Study on a Nonionic Surfactant/Nanoparticle Composite Flooding System for Enhanced Oil Recovery

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ABSTRACT: The composite flooding system composed of a surfactant and nanoparticles has shown great application potential in enhancing oil recovery. However, at present, these research studies are mainly focused on anionic surfactants. Relatively speaking, alkanolamide (CDEA), a nonionic surfactant, has the characteristics of a small adsorption amount on the rock surface, no cloud point, good temperature resistance, and good salt resistance. However, to the best of our best knowledge, there is no research report on the composite flooding system composed of CDEA and nanoparticles. Therefore, the surfactant/nanoparticle (S/NP) flooding system based on CDEA and nano-SiO\textsubscript{2} was studied in this paper. The S/NP flooding system (0.1\% CDEA + 0.05\% SiO\textsubscript{2}) was constructed based on the performance in reducing the oil–water interfacial tension (IFT) and the stability of the composite system. The IFT between the S/NP flooding system and the crude oil can reach ultra-low values (3 × 10\textsuperscript{-3} mN/m), and there is no obvious sedimentation within 72 h. The sandpack flood tests show that the oil recovery rate is increased by 16.8\% compared with water flooding and finally reaches 58.2\%. Based on micromodel flooding tests, the mechanisms of the S/NP flooding system are studied as follows: the synergistic effect of nanoparticles and surfactants can re-enforce its oil–water interface performance and improve the oil displacement efficiency and the Jamin effect of emulsified oil droplets, combined with the thickening property and retention plugging of nanoparticles, improves the sweep efficiency. As the surfactant and nanoparticle used in this study are commercially available industrial products, the research results have important guiding significance for promoting the industrial application of surfactant/nanoparticle composite flooding technology.

1. INTRODUCTION

Petroleum is a kind of nonrenewable resource, but with the rapid development of economy and technology, the world’s energy demand is constantly increasing. This requires not only the increase in the output of crude oil but also further improvement in the oil production efficiency, and enhancing oil recovery (abbreviated as EOR) has also become an important strategy for energy development in almost all countries. Among all the EOR technologies, chemical flooding is an effective method. Surfactant flooding can significantly improve oil washing efficiency, which is an important chemical flooding technology. Anionic surfactants (such as petroleum sulfonate, alkylbenzene sulfonate, olefin sulfonate, etc.) are widely used due to their advantages of less adsorption loss, high oil–water interfacial activity, and good temperature resistance. In recent years, with the rise of nanotechnology, surfactant/nanoparticle composite flooding technology has been carried out for different kinds of anionic surfactants. Zhu et al. studied the oil–water interfacial properties of nano-silica (SiO\textsubscript{2}), modified nano-silica (M-SiO\textsubscript{2}), and petroleum sulfonate (PS), and the results showed that the PS/SiO\textsubscript{2} composite system could reduce the oil–water interfacial tension (IFT) to 0.01 mN/m, while it is 0.001 mN/m for the PS/M-SiO\textsubscript{2} composite system. The results indicate that the IFT can be further reduced by the combination of the nanoparticles and surfactants. It is pointed out that the mechanism lies in the complementary adsorption of SiO\textsubscript{2} nanoparticles and PS on the oil–water interface, which enhances the thickness and mechanical strength of the interface film. Arab et al. comparatively studied the oil displacement performance of sodium alkane sulfonate, modified nano-SiO\textsubscript{2} dispersion, and their composite system. The results showed that the final

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recovery rate of the S/NP flooding system was 48%, which was significantly higher than that of pure surfactant flooding (16%) or pure nanoparticle flooding (36%). Suleimanov et al. pointed out that the oil recovery rate of the S/NP composite system based on nonferrous metal nanoparticles with a particle size of 70−150 nm and sulphanole-alkyl aryl sodium sulphonate was 4.7 times that of water flooding and 1.5 times that of surfactant flooding. They claimed that this could be attributed to the decrease in oil−water interfacial tension and the increase in oil displacement viscosity. In addition, Xu et al. studied the effect of nano-SiO<sub>2</sub> on the performance of the commercial anionic surfactant KD. The results showed that the dosage of nano-SiO<sub>2</sub> had a significant effect. Adding an appropriate dosage of nano-SiO<sub>2</sub> could further reduce the interfacial tension, improve the temperature resistance, and also improve the stability of its emulsion. For the ultra-low IFT nanofluid system (0.05% KD + 0.01% SiO<sub>2</sub>), the recovery rate can be increased by 21.12%, and the injection pressure can also be reduced by nearly 50%.

However, the anionic surfactants have the disadvantages of poor salt tolerance and high critical micelle concentration, and a large number of pollutants will be emitted during the production and processing of these surfactants, which is harmful to the environment. In contrast, the nonionic surfactant has good salt tolerance, low critical micelle concentration, low influence by strong acid and strong base, high stability, and good compatibility with other surfactants. Therefore, some scholars have carried out the research on the composite flooding technology of nonionic surfactants and nanoparticles. Zhao et al. used a nonionic surfactant (Triton X-100) as a dispersant for nano-silica and studied the properties of the composite system. They pointed out that the composite system has a synergistic effect in enhancing the system’s ability to peel off oil droplets and changing the wetting performance. The imbibition experiment showed that the recovery rate of the Triton X-100/SiO<sub>2</sub> composite system was twice that of Triton X-100. Zhong et al. studied the S/NP composite system based on polyethoxylated nonionic surfactants and hydrophilic silica nanoparticles and reached the same conclusions. Alkanolamide is a kind of nonionic surfactant with good biodegradability, low pollution, low price, environmental protection, and excellent performance. In chemical flooding, its advantages are reflected in the following aspects: excellent oil−water interfacial performance; low adsorption capacity on the rock surface, which can reduce the drug consumption in surfactant flooding; no cloud point, which makes it have good temperature resistance; less affected by ions; and good salt resistance. Therefore, alkanolamide is an ideal surfactant for chemical flooding. Freitas et al. studied the interfacial properties of the S/NP composite system based on aliphatic diethanolamide and mesoporous silica, and the results indicated that the surfactant could be adsorbed on the surface of nanoparticles, and the oil−water IFT could be reduced under their synergistic effect. This study shows that the alkanolamide has the potential to construct a S/NP composite flooding system with nanoparticles.

To the best of our best knowledge, there is no research report on the composite flooding system based on alkanolamide and nanoparticles. Therefore, nano-silica was added into alkanolamide solution in this paper to construct a stable S/NP composite flooding system. The oil−water interfacial performance, dispersion stability, oil displacement performance, and microscopic displacement mechanism were systematically studied. Because the alkanolamide used in this study is a commercial product, the experimental results have important practical significance for the promotion of surfactant/nanoparticle composite oil displacement technology.

2. RESULTS AND DISCUSSION

2.1. IFT between Crude Oil and Flooding Solution.

2.1.1. IFT between Crude Oil and CDEA Solution. The IFT between crude oil and surfactant solution with different mass fractions of CDEA is shown in Figure 1. It can be seen in Figure 1 that for CDEA solutions with the mass fraction of 0.03 and 0.05%, the oil droplets cannot fall off the sample tube wall in a short time even under high-speed spinning. The IFT could be recorded after 10 and 5 min of high-speed spinning, and the equilibrium value was higher than 1.0 × 10<sup>−2</sup> mN/m. When the mass fraction of CDEA was increased to 0.1−0.3%, the IFT decreased by an order of magnitude, reaching the order of 10<sup>−4</sup> mN/m. It can be concluded that the CDEA mass fraction corresponding to the order of IFT from small to large was 0.1% < 0.2% < 0.3%, as shown in Figure 1 (right). Therefore, the mass fraction of CDEA solution was determined to be 0.1% in the follow-up studies. Nano-SiO<sub>2</sub> was added into the surfactant solution to further study the influence of nanoparticles on oil−water interfacial tension.

2.1.2. IFT between Crude Oil and CDEA/SiO<sub>2</sub> Dispersion. When nanoparticles are added into the surfactant solution, the

![Figure 1. Effect of CDEA dosage on IFT: (left) dynamic interfacial tension and (right) IFT at 30 min.](https://doi.org/10.1021/acsomega.1c01038)
nanoparticles can be adsorbed on the oil-water interface, and the surfactant and nanoparticles will have a synergistic effect to further reduce the oil-water interfacial tension. Therefore, nano-silica was added into CDEA solution to study the effect of nanoparticles on the IFT between CDEA solution and crude oil. The mass fraction of the surfactant was 0.1%, and the IFT between the S/NP composite solution and crude oil after adding different amounts of nano-SiO₂ was measured. The results are shown in Figure 2.

Figure 2. Effect of the dosage of nano-SiO₂ on IFT between crude oil and the 0.1% CDEA solution.

It can be seen in Figure 2 that the IFT decreased even if only 0.001% nanoparticles were added, indicating that adding a small amount of nanoparticles into the CDEA solution can improve the interfacial activity. However, the IFT did not decrease by orders of magnitude, when continuing to increase the amount of nano-SiO₂ (in the range of 0.001–0.1%). By comparing the curves in Figure 2, it can be seen that when the dosage of SiO₂ was 0.1 and 0.05%, their IFT was relatively lower than other dosages. The difference between the dosage of 0.1 and 0.05% was small. Therefore, the dosage of nano-SiO₂ in the 0.1% CDEA solution was determined to be 0.05% in the follow-up experiments.

The solutions used in the determination of the oil-water interfacial tension in Figures 1 and 2 were all prepared with distilled water. However, when chemical flooding is carried out in an oilfield, all injection fluids are prepared based on formation water. Therefore, the S/NP dispersion (0.1% CDEA + 0.05% SiO₂) was prepared with the simulated formation water, and the IFT was measured again. The results are shown in Figure 3. It can be seen in Figure 3 that for the S/NP composite flooding system prepared with the simulated formation water, the oil drop was pulled off after 20 min of the IFT determination process (as shown in Figure 3), and the oil-water interfacial tension was reduced to 3 × 10⁻³ mN/m, reaching the state of ultra-low interfacial tension, which shows that the surfactant/nano-SiO₂ flooding system has good oil washing ability in simulated formation water and can fully meet the oil displacement requirements.

2.2. Suspension Stability of Nanoparticle Dispersion.

Among all the nanomaterials, nano-SiO₂ has always been a research hotspot in the field of oil and gas industry. For example, its thickening effect in the water phase makes it useful for profile control and water shutoff, and its effect of reducing the oil-water interfacial tension makes it useful for EOR. However, due to the influence of van der Waals force and Brownian motion, nano-SiO₂ tends to sediment in dispersions, which limits its application in oil and gas production. Adding a polymer or surfactant to the nano-SiO₂ dispersion is a common method to improve its dispersibility in water-based systems.

Because nano-SiO₂ is insoluble in water, its dispersion is turbid; therefore, measuring the turbidity is a common method to evaluate the stability of nanoparticle dispersions. The more the amount of nano-SiO₂ contained in the dispersion, the more turbid the dispersion and the higher the corresponding turbidity value. With the prolongation of the storage time, some nano-SiO₂ particles will deposit, and the turbidity of the dispersion will decrease. In other words, if the turbidity of the nano-SiO₂ dispersion is low, the amount of nano-SiO₂ in the dispersion is less. If the time factor is taken into consideration, the relationship between turbidity and time can be obtained. The faster the turbidity decreases, the more the nano-SiO₂ will deposit in a short time and the more unstable the dispersion is. Therefore, the suspension stabilities of the nanoparticle dispersions and the samples added with surfactants were evaluated by their turbidities, and the experimental results are shown in Figures 4 and 5.

It can be seen in Figure 4 that when the mass fraction of nano-SiO₂ was 0.005 and 0.01%, the initial turbidity was lower,
while increasing the content to 0.05 and 0.1% significantly increased the initial turbidity. This indicates that the initial turbidity of the dispersion was closely related to the content of nanoparticles, and the higher the turbidity, the more the nanoparticles dispersed in water. In addition, the turbidity of the four nano-SiO₂ dispersions decreased with the prolonging of the standing time. However, the decrease rate of the turbidity of the dispersion with the mass fraction of 0.1% was the largest, indicating that this dispersion was the most unstable. In conclusion, considering that the dispersion needs to contain the most nano-SiO₂ and have the best dispersion stability, the dispersion with the mass fraction of 0.05% was taken as the optimal candidate.

By comparing the dispersion stability of 0.1% CDEA solution, 0.05% SiO₂ dispersion, and 0.1% CDEA + 0.05% SiO₂ dispersion in Figure 5, the following two conclusions can be obtained. First, the turbidity of the 0.05% SiO₂ dispersion was significantly improved by adding 0.1% CDEA. The turbidity of the 0.1% CDEA solution was very small and can be ignored, which indicated that the addition of the surfactant CDEA could improve the dispersion of nano-SiO₂ particles in water. Second, comparing the ratio of the turbidities of nanoparticle dispersion and S/NP dispersion before and after 72 h, it can be found that the turbidity of S/NP dispersion had little changes, which indicated that the dispersion stability of nano-SiO₂ dispersion had also been significantly improved. The reason for the abovementioned phenomenon is that the nonionic surfactant CDEA adsorbed on the surface of nano-SiO₂, increasing the hydrodynamic radius of nano-SiO₂, that is, increasing the steric hindrance effect of nanoparticles. Therefore, the agglomeration of nanoparticles can be inhibited, thus improving their dispersion stability. Improving the stability of the dispersion means that more nanoparticles can be adsorbed on the oil–water interface after being pumped from the surface to the reservoir, reducing the interfacial tension between the oil displacement fluid and the crude oil, so as to increase the oil displacement efficiency and ultimately improve the crude oil recovery.

2.3. Sandpack Flood Test. The oil displacement performance of surfactant flooding and S/NP flooding was comparatively studied through sandpack flood experiments. Two groups of oil displacement experiments were carried out, in which 0.1% CDEA solution and 0.1% CDEA + 0.05% SiO₂ dispersion were injected, and the injection amount of the chemical agent was 0.5 PV. The parameters of the sandpack model and the results of the tests are shown in Table 1.

From the results of the oil displacement experiments in Table 1, it can be seen that when 0.1% CDEA was injected, the recovery rate of surfactant flooding increased by 6.6% compared with that of water flooding, showing that it was difficult to effectively improve the oil recovery rate using the surfactant alone. The reason lies in that even surfactants can reduce the oil–water interfacial tension to an ultra-low range; the mobility (λ = k/μ, in which λ is the mobility of the fluid, μ is its viscosity, and k is the permeability of the fluid that flows in the porous media) of the flooding fluid is still much greater than that of the oil phase. Accordingly, during the flooding process, a serious fingering phenomenon occurred, resulting in the failure of the surfactant solution to sweep to the large remaining oil area after water flooding. This means that the sweep efficiency of the oil displacement was low, which led to a limited increment in the oil recovery rate.

However, the increase in oil recovery rate was 16.8% compared with that in water flooding, when the flooding fluid of 0.1% CDEA + 0.05% SiO₂ was injected. The results can be explained by the change law of the oil recovery, water content, and differential pressure curves of surfactant flooding and S/NP flooding in Figure 6. As can be seen in the water flooding process, oil displacement pressure experienced a first-increasing and then-decreasing process. This is because in the process of the injected water passing through the sandpack, a dominant channel has been formed in the simulated porous media due to the washing effect of the injected water, along which the injected water mainly flows. However, in areas with higher oil saturation, less oil displacing fluid swept, so the water flooding recovery cannot be further improved. After the injection of the 0.5 PV chemical solution, the differential pressure began to rise in both experiments, but the pressure of the S/NP flooding was even greater. It can be explained from two aspects: on one hand, the addition of nano-SiO₂ into the aqueous phase had a certain thickening effect; on the other hand, some nanoparticles in the oil displacement system stayed in the smaller pore throats through a “bridging effect”, which could temporarily block the dominant water flow channel and allow the displacement fluid to enter the unswept oil enrichment areas. Compared with the surfactant flooding, the sweep efficiency of oil displacement fluid was increased, and the increment of oil recovery was of 10.2%. Therefore, the enhanced oil recovery effect of the S/NP composite flooding system is better than that of surfactant flooding.

Figure 5. Comparison of the stability of the nano-SiO₂ dispersion and S/NP dispersion.

Table 1. Parameters and Results of Sandpack Displacement Tests

| test no. | porosity(%) | permeability/(10⁻³ μm²) | initial oil saturation(%) | chemical flooding system | oil recovery(%) |
|---------|-------------|--------------------------|--------------------------|--------------------------|----------------|
|         |             |                          |                          | water flooding | chemical flooding | final recovery |
| 1       | 39.8        | 1406                     | 86.4                     | 0.1% CDEA     | 43.6            | 6.6           | 50.2          |
| 2       | 42.3        | 1370                     | 82.4                     | 0.1% CDEA + 0.05% SiO₂ | 41.4            | 16.8          | 58.2          |
2.4. Microscopic Displacement Mechanisms. In order to study the mechanism of S/NP composite flooding to enhance oil recovery, microscopic chemical flooding (0.1% CDEA solution and 0.1% CDEA + 0.05% SiO₂ system) experiments were carried out after water flooding. The pictures of microdisplacement experiments of water flooding are shown in Figures 7 and 8. As can be found, the injected water mainly moved along the diagonal direction, and the sweep efficiency was low. In the swept area, the oil displacement efficiency was also low, and there was still a large amount of crude oil remaining in the pores. The residual oil existed in the form of island remaining oil, cylindrical residual oil, film-like residual oil, and cluster residual oil, in which, the island remaining oil and film-like residual oil were mainly distributed in large pores, while cylindrical residual oil and cluster residual oil were mainly columnar and clustered and distributed in the small channels. However, after chemical flooding (as shown in Figure 9), it can be found that both the sweep efficiency and displacement efficiency were significantly improved.

The mechanism of S/NP flooding can be explained from two aspects. From the perspective of oil displacement efficiency, it can be explained as follows. First, the adsorption of the surfactant contained in the system on the oil—water interface can reduce the oil—water interfacial tension. According to the formula of adhesion work, the decrease in oil—water IFT means the decrease in adhesion work, that is, oil droplets are easy to be washed off the formation surface, which improves the oil displacement ability of the flooding fluid. Second, the active water with low IFT can soften the interfacial film and deform the remaining oil, as can be found at the position indicated by the red arrow in Figure 10. When the oil droplets flowed with the flooding fluid and passed through the narrow throat, some oil droplets were elongated (as can be seen at the position indicated by the green arrow in Figure 10), which was conducive to the forward migration of oil droplets through the throat, that is, the softening—deforming mechanism improves the oil displacement efficiency. Third, the remaining oil was emulsified under the action of surfactants and the formed O/W emulsion, as shown in Figure 11. The emulsified oil droplets dispersed in the O/W emulsion were not easy to re-adhere to the formation surface when flowing in
the porous medium, that is, the emulsifying—carrying mechanism improves the oil displacement efficiency. Furthermore, the addition of nano-SiO₂ into the CDEA flooding fluid would generate competitive adsorption with CDEA on the oil—water interface, which could further reduce the oil—water interfacial tension, enhance the interfacial activity of oil displacement fluid, and further strengthen the abovementioned three oil displacement mechanisms. Therefore, the residual oil saturation in the swept area after S/NP composite flooding was very low (as shown in Figure 12), and the oil displacement efficiency was better than that of surfactant flooding.

From the perspective of oil sweep efficiency, it can be explained as follows. First, the emulsified oil droplets generated the Jamin effect at the small pore throat, as shown in the yellow circle in Figure 13b, which increased the resistance of the oil displacement fluid, changed the flow direction (as can be found in the changes in the arrow direction of the red curve in Figure 13a,b), and displaced the remaining oil in the untouched places. Then, these washed oil droplets blocked other pore throats again (as shown in the blue circle in Figure 13d) and changed the flow direction again (as shown in Figure 13c,d). The repeated occurrence of the Jamin effect in different places like this made the oil-displacing fluid propel to the production well more evenly in the formation and improved the sweep efficiency. Second, the dispersion of nano-SiO₂ had a shear viscosity-increasing effect. Hence, the viscosity of the CDEA solution was improved after adding nano-SiO₂, which made it have the oil displacement effect similar to that of a polymer, that is, reducing the water—oil mobility ratio and increasing the sweep efficiency. Third, the nanoparticles in the composite system gathered and blocked at the small throat through a bridging effect, thus changing the flow direction, increasing the flow area, and increasing the sweep efficiency of the oil displacement fluid compared with the surfactant flooding. This phenomenon could not be observed directly in this microscopic glass model because the average size of the nanoparticles was 20 nm. However, during our experiments, it was found that when the mass fraction of SiO₂ in the S/NP
system was increased to 1.0%, the glass model was blocked, resulting in the scrapping of the microscopic glass model. This phenomenon indirectly showed that the nanoparticles could block the flow channel with a smaller pore diameter, increase the injection pressure, and improve the sweep efficiency.

In conclusion, the low-interfacial tension mechanism, the softening–deforming mechanism, and the emulsifying–carrying mechanism of the composite flooding system improved the oil displacement efficiency, and the Jamin effect of the emulsified oil droplets, the thickening properties of nanoparticles, and the bridging effect of nanoparticles increased the sweep efficiency, thereby ultimately improving the oil recovery.

3. CONCLUSIONS

Nano-SiO₂ and CDEA have a synergistic effect. On one hand, the addition of nano-SiO₂ can further reduce the oil–water interfacial tension. The IFT between the S/NP flooding system and crude oil in the formation water situation can reach the ultra-low state \(3 \times 10^{-3} \text{mN/m}\), which makes it suitable for chemical flooding. On the other hand, the nonionic surfactant CDEA can be adsorbed on the surface of nano-SiO₂, which can increase the steric hindrance effect, inhibit the agglomeration of nanoparticles, and improve the dispersion stability. Also, turbidity analysis shows that the oil displacement system does not have an obvious sedimentation phenomenon within 72 h. Based on this, the S/NP composite flooding system (0.1% CDEA + 0.05% SiO₂) was constructed.

The S/NP composite flooding system could increase the oil recovery rate by 16.8% after water flooding. Compared with pure surfactant flooding, the recovery factor was also increased by 10.2%, which shows that the EOR effect of the S/NP composite flooding system was better than that of pure surfactant flooding. Micromodel displacement experiments showed that the EOR mechanism of the S/NP composite flooding included two aspects. On one hand, the synergistic effect of nanoparticles and surfactants can re-enforce its oil–water interface performance and improve the oil displacement efficiency; on the other hand, the direction change of liquid flow caused by the Jamin effect of emulsified oil droplets, coupled with the thickening property and retention plugging of nanoparticles, increased the oil displacement pressure, improved the sweep efficiency to some extent, and ultimately enhanced the oil recovery.

4. MATERIALS AND METHODS

4.1. Materials. The crude oil sample was obtained from an eastern China oilfield, with a viscosity of 353 mPa·s at 50 °C. The surfactant of alkanolamide was purchased from Haian Petrochemical Plant with a purity of 99%. The nanoparticles were purchased from Shanghai XiaoGe Nano Material Company, and the average particle size was 20 nm. Other chemicals are all of analytical grade and purchased from Sinopharm China. The simulated formation water is composed of chemical solution or CDEA/SiO₂ solution and crude oil. The temperature was 70 °C, the spinning speed was 5000 rpm, and the oil–water density difference was 0.14 g/cm³.

Its procedures and mechanisms are as follows: first, we determine the density of the crude oil and the chemical solution and then use the WZS-1 Abbe refractometer to measure the refractive index of the chemical solution; second, the length and diameter of the oil drop in the solution are determined using the IFT meter; when the length of the oil drop is more than four times its diameter, the dynamic interfacial tension can be calculated according to the following formula

\[
s = 1.2336 \Delta \rho (D/n)^3 \omega^2
\]

where \(\omega\) is the rotational velocity \((\text{rpm})\), \(n\) is the refractive index of the water phase, \(D\) is the diameter of the oil drop \((0.0001 \text{m})\), \(\Delta \rho\) is the density difference of the water and oil phase \((\text{g/cm}^3)\), and \(s\) is the oil–water interfacial tension \((\text{mN/m})\).

4.2.2. Determination of the Suspension Stability of the Nanoparticle Dispersions. The turbidities of surfactant solutions, nanoparticle dispersions, and surfactant/nanoparticle composite dispersions were measured using a turbidity scanner (Shanghai Xinrui Instruments Co., LTD, WGZ-2000AP, China) to quantify the stability of the nano-SiO₂ dispersion, and the influence of CDEA on its dispersion was evaluated. All the solutions or dispersions were standing for different times according to the experimental requirements.

4.2.3. Determination of Oil Recovery Rate by Sandpack Flood Test. In order to study the enhanced oil recovery effect of chemical flooding, the oil displacement experiment was carried out using sandpack models (the length is 20 cm; the diameter is 2.5 cm). The sandpack was filled as follows: we place the sandpack vertically, appropriate amounts of quartz sand and formation water are added each time, and the model is shaken to make the sand compact. During the process, we make sure that the water surface is higher than the sand surface to prevent air from entering. The flooding experiments were conducted as follows: we vacuum the sandpack, inject the simulated formation water at the rate of 0.5 mL/min to saturate the sandpack, and then calculate the permeability and porosity; crude oil is injected to saturate the sandpack until the water content of the effluent was less than 2% and then the initial oil saturation is calculated; simulated formation water is injected for water flooding until the water content of the effluent was larger than 98%, surfactant solution or S/NP dispersion is injected for chemical flooding (the injected volume was 0.5 PV), and then, the subsequent water flooding was carried out until the water content was 98%; and the oil recovery rates of water flooding and chemical flooding and the final recovery rate were calculated.

4.2.4. Micromodel Displacement Experiment. The micro-displacement glass model was hydrophilic and its size was 30 mm × 30 mm. The process of the oil displacement experiment is as follows: the micromodel is vacuumed, saturated with the simulated formation water, and saturated with crude oil at the formation temperature, and the glass model is aged for 24 h; we inject the simulated formation water or chemical solution, which stained with eosin at the rate of 2 μL/min to conduct the flooding test, and the video of the displacement process was recorded.
The authors declare no competing financial interest.

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