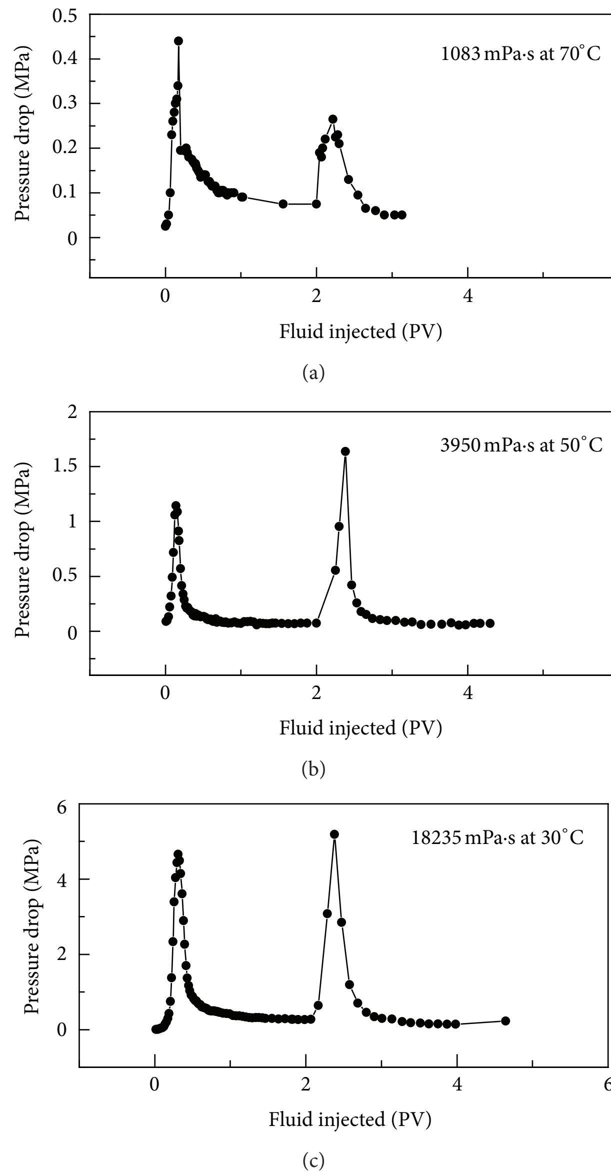
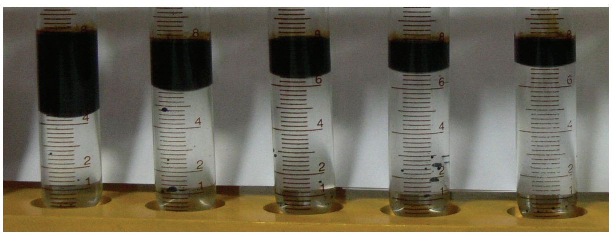


FIGURE 7: Pressure changes during alkaline flooding for Xia-8 heavy oil with different viscosities.

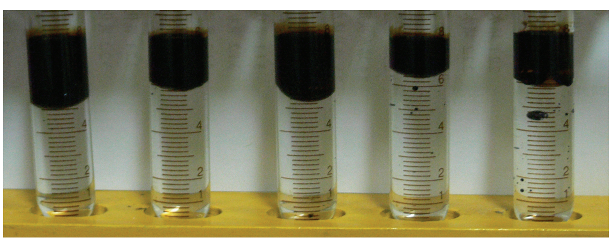
In Figure 7, the displacement pressure drop is plotted as a function of the injected volume. It shows that the peak pressure drop during alkaline flooding is higher than that during water flooding for the Xia-8 heavy oil, except for the oil at low-viscosity (70°C). It means that the plugging effect of water drops formed by injected alkaline solution is weakened for the low-viscosity oil sample. This result is consistent with the results of the sandpack flooding tests. Pictures of the effluent in these tests are shown in Figure 8. It can be seen that the interface of the produced fluid is clear, and the upper phase is the water drops inside the oil phase when the oil viscosity is high (30°C and 50°C). However, because the formation of water drops inside the oil phase cannot be implemented easily for the oil with low-viscosity (70°C), the alkaline solution injected into the

Table 3: Summary of sandpack flooding tests for Xia-8 and Binnan heavy oil.

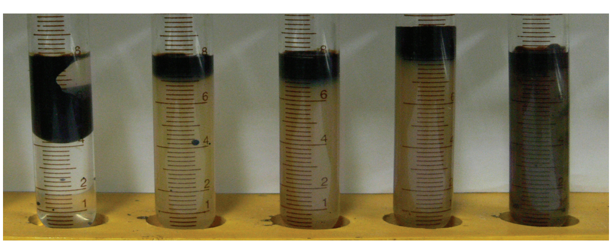
Run no.	Heavy oil	Viscosity (mPa·s)	Permeability (mD)	Initial oil saturation (%)	Recovery (%)		
					Water flooding	Alkali flooding	Total
1	Xia-8	18235	1425	83.4	34.7	20.1	54.8
2	Xia-8	3950	1380	82.7	37.6	20.4	58.0
3	Xia-8	1083	1580	85.9	43.3	8.9	52.2
4	Binnan	15030	1380	82.9	37.8	16.1	53.9
5	Binnan	2500	1425	83.7	39	16.9	55.9
6	Binnan	472	1380	87.1	42.9	3.9	46.8



(a) 18235 mPa·s at 30°C



(b) 3950 mPa·s at 50°C



(c) 1083 mPa·s at 70°C

Figure 8: Pictures of the fluid produced during the displacement tests of Xia-8 heavy oil with different viscosities. (Effluents during alkali injection and the extended water flooding were collected in the tubes from left to right in turn. The pictures show their appearances at the end of flooding, without demulsification.)

sandpack mainly streams forward along the water channels and forms a muddy oil in water (O/W) emulsion, as shown in Figure 8(c). Consequently, heavy oil with a relative low-viscosity is unfavorable for alkaline flooding.

3.2. Mechanism of Oil Viscosity on the Performance of Alkaline Flooding. In conventional oil reservoirs, high-permeability and low oil viscosity are both favorable for development. However, the results of sandpack flooding tests indicate that this behavior is different for alkaline flooding in heavy oil reservoirs. Microscopic flooding tests were conducted to investigate the mechanism of this anomalous phenomenon, and the images intercepted from the flooding process are shown in Figure 9. It can be seen that there are a lot of water drops inside the oil phase existing in the models for both Chenzhuang and Zhuangxi heavy oils. These drops can plug the pore throats and improve the sweep efficiency for displacing phase. Compared to Chenzhuang heavy oil, the size of water drops formed in Zhuangxi heavy oil is obviously smaller, and numerous drops can exist in the same pore throat. These smaller water drops can effectively plug the small pores in the low-permeability cores, but this capacity decreases intensively in the high-permeability sandpacks. Therefore, good flooding performance could be achieved only in the low-permeability sandpacks. Figure 10 shows the pressure changes during the flooding process for the Zhuangxi heavy oil in the cores with different permeabilities. The displacement pressure increased significantly when the alkaline solution was injected into the low-permeability sandpacks; however, it changed little in the medium- and high-permeability sandpacks, which indicated that the water drops cannot plug the pores effectively.

In contrast, when the alkaline solution penetrated into the oil with a higher viscosity, that is, the Chenzhuang heavy oil shown in Figures 9(d), 9(e), and 9(f), the water drops were large, and even the throat could be occupied by only one drop. These water drops could plug the pores in both the low- and medium-permeability sandpacks and resulted in the high tertiary oil recoveries, as shown in Figure 4. In conclusion, the high-viscosity of heavy oil is favorable for the improvement of sweep efficiency in alkaline flooding.

The results of the sandpack flooding tests discussed in Section 3.1 indicated that the two oil samples could exhibit similar behaviors when these tests were conducted at different temperatures. However, the changing temperature may influence the dynamic water/oil IFT, which is very important for chemical flooding in conventional oil reservoirs. Therefore, dynamic IFT between the alkaline solutions and crude oils was measured. The results are shown in Figures 11 and 12, and little change is observed as the temperature varies. These results are inconsistent with the conclusions of Chiwetelu et al. [9] and Trujillo [10] as described in Section 1. Besides, it can be seen from Table 2 that the efficiency of alkaline flooding has little relation to the equilibrium IFT. So, we think many factors must be considered to design an alkaline flooding plan for heavy oil besides the IFT.

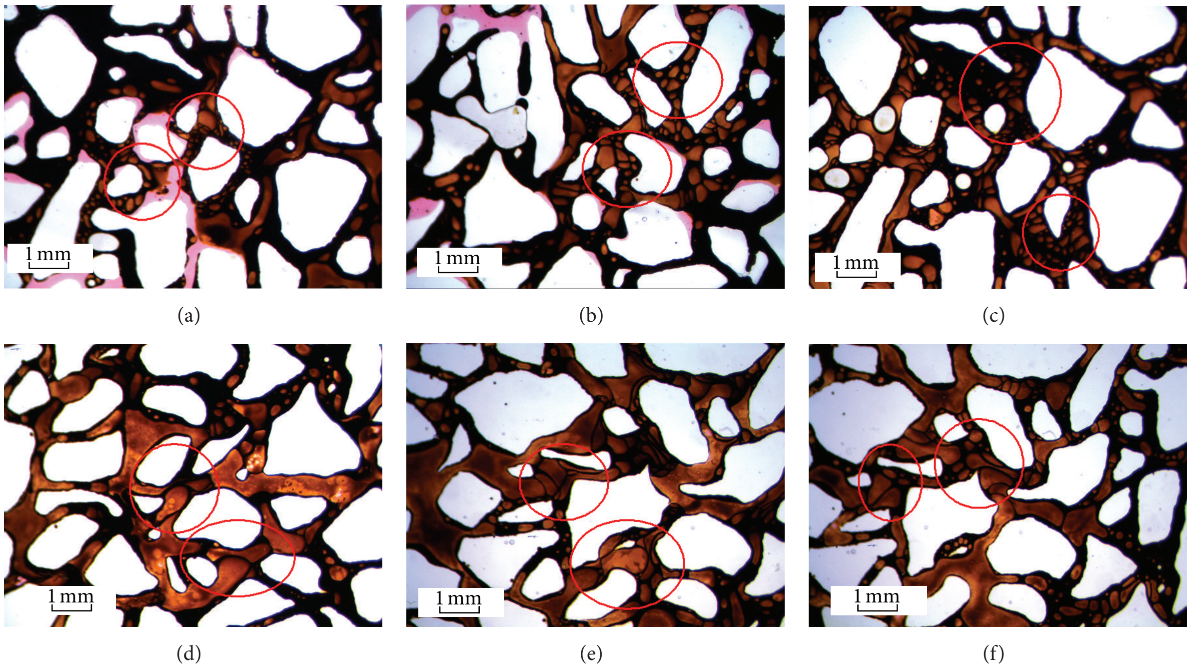


FIGURE 9: Microscopic images of alkaline flooding for different types of oil samples: (a), (b), and (c) Zhuangxi and (d), (e), and (f) Chenzhuang.

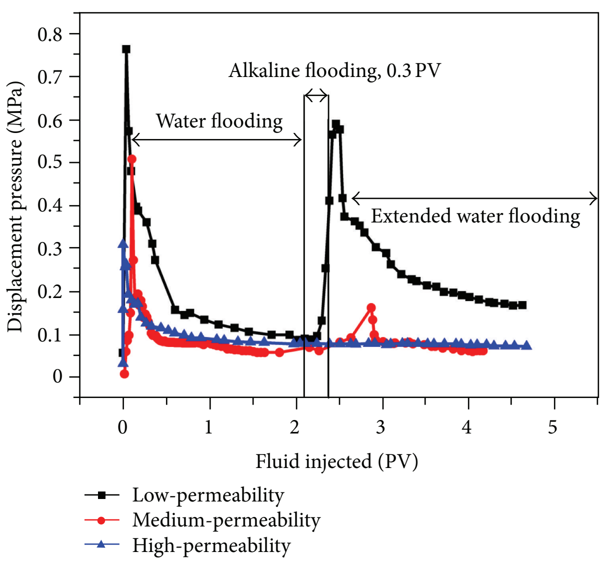


FIGURE 10: Pressure changes during alkaline flooding for Zhuangxi heavy oil (alkaline concentration = 0.5 wt%).

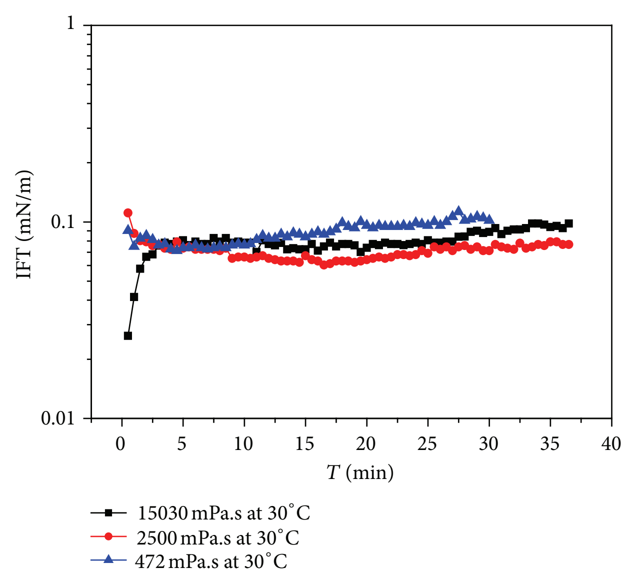


FIGURE 11: Dynamic IFT curves of Binnan heavy oil/0.5% NaOH + 0.5% NaCl.

As previously discussed, two stages occur in the water-drop formation process. The first stage is the penetration of the alkaline solution into the heavy oil and the occurrence of water columns covered with oil film. This process is related to the fast reduction in the oil/water IFT, which is difficult to measure using drop-spinning method. The second stage is the formation of discontinuous water droplets from the breakup of the water columns, which is caused by the non-uniform enrichment of *in situ* surfactant [11]. High temperature accelerates the reaction and diffusion rate between alkaline solution and heavy oil, which reduces the degree of non-uniform enrichment of *in situ* surfactant. The water columns then cannot be easily divided into small discontinuous water droplets. Therefore, the temperature militates the performance of alkaline flooding.

4. Conclusions

(1) The results of flooding tests indicated that a high tertiary oil recovery could be achieved only in the low-permeability sandpacks for the low-viscosity heavy

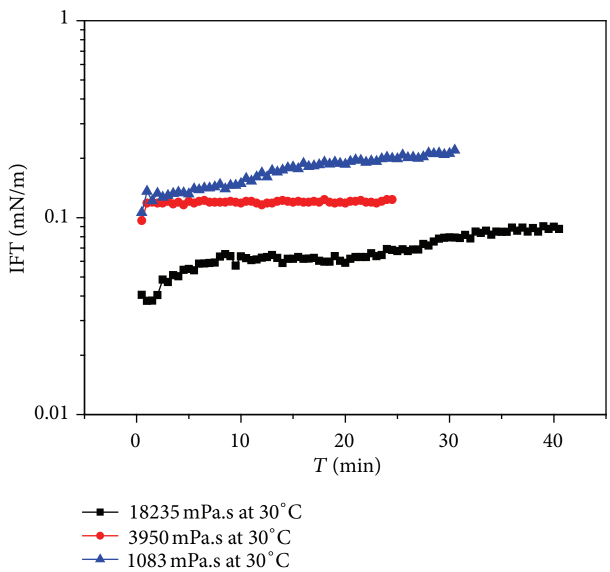


Figure 12: Dynamic IFT curves of Xia-8 heavy oil/0.5% NaOH + 0.5% NaCl.

oil; however, the high-viscosity heavy oil performed well in both the low- and medium-permeability sandpacks. In addition, the results of flooding tests for the same oil at different temperatures also indicated that the oil viscosity put a similar effect on alkaline flooding, and oil with a high-viscosity was favorable for alkaline flooding.

(2) Microscopic flooding tests were conducted to elucidate the influence of oil viscosity on the alkaline flooding. It indicated that the water drops produced during alkaline flooding for oils with different viscosities differed significantly in their sizes, which might influence the flow behaviors and therefore the sweep efficiencies of alkaline fluids.

Acknowledgments

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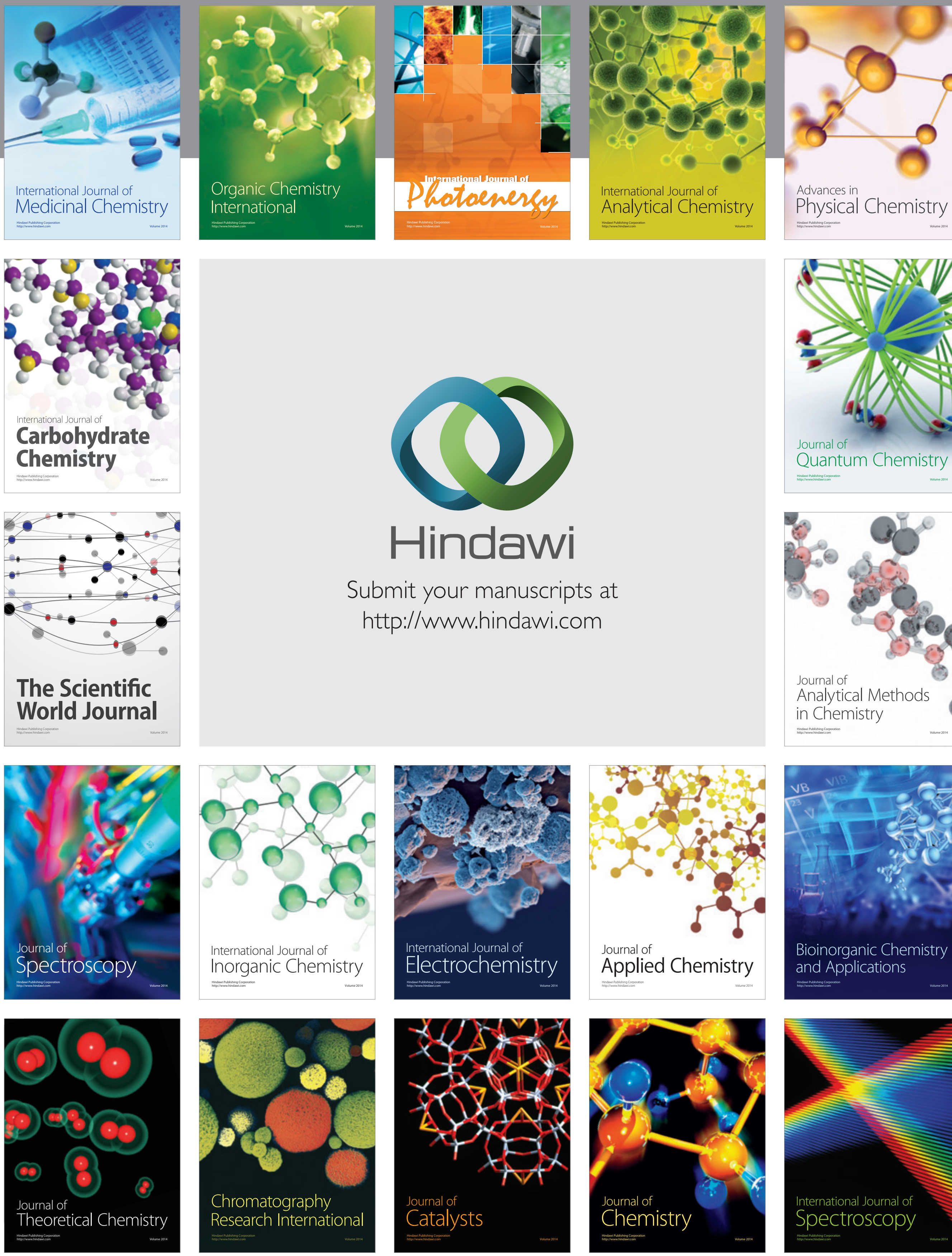
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