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The Research on Weak Alkali ASP Compound Flooding System for Shengli Heavy Oil

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Abstract

In order to avoid the disadvantages caused by strong alkali used in enhanced oil recovery, sodium metaborate was compounded with nonionic surfactant nonylphenol polyoxyethlene polyoxypropylene ether sulfate and hydrolyzed polyacrylamide for the first time as a chemical displacement agent for Shengli heavy oil. The interfacial tension between crude oil and aqueous solutions, emulsification tests, microscopic displacement properties and sandpack flooding were investigated. It can be observed that the interfacial tension was reduced to ultra-low value due to the synergy effect between the weak alkali and surfactant. The microscopic displacement tests showed that there was an optimum surfactant concentration for alkali-surfactant flooding system to obtain larger sweep efficiency. And the recovery efficiency can be further increased by addition of hydrolyzed polyacrylamide. The oil recovery increased with the increasing of hydrolyzed polyacrylamide concentration. The newly designed compound system was proven to have the application potential on pilot tests.

Key words: Weak alkali; Sodium metaborate; Compound flooding system; Nonylphenol polyoxyethlene polyoxypropylene ether sulfate; Heavy oil

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INTRODUCTION

With the rapid development of economy, the reserves and production of conventional reservoir can't meet the increasing demand. More and more attention is paid to the development of heavy oil reservoirs by every country. Water flooding is usually used to develop heavy oil reservoir that the oil viscosity is below 5000 mPa·s. Chemical flooding technology which has become relatively mature in tertiary oil recovery of conventional reservoir can be used as alternative technology for heavy oil reservoirs after water flooding. Enhanced oil recovery depends on the enlargement of swept volume and the improvement of displacement efficiency, so binary compound flooding or ASP flooding system is the main research direction of current chemical flooding research. The combination of different advantages for enhanced oil recovery of alkali, surfactant and polymer in these systems can result in a better synergistic effect.

The interactions between surfactant and alkali during emulsifying Canada heavy oil was studied by Dong et al (Liu *et al*., 2006; Liu *et al*., 2007), they indicated that the mechanism of synergistic effect between alkali and surfactant performed in enhanced oil recovery of heavy oil is the interfacial instability principle by sand pack experiment (Dong *et al*., 2009). Wang (Wang *et al*., 2009) studied the interfacial tension and oil-displacement capacity of binary system which is composed of polymer and the compound of petroleum sulfonate and nonionic surfactant, indicating that the compound of surfactants can reduce the oil-water interfacial tension to ultra-low in the absence of alkali and a desired oil displacement efficiency has been achieved from field test. Gong et al investigated the interfacial tension of HPAM and sodium oleate (Gong *et al*., 2008), CTAB and TX-100 (Gong *et al*., 2009). The results showed that ultra-low interfacial tension can be achieved and the polymer has a good compatibility with surfactant in these two systems. Li *et al*. developed an ASP flooding system which is constituted by natural carboxylate, sodium carbonate/sodium bicarbonate and HPAM, the result indicated that EOR can be increased by more than 25% using this compound system (Li *et al*., 20070). Petroleum sulfonate with good interfacial activities was synthesized and compounded with sodium carbonate and polymer to achieve a ultra-low interfacial tension ternary combination system (Zhu *et al*., 2010).

The strong alkali, such as NaOH, Na_2CO_3 is widely used in the compound flooding system to react with acidic species contained in the crude oil to generate interfacial activities which can generate synergy effect with added surfactants to reduce the IFT to ultra-low level. The addition of strong alkali can cause many problems, including the damage to the strum, the corrosion of pipelines and difficult to de-emulsify the production fluids. Sodium metaborate will not cause reservoir damage and form produced fluid that is difficult to demulsifying, at the same time, it can prevent the formation of scale. Nonionic-anionic surfactants which take advantages of anionic surfactant and nonionic surfactant have excellent temperature resistance and salt tolerance, and the HLB value of this kind of surfactants can be easily adjusted by changing the number of alkoxy chain according to the formation water with different salinity. In this paper, nonionic-anionic surfactant (NPPS), sodium metaborate and hydrolyzed polyacrylamide were used together as an ASP flooding formulation to get a higher oil recovery without any precipitation, and the interfacial tension between the compound system and Zhuangxi crude oil, micro displacement properties and sandpack flood tests were investigated.

1. EXPERIMENTAL

1.1 Materials

Nonylphenol polyoxyethlene polyoxypropylene ether sulfate (NPPS), effective content > 99%; sodium metaborate is of analytical reagent grade; HPAM with molecular weight 1400×10^4 and hydrolysis degree is 23-25%; The crude oil with a density 0.9302 g/cm^3 and viscosity 325 mPa·s at 50 °C is obtained from Zhuang 105-15-X18 well. The salinity of formation water is 5039mg/L and the concentrations of Ca^{2+} and Mg^{2+} are very low, therefore, the 0.5% NaCl solutions is adopted in the experiment. The sodium chloride is analytical reagent grade and used as received.

1.2 Measuring the IFT of Flooding System

The interfacial tension between the flooding system and crude oil were measured with spinning drop technology on a Texas-500 spinning drop interfacial tension apparatus at a temperature of 50 °C, which is consistent with the temperature of formation in Shengli oil field. The speed rotation of samples was set at 5000 rpm in all cases. The length and width of oil drop were recorded at different time with image acquisition and analysis software developed by our lab. Its major axis is L and minor axis is D. When L/D ≥ 4, the interfacial tension was obtained from Equation (1) below:

$$\mathrm{IFT} = \frac{\Delta\rho\omega^2 r^3}{4} \tag{1}$$

Where $\triangle\rho$, ω and r are the density difference between oil and water, angular velocity and oil drop minor axis semi diameter, respectively.

1.3 Emulsification Experiment

The diameter of formed emulsion was examined using a XSP-2CA microscope. 10 ml of AS solutions and 10 ml Shengli crude oil were added to the bottles successively. Then the bottles were left to rest for 10 minutes at 50 °C. After that, the bottles were quickly shaken up and down 50 times, and the emulsion properties were investigated by its photomicrograph (magnified 100 times).

1.4 Microscopic Displacement Experiments

The micro-model was made by etching a two-dimensional network of pores and throats on glass plates through a photochemical method. The experimental procedure was described as follows: after being vacuumed, the micro-model was saturated with 0.5 wt % NaCl solutions, and then the brine was displaced by Zhuangxi crude oil until there is no more water produced at the outlet of the micro-model. Different displacement fluids were injected into the micro-model at the same flow rate (0.003 ml/min), and the microscopic photos at different displacement stages were recorded using digital video acquisition apparatus.

1.5 Sandpack Flooding Test

A sandpack holder of 2.5 cm in inner diameter and 19.0 cm in length was used. The sandpack was packed as follows: fresh quartz sands with 100-120 mesh were added to the vertically positioned tube in several increments. In each step, the sand was shaken slightly after being poured. During this process, the water surface should be kept above the sand surface to prevent air permeating into the sand.

The permeability of the sandpacks in the presence of the formation brine were about 2 darcy measured by injecting 0.5% NaCl solutions at the rate of 1 ml/min. To saturate the wet-packed sandpack with Zhuangxi oil, the crude oil was injected continuously until water cut was less than 1% at 50 °C. The saturated sandpack was first displaced with formation brine until there was almost no oil produced (oil cut < 2 %). After that, 0.5 PV of chemical solution was injected followed by an extended water flood until the oil production became negligible. During the flooding, the injection pressure and volumes of produced oil and water (the emulsions needed deemulsion before calculating oil and water volume) were recorded as a function of time.

2. RESULTS AND DISCUSSION

2.1 IFT Measurement

To investigate the synergy effectiveness of sodium metaborate and NPPS in reducing the oil-water IFT, the dynamic IFT between solutions containing 0.2 wt % $NaBO_2$ and NPPS with different concentrations and crude oil was measured, as shown in Figure 1. The ultra-low IFT below 10^{-3} mN/m can be achieved when the NPPS concentration was 0.005 wt % and the IFT dropped rapidly to 10^{-4} mN/m in 5minutes by increasing NPPS concentration. The results indicated that the ultra-low IFT was resulted from the synergistic effect between $NaBO_2$ and NPPS.

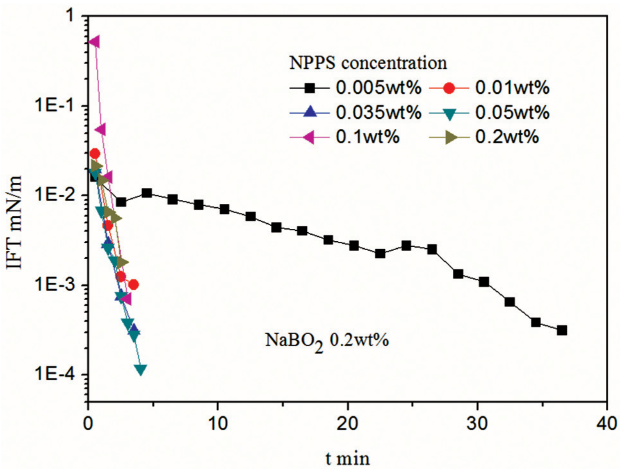


Figure 1
IFT of the Compound System of $NaBO_2$ and NPPS

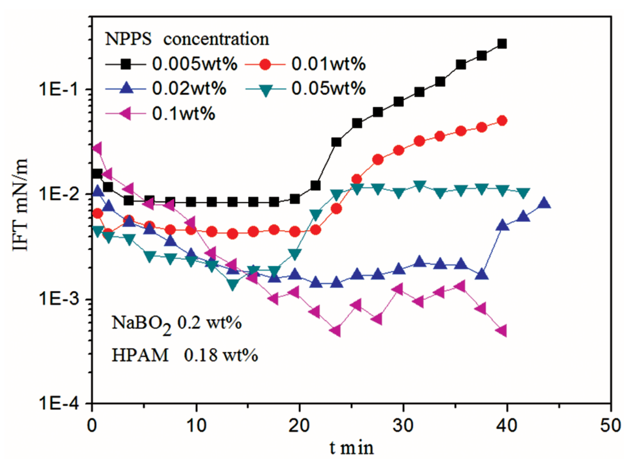


Figure 2
IFT of the Compound System of $NaBO_2$/NPPS/HPAM

The interfacial tensions between heavy oil and ASP compound systems consisting of 0.2 wt % $NaBO_2$, 0.18 wt % HAPM and different concentrations of NPPS ranging from 0.005 to 0.1 wt % were shown in Figure 2. It can be observed that the addition of HPAM increased the time needed to obtain ultra-low IFT and a lower NPPS concentration (<0.01 wt %) damps the lowering IFT ability of the compound system. This can be ascribed to increase the viscosity of solutions and lower the diffusion rate of molecules from aqueous phase to interface. When the NPPS concentration was higher than 0.01 wt %, the IFT was lower than 10^{-2} mN/m. The apparent viscosity of ASP compound system was hardly impaired by addition of $NaBO_2$ and NPPS.

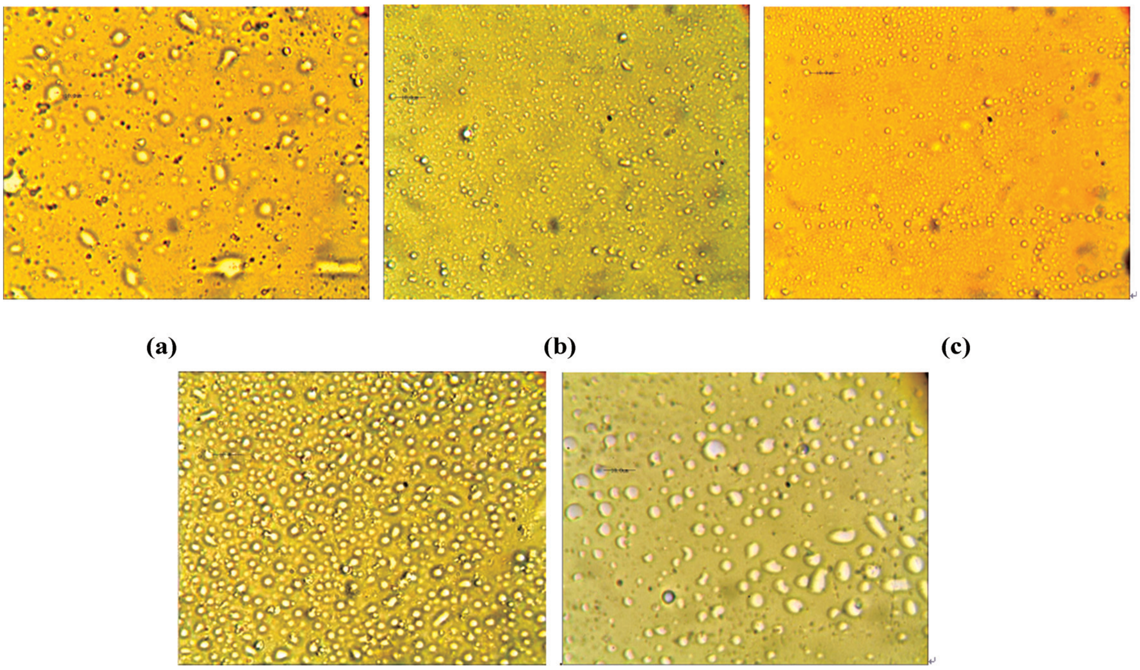
2.2 Emulsification Experiment

Figure 3 shows the microphotographs of emulsions with oil/water ratio of 1 taken after being shaken 50 times (magnified 100 times). The concentration of NPPS has a great influence on the drop size of formed emulsion. W/O emulsions with larger diameter and less number of emulsion particles will be formed when the concentration of NPPS is 0.005 wt % and 0.1 wt %. While a large amount of emulsion particles with uniform diameter will be formed when the concentration of NPPS is between 0.005 wt % and 0.1 wt %. The average diameter of the emulsion particles was about 20 μm and the emulsion could last for 2h before the emulsion breaking. According to Kokal (Kokal & Aramco, 2002), the obtained emulsions were classified to tight emulsions.

2.3 Microscopic Displacement Experiments

Enhanced oil recovery can be achieved by enlarging swept volume and increasing displacement efficiency. The phenomenon of displacing fluid bypassing oil is often observed in heavy oil displacement due to high viscosity properties. To investigate the microscopic properties of AS and ASP flooding for enhanced heavy-oil recovery, a set of micro-model flooding tests were conducted with the chemical addition of 0.2 wt % $NaBO_2$, 0.18 wt % HPAM and NPPS with different concentrations ranging from 0.02-0.1 wt %.

The mechanism of improved heavy-oil recovery has been investigated in great deal of researches. Emulsification (O/W, W/O or multiple emulsion) is considered as one of those theories. With the addition of alkali and surfactant in the brine water, the IFT is reduced to ultra-low level and the viscous oil is easily emulsified into water to form oil-in-water emulsions. The dispersed heavy-oil was carried in the aqueous phase and then will re-coalesce into the oil bank (Liu *et al*., 2007). The AS flooding system of $NaBO_2$ and NPPS has a good synergic effect to lower the IFT between Zhuangxi heavy oil and aqueous phase, which indicates the compound system has a better displacement efficiency than water flooding, as shown in Figure 4. The residual oil swept by flooding fluid was displaced entirely. It can be also seen that when the NPPS concentration is 0.05 wt %, the flooding formulation has a higher oil recovery due to a larger swept



(a) **(b)** **(c)**

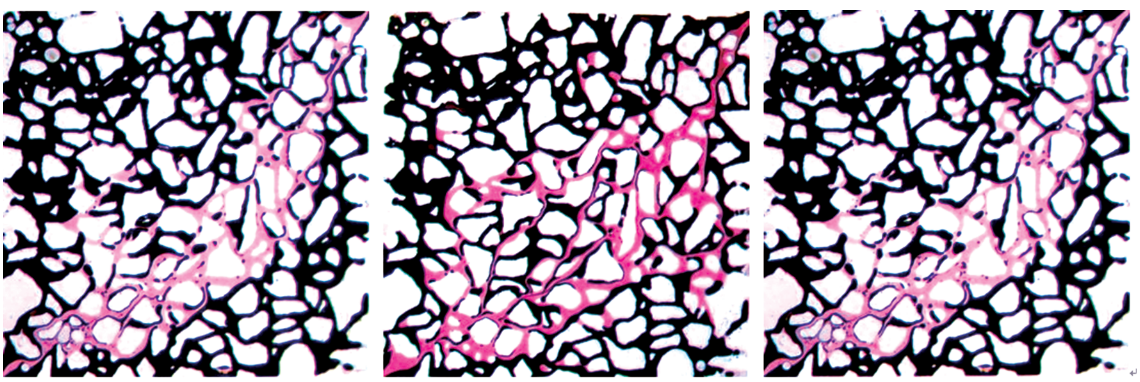
(d) **(e)**

Figure 3
Microscopic Images of Particle Size Distribution of Formed Emulsions

volume compared with other flooding formulations with the same IFT.

To investigate the effectiveness of flooding solutions composition with the same IFT on the displacement efficiency, the images of AS solutions flooding at breakthrough stage were studied, as shown in Figure 5. It can be observed that there were many discontinuous water columns covering with oil film at the edge of flooding solutions (marked with red circles) when the NPPS concentration was 0.05 wt %. For the other two concentrations this phenomenon was rarely (0.1 wt %) or not (0.02 wt %) appeared. Ding (Ding *et al*., 2010) indicated that the permeation of alkaline solutions in crude oil was the main mechanism to improve sweep efficiency for alkaline displacement. Pei *et al*. compared the alkaline and AS flooding indicating that the addition of surfactant weakened the penetration ability of alkaline solutions (Pei *et al*., 2012). Therefore, the compound system containing 0.05 wt % NPPS can maintain the property of reducing IFT to ultra-low value without damping the penetration ability of alkaline.

To investigate the effectiveness of HPAM on improving the sweep efficiency of AS flooding system, the micro-model tests were conducted with addition of 0.2 wt % $NaBO_2$, 0.05 wt % NPPS and 0.12, 0.18 wt % HPAM. The images of ASP displacement at different stages were shown in Figure 6.



(a)0.02% **(b)0.05%** **(c)0.1%**

Figure 4
Microscopic Images of Compound Systems with 0.2 wt% $NaBO_2$ + Different Concentrations NPPS (Magnification of 1.5 Times)

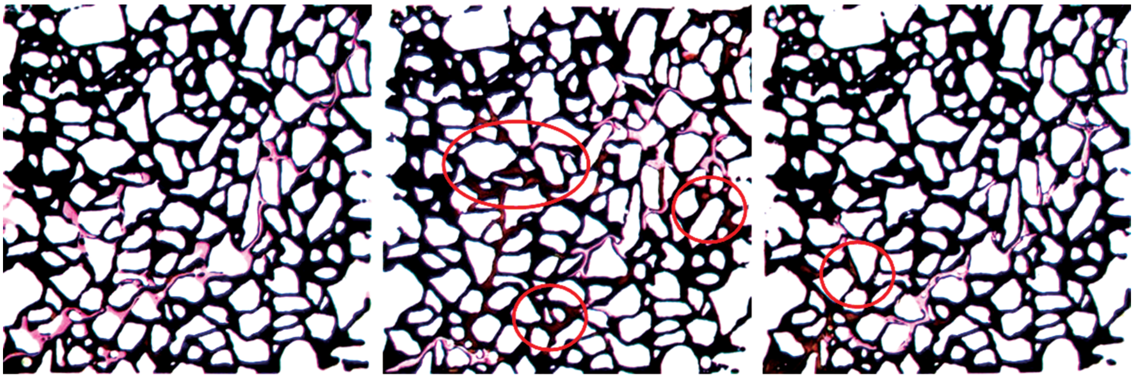


Figure 5
Microscopic Images of AS Flooding when Displacement Solutions Break Through (Magnification of 1.5 Times)

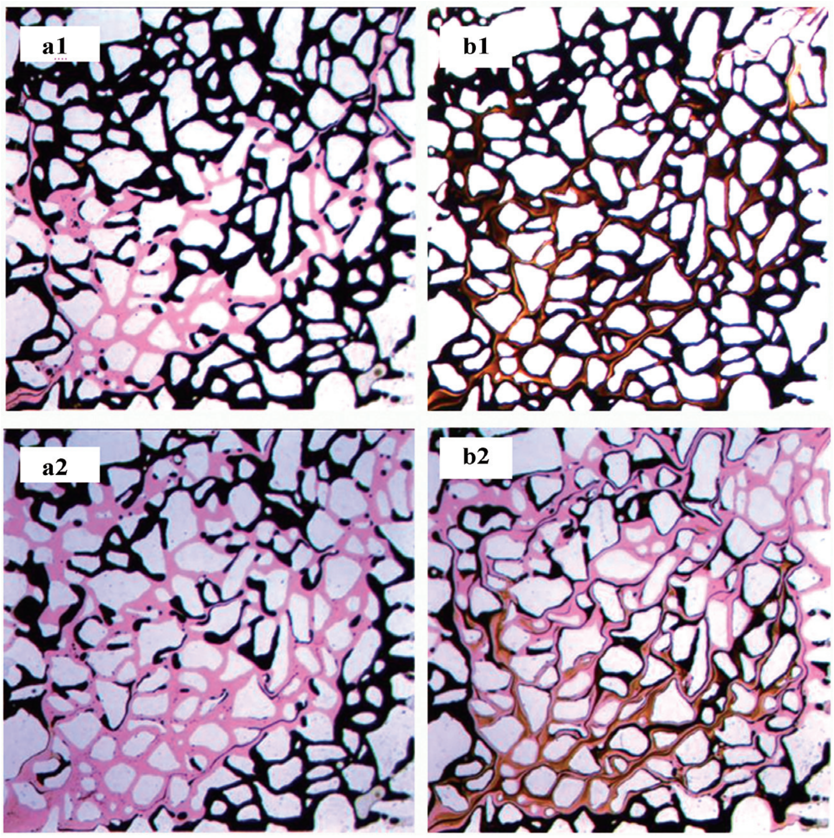


Figure 6
Microscopic Images of ASP Compound Systems Flooding (Magnification of 1.5 Times) a1, b1- Breakthrough Stage; a2, b2- End of Flooding

Figure 6 (a)-1 and (b)-1 show the images of ASP solutions front reached its outlet. Compared with AS displacement, ASP solution has a better sweep efficiency at the breakthrough stage due to the increased viscosity of solutions by addition of HPAM. It is can be concluded that the sweep efficiency at breakthrough stage decides the ultimate oil recovery. When the HPAM concentration was 0.18%, brown water columns covered with oil film appeared over the whole micromodel and the adverse viscous fingering was damped. At the end of test, the ASP flooding achieved a much larger swept area than AS flooding and the increasing the concentration of HPAM could increase the sweep efficiency. Due to the high sweep efficiency and displacement efficiency, high oil recovery was obtained.

2.4 Sandpack Flood Tests

A set of sandpack flood tests were conducted to investigate the effect of AS and ASP flooding systems chemical composition on the tertiary oil recovery of Zhuangxi heavy oil. The injected volume of chemical solution was maintained at 0.3 PV, and the other parameters of the sandpacks, chemical formulas and flood results are summarized in Table 1. The oil recoveries of water flood were about 40% IOIP. For AS flooding systems, when the NPPS concentration was 0.05 wt %, a higher oil recovery was obtained. The addition of HPAM to the AS flooding system can further increase the oil recovery by 25.82 % and 32.64 % when the concentration of HPAM was 0.12 wt % and 0.18 wt % respectively. Besides, we can observe that there was a significant increasing in the pressure drop during AS solutions injection and a bigger one in ASP solutions injection. The increased pressure drop is probably due to blocking the high permeability path for water by forming of emulsion. The addition of HPAM can greatly increase the oil recovery due to the good performance of thickening and synergy effect with alkali and surfactant. The obtained oil recoveries from sandpack tests were consistent with the phenomenon observed from micromodel tests indicating that the weak alkaline ASP compound system performs satisfactory in chemical flooding for Zhuangxi heavy oil.

Table 1
Sandpack Tests for AS and ASP Flooding

Test	Porosity (%)	Permeability (mD)	Initial oil saturation (%)	Waterflood recovery (%)	Chemical formula	Tertiary recovery (% IOIP)	Final recovery (% IOIP)
1	44.84	1998	92.32	42.53	0.2 % $NaBO_2$+0.02 % NPPS	11.49	54.02
2	45.86	2192	92.80	42.31	0.2 % $NaBO_2$+0.05 % NPPS	18.78	61.09
3	43.82	1988	91.35	41.27	0.2 % $NaBO_2$+0.10% NPPS	13.62	54.89
4	45.18	2047	91.67	42.64	0.2 % $NaBO_2$+0.05 % NPPS+ 0.12 %HPAM	25.82	68.46
5	47.56	2131	92.38	43.06	0.2 % $NaBO_2$+0.05 % NPPS+ 0.18 %HPAM	32.64	75.70

CONCLUSIONS

(1) Ultra-low interfacial tension between Zhuangxi crude oil and chemical solutions can be achieved by the synergistic effect of the compound system consisting of sodium metaborate and nonylphenol polyoxyethlene polyoxypropylene ether sulfate. The AS system has a good performance of emulsification and the crude oil can be dispersed into the aqueous phase with slight oscillation. The viscosifying capacity of polymer will not be affected and ultra-low interfacial tension can be kept when polymer is added to binary system.

(2) The micro-model experiments show that the ability of permeating into the crude oil of sodium metaborate will not be influenced when the concentration of NPPS is selected appropriately (0.05 wt %), thus a large swept volume will be obtained under ultra-low interfacial tension condition. Laboratory sandpack flooding tests showed that the oil displacement efficiency of ASP flooding was 13.86 % higher than that of AS flooding.

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