Dilational Rheological Properties of Surfactants at the Crude Oil–Water Interface: The Effect of Branch-Preformed Particle Gels and Polymers

Fang-Jian Zhao, Fu-Qing Yuan, Bin-Lin Pan, Zhi-Cheng Xu, Qing-Tao Gong, Lei Zhang, Jian Hou,* and Lu Zhang*

ABSTRACT: The interfacial properties of a heterogeneous composite flooding system containing a surfactant fatty alcohol polyoxyethylene carboxylate (C₁₂EO₃C), branched-preformed particle gel (B-PPG), and polymer partly hydrolyzed polyacrylamide (HPAM) at the crude oil–water interface were investigated by a dilational rheology method. The results demonstrated that the C₁₂EO₃C molecules can form an elastic interfacial film with certain strength at the crude oil–water interface. The addition of HPAM to the C₁₂EO₃C solution has a detrimental effect on the interfacial film formed by C₁₂EO₃C molecules, leading to a decrease in the dilational modulus and an increase in the phase angle. Moreover, the addition of B-PPG to the C₁₂EO₃C solution also disrupts the stability and strength of the interfacial film of C₁₂EO₃C. In particular, linear HPAM with a lower steric hindrance is more likely to insert into the interfacial film of C₁₂EO₃C; thus, HPAM possesses a stronger destruction ability for the interfacial film of C₁₂EO₃C than B-PPG. When HPAM is compounded with B-PPG, a superimposed effect exists to cause more severe disruption for the interfacial film. The heterogeneous composite flooding system not only enhances oil recovery by increasing the viscosity of the bulk phase but also weakens the interfacial film to facilitate the post-treatment of the recovered crude oil. Thus, the heterogeneous composite flooding system exhibits promising prospects in practical application.

1. INTRODUCTION

With the increasing demand for petroleum fuels, enhanced oil recovery (EOR) has become an urgent task for the oil industry. In order to enhance crude oil recovery, various EOR techniques have been developed to improve the physical and chemical properties of oil reservoirs, including chemical flooding,¹ thermal flooding,² gas flooding,³ and microbial flooding.⁴ Currently, chemical flooding is considered to be an economical and effective means for EOR.⁵,⁶ The injection of specific chemicals into oil reservoirs can increase the pore pressure, reduce the interfacial tension (IFT), and increase the flow ability of crude oil, thus extracting the residual oil trapped in the pore space or blind areas of the rock more easily.⁷

Chemical flooding mainly includes alkali flooding, surfactant flooding, and polymer flooding.⁸,⁹ The essence of alkali flooding and surfactant flooding is reducing the IFT between water and crude oil to improve the oil recovery efficiency, while polymer flooding increases the viscosity of aqueous solutions and improves the oil recovery efficiency via enlarging the swept region of the aqueous solution.¹⁰,¹¹ Nowadays, the compounds of surfactants and polymers have received considerable attention for their ability to further enhance oil recovery.¹²,¹³ As known, the most frequently used EOR polymer is the partially hydrolyzed polyacrylamide (HPAM).¹⁴ However, it is inevitable for HPAM to undergo shear thinning and adsorption losses during the transport in porous media of the subsurface oil formation, which results in a significant decrease in the viscosity of the polymer solution. Moreover, the –CONH₂ group in the HPAM molecule is prone to be hydrolyzed and degraded at high temperatures, which also has an adverse impact on the oil recovery efficiency. In the process of solving these problems, a novel partially branched and partially cross-linked polyacrylamide gradually attracts the attention of researchers.¹⁵,¹⁶ This polyacrylamide derivative is a branch-preformed particle gel (B-PPG) with a star-like or netlike structure. The viscoelastic characteristic of the B-PPG
allows it to swell in water and endow the bulk phase with a higher viscosity. Meanwhile, B-PPG possesses a better temperature resistance, strong salt resistance, superior anti-shearing ability, and robust migration and plugging capabilities, as compared with HPAM. Therefore, surfactants, B-PPG, and HPAM are often simultaneously added into oil reservoirs to enhance the stability and viscosity of the displacing fluid more effectively.

In the oil recovery process, the properties of the interface between the displacing fluid and the crude oil play a critical role in the oil recovery efficiency. Moreover, crude oil is extracted in the form of an emulsion and the post-treatment of the recovered crude oil is of enormous importance. It is known that the nature of the interfacial film is closely related to the stability of the emulsion. Lei et al. found that a thick interfacial film with large dilational modulus improved the stability of an emulsion. Marquez et al. proposed that the stability of emulsions was related to the interfacial compression elasticity in their study of the interfacial properties in the surfactant–oil–water system. Politova et al. found that different concentrations of surfactant Span 80 formed water–oil–water emulsion films with different thicknesses, affecting the lifetime of the interfacial film and the stability of the emulsion. Therefore, the research of the characteristics of the fluid interface between the displacing fluid and crude oil is of great significance. However, few research studies focus on the interfacial properties of heterogeneous systems containing a surfactant, B-PPG, and polymer.

Interfacial rheology is an effective method to study the properties of the interfacial film through the regular perturbations of the interface. In particular, interfacial dilational rheology provides information on the viscoelastic properties of the interfacial adsorption film, the arrangement of the molecules at the interface, and the strength of the interfacial film by periodically expanding and compressing the interfacial area. Up to now, with the help of the interfacial dilational rheology method, the oil–water interfacial characteristics of multiple different types of surfactants and their mixtures, such as anionic, cationic, zwitterionic, and gemini surfactants, have been investigated. By using interfacial rheology, researchers come to realize that the oil–water interfacial film formed by surfactants exhibits multiple intriguing behaviors after the addition of polymers. Zhu et al. found that the addition of the polymer to the surfactant solution would result in a mixed adsorption film, which is formed by the hydrophobic interactions between polymer chains and the alkyl chains of the surfactant molecules. Thus, the dilational characteristics of the surfactant adsorption layer at the oil–water interface were remarkably changed. The interfacial behaviors of similarly charged and oppositely charged polymer–surfactant mixtures were explored by Dong et al. It was found that there is a stronger interaction between the cationic surfactant DTAB and the polymer HPAM, and a more hydrophobic interfacial active complex was formed to affect the interfacial properties of the polymer–surfactant mixtures. In addition, the adsorption kinetics of the polymer–surfactant mixture was determined by diffusion exchange and electrostatic interactions. When salts (NaCl and CaCl₂) were added, the charges of the ionized functional groups of the polymer and surfactant were shielded, resulting in the decrease in the dilational viscoelasticity of the polymer–surfactant mixture with the increasing concentration of ions. Due to the unique advantages of viscoelastic particles of B-PPG in the oil recovery process, researchers began to explore the interfacial rheological properties of a preformed particle gel (PPG) at the oil–water interface. Tang et al. found that as the concentration of the PPG increased, a network structure was gradually formed by PPG molecules at the interface, and thus the interfacial dilational elasticity and viscosity increased significantly. The electrolytes neutralized the excess charge of PPG molecules, which resulted in a significant decrease in the dilational elasticity and viscosity. When crude oil fractions existed, the acidic components interacted with PPG molecules and replaced the interfacial PPG molecules to form a mixed adsorption film, while asphaltene had little effect on the interfacial film formed by PPG. Wang studied the effect of different nonionic polyether demulsifiers and the cationic reverse emulsifier on the interfacial properties of the PPG film. It was demonstrated that nonionic polyether demulsifiers would displace PPG molecules at the interface and destroy the interfacial film. The cationic reverse emulsifier affected the properties of the PPG interfacial film by electrostatic interactions, and the strength of the interfacial film of PPG was determined by the concentration of the cationic reverse emulsifier. Deng et al. found that the interfacial tension of the heterogeneous composite flooding system containing B-PPG molecules decreased as the salinity increased. Moreover, the diffusion exchange between the bulk phase and the interface increased with the increasing salinity. Both the divalent cation and the alkali would promote the compacted arrangement of the interfacial film at low concentrations but promote the diffusion exchange process at high concentrations. The decrease in interfacial modulus may be advantageous for EOR because low modulus will facilitate the formation of oil bank and weaken the Jamin effect.

Although the combination of a surfactant, B-PPG, and polymer can increase the sweep efficiency of surfactant solutions in the subsurface pores, such a heterogeneous composite flooding system may change the oil–water interfacial properties and affect the post-treatment of the recovered crude oil. Therefore, it is necessary to investigate the interfacial properties of the heterogeneous system. Herein, the interfacial properties of the heterogeneous composite flooding system at the crude oil–water interface were investigated using the dilational rheology method. Furthermore, the effect of the branched-preformed particle gel (B-PPG) compounded with the polymer (HPAM) in different ratios on the interfacial film formed by fatty alcohol polyoxyethylene carboxylate (C₁₂EO₃C) was further explored, which is meaningful for the understanding of the oil–water interfacial properties in heterogeneous flooding systems.

2. EXPERIMENTAL SECTION

2.1. Materials. The crude oil sample was Tuo 28 crude oil from Sheng Li Oilfield in China, with an acid number of 0.99 mg KOH/g and a density of 0.9487 g/cm³ at 30 °C. The contents of saturates, aromatics, resins, and asphaltenes are...
48.4, 19.2, 28.5, and 3.9%, respectively. The surfactant dodecanol carboxylate with three polyoxyethylene (EO) groups (C\textsubscript{12}EO\textsubscript{3}C) was an ethoxylated anionic surfactant with three polyoxyethylene groups, as shown in Scheme 1, which was synthesized in our laboratory with a purity of about 90%. The polymer, partially hydrolyzed polyacrylamide (HPAM), was provided by the Exploration and Development Research Institute, Sheng Li Oilfield, SINOPEC with a hydrolysis degree of 13.2%, a solids content of 90%, and a molecular weight of approximately 17 million. The branch-preformed particle gel (B-PPG) was also supplied by the Exploration and Development Research Institute, Sheng Li Oilfield, SINOPEC with a solids content of 90% and a median particle size of 813 \textmu m. The water used for the experiments was the formation brine from Tuo 28, and the mass concentration of the ions in the formation brine is shown in Table 1.

### Table 1. Composition of the Tuo 28 Formation Brine

| ions         | Cl\textsuperscript- | SO\textsubscript{4}\textsuperscript{2-} | CO\textsubscript{3}\textsuperscript{2-} | HCO\textsubscript{3}\textsuperscript- | Na\textsuperscript+ + K\textsuperscript+ | Ca\textsuperscript{2+} | Mg\textsuperscript{2+} | TDS content of ions (mg/L) |
|--------------|---------------------|----------------------------------------|--------------------------------------|----------------------------------------|-------------------------|-------------------------|-------------------------|
| content of ions (mg/L) | 12,289 | 0 | 0 | 606 | 7477 | 428 | 121 | 20,921 |

Figure 1. Dynamic (A) and equilibrium (B) interfacial tensions of C\textsubscript{12}EO\textsubscript{3}C solution against crude oil at different concentrations.

Figure 2. Effect of frequency on the interfacial dilational modulus (A) and phase angle (B) of C\textsubscript{12}EO\textsubscript{3}C solution at different concentrations.

2.2. Methods. All experiments were tested by an oscillating drop method via an interfacial dilational rheometer (Data-Physics Instruments, Germany) according to the literature. First, a crude oil droplet was injected into the heterogeneous composite flooding system by a computer-controlled micro-injector to create an oil–water interface. Subsequently, the volume of the oil drop was perturbed at a frequency of 0.1 Hz to evaluate the dynamic changes in rheological properties of the interfacial film. In addition, the interfacial tension was obtained by drop profile analysis, and the change in the interfacial tension value over time was observed to determine whether the oil–water interface was in equilibrium. To clarify the influence of frequency on the relaxation process at the oil–water interface, the equilibrated interface was disturbed (dA/A = 10%) and the oscillation frequency was varied from 0.005 to 0.1 Hz. The measured errors of modulus and phase angle are ±1 mN/m and ±2 degree, respectively. All experiments were performed at 30.0 ± 0.5 °C.
3. RESULTS AND DISCUSSION

3.1. Interfacial Properties of the Surfactant. The heterogeneous composite flooding system contains surfactants, branch-preformed particle gels, and polymers. Since the concentration of the surfactant has a critical impact on its interfacial activity, C\textsubscript{12}EO\textsubscript{3}C solutions with different concentrations were prepared to investigate the IFTs against crude oil (Figure 1). It can be seen that more C\textsubscript{12}EO\textsubscript{3}C molecules accumulate at the interface with the aging time, leading to a decrease in the IFT. Meanwhile, the dynamic IFT reaches an equilibrium value more quickly as the surfactant concentration increases (Figure 1a). In Figure 1b, it is obvious that the equilibrium IFT gradually decreases with the increase in C\textsubscript{12}EO\textsubscript{3}C concentration. With the addition of 50 ppm C\textsubscript{12}EO\textsubscript{3}C, the equilibrium IFT can be reduced to approximately 6 mN/m.

The interfacial film formed by C\textsubscript{12}EO\textsubscript{3}C molecules has a diffusion-exchange process with the bulk phase. When the equilibrated interface is disturbed, the responses of IFTs and the calculated dilational rheological parameters are directly related to the frequency of disturbance, thus reflecting the viscoelastic characteristics of the interfacial film.\textsuperscript{22,23} The effect of oscillating frequency on the interfacial dilational modulus and phase angle of the C\textsubscript{12}EO\textsubscript{3}C solution is shown in Figure 2. It is observable that the dilational modulus of the C\textsubscript{12}EO\textsubscript{3}C solution gradually increases as the oscillating frequency increases (Figure 2a). This can be attributed to the occurrence of fast relaxation processes such as diffusion-exchange oscillating frequency, which will eliminate the change in IFT from the disturbed interface at low oscillating frequency.\textsuperscript{37} At low frequencies, the surfactant has enough time to adapt to the deformation of the interface, which means that there is no resistance to the disturbance. In Figure 2b, as the oscillating frequency increases, the phase angle decreases slightly at low concentrations (0.5–10 ppm) and then changes a little at high concentrations (≥50 ppm). Additionally, the value of phase angle is relatively low over the entire range of frequencies. On the one hand, the active components in crude oil, which possess strong interactions, result in a relatively large proportion of dilational elasticity. On the other hand, the EO group of the C\textsubscript{12}EO\textsubscript{3}C molecule may lie flat at the interface. The existence of the EO group also enhances the elasticity of the interfacial film.\textsuperscript{38} Therefore, the phase angle is

![Figure 3](image-url)  
**Figure 3.** Effect of concentration on the interfacial dilational modulus (A) and phase angle (B) of C\textsubscript{12}EO\textsubscript{3}C solution.

![Figure 4](image-url)  
**Figure 4.** Effect of polymer concentration on the interfacial dilational modulus (A) and phase angle (B) of C\textsubscript{12}EO\textsubscript{3}C solution as a function of frequency.
relatively low and the interfacial film is predominantly elastic over the entire experimental concentration range.

The effect of concentration on the interfacial dilational modulus of $C_{12}EO_3$ solution is illustrated in Figure 3a. For comparison, the dilational modulus of the crude oil–water interface without the addition of surfactants was first measured. Under this condition, the active components in crude oil will form an interfacial film, which endows the interfacial film with certain strength. When a small number of surfactants (0.5 ppm $C_{12}EO_3$) were added, the dilational modulus decreased slightly. This phenomenon can be attributed to the better adsorption capacity of $C_{12}EO_3$ molecules that enables $C_{12}EO_3$ molecules to replace some of the active components at the interface. As a result, the previous interfacial film formed by the active components is weakened. As the concentration of the surfactants continues to increase, the surfactant adsorption film begins to be formed and the dilational modulus starts to rise. In comparison to the phase angle without surfactants, the addition of a small number of $C_{12}EO_3$ molecules (0.5 ppm) causes the phase angle to increase sharply to approximately 45° at 0.005 Hz. The interfacial film formed by the active components in the crude oil is elastic, and diffusion exchange plays an important role in the interfacial film of the $C_{12}EO_3$ molecules. Thus, when a small quantity of $C_{12}EO_3$ molecules replaces the active components at the interface, the phase angle increases significantly and the frequency dependence phenomenon becomes more evident. As the concentration of $C_{12}EO_3$ solution continues to increase, the contribution of elasticity to the interfacial film formed by $C_{12}EO_3$ molecules is higher than that of viscosity; accordingly, the phase angle decreases (Figure 3b). Taking into account the high strength of the interfacial film, 10 ppm $C_{12}EO_3$ was finally selected for the subsequent study.

3.2. Effect of the Polymer on the Interfacial Properties of the Surfactant. Polymers, which can increase the viscosity of aqueous solutions and the sweep efficiency of surfactant solutions, are extensively used for oil recovery. To explore the influence of polymers on interfacial properties of surfactants, the interfacial dilational modulus and phase angle of polymer-$C_{12}EO_3$ solutions at different polymer concentrations were investigated in Figures 4 and 5. One can see from Figure 4 that the water-soluble polymer HPAM show little effect on the trend of frequency dependences for both modulus and phase angle. After the addition of HPAM, the dilational modulus of the polymer-$C_{12}EO_3$ system gradually increases (Figure 4a), while the phase angle gradually decreases as the oscillating frequency increases (Figure 4b). This trend is consistent with that without HPAM. However, for the polymer-$C_{12}EO_3$ system, the interfacial dilational modulus decreases remarkably when the concentration of HPAM increases. In particular, the dilational modulus can be reduced to 8 mN/m with the addition of 2400 ppm HPAM. Meanwhile, the phase angle gradually increases as the concentration of HPAM increases, and 2400 ppm HPAM polymers can increase the phase angle to 17° (Figure 5).

It is well-known that the polymer chains of linear HPAM can insert into the interfacial film randomly, which will destroy the previous compact interfacial film and weaken the strength of film. The experimental results in Figures 4 and 5 indicate that HPAM affects the nature of films by the insertion into the adsorption layer and bulk viscosity has little effect on interfacial rheological data.

3.3. Effect of B-PPG on the Interfacial Properties of the Surfactant. As the preformed particle gels are also used in the oilfield, the effect of the B-PPG was explored. When B-PPG is added to the $C_{12}EO_3$ system, the dilational modulus of the system will gradually increase with the increasing frequency (Figure 6a), while the phase angle gradually decreases with the increasing frequency as well (Figure 6b). However, the addition of B-PPG results in a decrease in the dilational modulus and a slight increase in the overall phase angle. Similar to that of polymer HPAM, this phenomenon demonstrates that the addition of preformed particle gels disrupts the interfacial film formed by the surfactant instead. Tang et al. found that when branch-preformed particle gels were present alone, they would first form a compact monolayer adsorption layer near the interface. As the concentration of B-PPG increases, B-PPG would eventually form a disorganized and rigid multilayer structure near the interface. Therefore, the individual B-PPG can form a tight interfacial film. Interestingly, the surfactant showed detrimental impact on the interfacial film of preformed particle gels. Due to the strong adsorption capacity of the surfactant itself, preformed particle gels cannot form their own interfacial film after forming the surfactant’s film. Thus, only small quantities of B-PPG can insert into the interfacial film formed by the surfactant, which hinders the effect of the surfactant instead. In particular, 2400 ppm B-PPG can merely reduce the dilational modulus to 10 mN/m, and the phase angle only increases to 12° (Figure 7). Compared with the interfacial properties when HPAM exists (Figure 5), the decrease in the dilational modulus and the increase in the phase angle are smaller. The linear HPAM can insert into the interface easily, while spherical B-PPG can hardly insert into the interface due to the steric hindrance effect. Consequently, the disruption for the interfacial film by B-PPG is less than the linear HPAM. The schematic diagrams of adsorption behaviors will be plotted later.

3.4. Interfacial Properties of Surfactant, B-PPG, and Polymer Systems. 3.4.1. Effect of Concentration at a Constant Ratio of B-PPG to HPAM. The heterogeneous systems, which contain surfactants, preformed particle gels, and polymers, are always used in the oilfield. At high temperatures, the use of polymers with branch-preformed particle gels improves the viscosity of the aqueous solution and consequently enhances the sweep efficiency more effectively in the pores. Such a heterogeneous system, however, may
change the interfacial properties of the crude oil, thus affecting the post-treatment of the produced fluid. Therefore, the interfacial properties of the heterogeneous system need to be investigated. To clarify the role of polymers and preformed particle gels under practical conditions, both HPAM and B-PPG were added simultaneously to the C₁₂EO₃C solution, in which the concentration ratio of B-PPG to HPAM was fixed at 1:2. The effects of oscillating frequency and concentration on the dilational modulus and phase angle of the polymer-PPG-C₁₂EO₃C system are, respectively, shown in Figures 8 and 9.

The dilational modulus of the heterogeneous system decreases notably and the phase angle increases when HPAM, B-PPG, and C₁₂EO₃C exist simultaneously. In particular, the mixture of HPAM and B-PPG can reduce the dilational modulus to 5 mN/m and increase the phase angle to 19° at a concentration of 2400 ppm (Figure 9). This result indicates that there is a superposition effect to result in a more detrimental impact on the interfacial film formed by the C₁₂EO₃C molecules. This phenomenon may be attributed to the branch-preformed particle gels, which further expand the insertion of the polymers at the interface after the insertion of the linear HPAM. Tang et al.³² found that when linear HPAM was added to the PPG solution, HPAM with low

Figure 6. Effect of B-PPG concentration on the interfacial dilational modulus (A) and phase angle (B) of C₁₂EO₃C solution as a function of frequency.

Figure 7. Effect of B-PPG concentration on the interfacial dilational modulus and phase angle of PPG-C₁₂EO₃C solutions at 0.1 Hz.

Figure 8. Interfacial dilational modulus (A) and phase angle (B) of the HPAM-BPPG-C₁₂EO₃C solutions at different concentrations (B-PPG to HPAM ratio = 1:2) as a function of frequency.
concentrations would destroy the original interfacial network structure of B-PPG, resulting in a decrease in the strength of the interfacial film. In contrast, HPAM with high concentrations interacted with PPG to form spherical aggregates at the interface, which enhanced the elasticity and viscosity of the interfacial film. This result is completely different from the consequence in the presence of the surfactant (C\textsubscript{12}EO\textsubscript{3}C).

Once the surfactant is present, the superposition effect between HPAM and B-PPG results in an enhanced displacement effect and a significant reduction in the strength of the surfactant adsorption film.

### 3.4.2. Effect of the Ratio of B-PPG to HPAM at a Constant Concentration.

The effects of oscillating frequency and concentration ratios of B-PPG to HPAM on the interfacial dilational modulus and phase angle of the polymer-PPG-C\textsubscript{12}EO\textsubscript{3}C system at 0.1 Hz are depicted in Figures 10 and 11. The illustrations of adsorption behaviors for C\textsubscript{12}EO\textsubscript{3}C, B-PPG, and HPAM molecules at the crude oil-water interface are depicted in Figure 12. When HPAM and B-PPG are simultaneously added to the C\textsubscript{12}EO\textsubscript{3}C solution, it is found that the concentration ratio of B-PPG to HPAM has a crucial influence on the viscoelastic properties of the oil–water interface. This implies that C\textsubscript{12}EO\textsubscript{3}C can form a relatively compacted interfacial film with active components of crude oil before the addition of HPAM or B-PPG (Figure 12A). Besides, the addition of 2400 ppm HPAM reduces the dilational modulus and increases the phase angle to a greater extent than 2400 ppm B-PPG, indicating that HPAM has a stronger ability to disrupt the interfacial film than B-PPG. This is caused by the fact that the linear HPAM, which has a smaller steric hindrance, is easier to insert into the interface than the spherical B-PPG. Furthermore, when HPAM is compounded with B-PPG, the interfacial dilational modulus decreases and the phase angle increases even more. This demonstrates that the mixed system of HPAM and B-PPG has a superposition effect to cause more severe interfacial film disruption.

It is important to point out that the heterogeneous composite flooding system increases the viscosity of the bulk phase via B-PPG and HPAM, which is beneficial to enhance oil recovery. On the other hand, the heterogeneous composite
flooding system disrupts the stability of the crude oil–water interfacial film, which is conducive to the post-treatment of the produced fluid. Thus, the heterogeneous composite flooding system has a promising application prospect in EOR.

4. CONCLUSIONS

Herein, the influences of the surfactant (C_{12}EO_{3}C), branch-preformed particle gel (B-PPG), and polymer (HPAM) on the dilational rheological properties of the heterogeneous system were explored. Through this investigation, the following conclusions can be drawn:

1. The surfactant C_{12}EO_{3}C can form an elastic interfacial film at the crude oil–water interface with certain strength by replacing the active components in crude oil.

2. The linear HPAM inserts into the crude oil–water interface and disrupts the interfacial film formed by C_{12}EO_{3}C molecules, resulting in a significant decrease in the dilational modulus and an increase in the phase angle.

3. The addition of B-PPG to the C_{12}EO_{3}C solution also has a damaging effect on the crude oil–water interfacial film formed by C_{12}EO_{3}C molecules, which decreases the strength of the interfacial film.

4. Due to the steric hindrance, linear HPAM inserts into the crude oil–water interfacial film of C_{12}EO_{3}C easier than spherical B-PPG. Thus, HPAM possesses a stronger ability to disrupt the interfacial film.

5. When HPAM is mixed with B-PPG, there is a superimposed effect to cause more severe disruption to the interfacial film of the heterogeneous composite flooding system containing C_{12}EO_{3}C, B-PPG, and HPAM, which is conducive to the post-treatment of the recovered crude oil.

■ AUTHOR INFORMATION

Corresponding Authors
Jian Hou – School of Petroleum Engineering, China University of Petroleum (East China), Qingdao City, Shandong Province 266580, China; Email: houjian@upc.edu.cn; Fax: 86-10-62554670

Lu Zhang – Key Laboratory of Photochemical Conversion and Optoelectronic Materials, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing 100190, P. R. China; orcid.org/0000-0001-8355-900X; Phone: 86-10-82543588; Email: luyiqiao@mail.ipc.ac.cn; Fax: 86-10-62554670

Authors
Fang-Jian Zhao – School of Petroleum Engineering, China University of Petroleum (East China), Qingdao City, Shandong Province 266580, China; orcid.org/0000-0002-6966-924X; Phone: 86-10-82543588; Email: luyiqiao@mail.ipc.ac.cn; Fax: 86-10-62554670

Notes
The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This study is financially supported by the National Key R&D Program of China (NO. 2019YFA0708700).

■ REFERENCES

(1) Bashir, A.; Sharifi Haddad, A.; Rafati, R. A review of fluid displacement mechanisms in surfactant-based chemical enhanced oil...
(2) Wang, Y.; Liu, H.; Zhang, Q.; Chen, Z.; Wang, J.; Dong, X.; Chen, F. Pore-scale experimental study on EOR mechanisms of combining thermal and chemical flooding in heavy oil reservoirs. J. Pet. Sci. Eng. 2020, 185, No. 106649.

(3) Monette, M.; Nguyen, Q. P. Investigation of the effect of gas compositions on low-tension-gas flooding. J. Pet. Sci. Eng. 2021, 207, No. 109140.

(4) Niu, J. J.; Liu, Q.; Lv, J.; Peng, B. Review on microbial enhanced oil recovery: Mechanisms, modeling and field trials. J. Pet. Sci. Eng. 2020, 192, No. 107350.

(5) Afolabi, F.; Mahmood, S. M.; Yeeken, N.; Akbari, S.; Sharifi, S.; Gulati, H. Polymeric surfactants for enhanced oil recovery: A review of recent progress. J. Pet. Sci. Eng. 2022, 208, No. 109338.

(6) Sun, L. D.; Wu, X. L.; Zhou, W. F.; Li, X.; Han, P. Technologies of enhancing oil recovery by chemical flooding in Daqing Oilfield, NE China, Pet. Explor. Des. 2018, 45, 673–684.

(7) Varel, F. T.; Dai, C.; Shaikh, A.; Li, J.; Sun, N.; Yang, N.; Zhao, G. Chromatography and oil displacement mechanism of a dispersed particle gel strengthened Alkali/Surfactant/Polymer combination flooding system for enhanced oil recovery. Colloids Surf., A 2021, 610, No. 125642.

(8) Fu, L. P.; Zhang, G. C.; Ge, J. J.; Liao, K. L.; Pei, H. H.; Jiang, P.; Li, X. Q. Study on organic alkali-surfactant-polymer flooding for enhanced ordinary heavy oil recovery. Colloids Surf., A 2016, 508, 230–239.

(9) Rezaei, A.; Riasi, M.; Escrochi, M.; Elhaimi, R. Integrating surfactant, alkali and nano-fluid flooding for enhanced oil recovery: A mechanistic experimental study of novel chemical combinations. J. Mol. Liq. 2020, 308, No. 113106.

(10) Kang, W. L.; Kang, X.; Lashari, Z. A.; Li, Z.; Zhou, B. B.; Yang, H. B.; Sarsenbekuly, B.; Aidarova, S. Progress of polymer gels for connorance control in oilfield. Adv. Colloid Interface Sci. 2021, 289, No. 102363.

(11) Rafa, P.; Broekhuis, A. A.; Picchioni, F. Polymeric surfactants for enhanced oil recovery: A review. J. Pet. Sci. Eng. 2016, 145, 723–733.

(12) Tvakkoli, O.; Kamyab, H.; Shariati, M.; Mustafa Mohamed, A.; Junin, R. Effect of nanoparticles on the performance of polymer/surfactant flooding for enhanced oil recovery: A review. Fuel 2022, 312, No. 122867.

(13) Driuetta, P.; Picchioni, F. Surfactant-Polymer Interactions in a Combined Enhanced Oil Recovery Flooding. Energies 2020, 13, 6520.

(14) Rezaei, A.; Abdi-Khangah, M.; Mohebbi, A.; Tatar, A.; Mohammadi, A. H. Using surface modified clay nanoparticles to improve rheological behavior of Emulsified Polycryliclamid (HPAM) solution for enhanced oil recovery with polymer flooding. J. Mol. Liq. 2016, 222, 1148–1156.

(15) Seidy, E. M.; Khodapanah, E.; Tabatabaei-Nezhad, S. A. Comprehensive review on the research and field application of prefomed polymer gel connorance control technology. J. Pet. Sci. Eng. 2021, 202, No. 108440.

(16) Salunkhe, B.; Schuman, T.; Al, B. A.; Bai, B. Ultra-high temperature resistant prefomed particle gels for enhanced oil recovery. Chem. Eng. J. 2021, 426, No. 130712.

(17) Lai, N.; Chen, S.; Tang, L.; Huang, Y.; Xu, H. Migration characteristics and profile control capabilities of preformed particle gel in porous media. Petroleum, 2021, DOI: 10.1016/j.petlm.2021.07.006.

(18) Ravera, F.; Dzika, K.; Santini, E.; Cristofolini, L.; Liggieri, L. Emulsification and emulsion stability: The role of the interfacial properties. Adv. Colloid Interface Sci. 2021, 288, No. 102344.

(19) Lei, J.; Gao, Y.; Ma, Y.; Zao, K.; Fu, X. Improving the emulsion stability by regulation of dilational rheology properties. Colloids Surf., A 2019, No. 123906.

(20) Marquez, R.; Forgariini, A. M.; Langevin, D.; Salager, J.-L. Instability of Emulsions Made with Surfactant-Oil-Water Systems at Optimum Formulation with Ultralow Interfacial Tension. Langmuir 2018, 34, 9252–9263.

(21) Politova, N.; Tcholakova, S.; Denkov, N. D. Factors affecting the stability of water-oil-water emulsion films. Colloids Surf., A 2017, 522, 608–620.

(22) Karbaschi, M.; Lotfi, M.; Kraegel, J.; Javadi, A.; Bastani, D.; Miller, R. Rheology of interfacial layers. Curr. Opin. Colloid Interface Sci. 2014, 19, 514–519.

(23) Ravera, F.; Loglio, G.; Kovalchuk, V. I. Interfacial dilational rheology by oscillating bubble/drop methods. Curr. Opin. Colloid Interface Sci. 2010, 15, 217–228.

(24) Lai, L.; Mei, P.; Wu, X. M.; Chen, L.; Liu, Y. Interfacial dynamic properties and dilational rheology of mixed anionic and cationic Gemini surfactant systems at air–water interface. Colloids Surf., A 2016, 509, 341–350.

(25) Zhang, Y.; Cai, H. Y.; Hu, S. S.; Li, J. G.; Gong, Q. T.; Ma, W. J.; Liu, Z. Y.; Zhang, L.; Zhang, L.; Zhao, S. Interfacial Dilational Properties of Betaines and Novel Sulfonate Mixtures: Effects of Alkyl Chain Length. J. Dispersion Sci. Technol. 2020, 41, 195–206.

(26) Wang, C.; Zhao, L.; Xu, B. C.; Cao, X. L.; Guo, L. L.; Zhang, L.; Zhao, S. Effect of Dynamic Interfacial Dilational Properties of Cationic Surfactant Mixtures on the Foam Stability in the Presence of Oil. Colloids Surf., A 2018, 541, 78–86.

(27) Sun, H. Q.; Guo, Z. Y.; Cao, X. L.; Zhu, Y. W.; Pan, B. L.; Liu, M.; Zhang, L.; Zhao, L. Interfacial interactions between oleic acid and betaine molecules at decane-water interface: a study of dilational rheology. J. Mol. Liq. 2020, 316, No. 113784.

(28) Yang, S. J.; Liu, H. L.; Feng, J.; Ma, H. H.; Zhu, Y.; Zhang, L.; Zhang, L. Interfacial Dilational Properties of Anionic Gemini Surfactants with Polyethylene Spacers. J. Dispersion Sci. Technol. 2018, 39, 531–538.

(29) Guzmán, E.; Llamas, S.; Maestro, A.; Fernández-Peña, L.; Akanno, A.; Miller, R.; Ortega, F.; Rubio, R. G. Polymer–surfactant systems in bulk and at fluid interfaces. Adv. Colloid Interface Sci. 2016, 233, 38–64.

(30) Zhu, Y. W.; Song, X. W.; Zhang, L.; Luo, L.; Zhang, L.; Zhao, S.; Yu, J. Y. Effect of electrolyte on interfacial dilational properties of chemical flooding systems by relaxation measurements. Fuel 2011, 90, 3172–3178.

(31) Dong, Z.; Gao, R.; Sun, D.; Wu, T.; Li, Y. Combined effects of polymer/surfactant mixtures on dynamic interfacial properties. Asia-Pac. J. Chem. Eng. 2017, 12, 489–501.

(32) Tang, L.; Luo, L.; Fang, H. B.; Zong, H.; Zhang, L.; Zhao, S. Dilational rheology properties of branch-performed particle gel by relaxation measurements. Chem. Res. Chin. Univ. 2013, 34, 1434–1440.

(33) Tang, L.; Fang, H. B.; Zong, H.; Zhang, L.; Zhao, L.; Zhang, L. Dilational Rheological Properties of Interfacial Films Containing Branch-Preformed Particle Gel and Crude Oil Fractions. J. Appl. Polym. Sci. 2015, 132, 41337.

(34) Wang, F. Effect of demulsifiers on interfacial dilational rheological properties of performed particle gel. J. China Univ. Pet. 2015, 39, 163–168.

(35) Deng, Z. Y.; Zhu, Y. W.; Zhu, Y.; Zhang, L.; Zhang, L. Influence of reservoir conditions on interfacial dilational rheological properties of heterogeneous flooding system. J. WuHan Univ. Technol. 2020, 42, 40–45.

(36) Yan, F.; Zhang, L.; Zhao, R. H.; Huang, H. Y.; Dong, L. F.; Zhang, L.; Zhao, S.; Yu, J. Y. Surface Dilational Rheological and Foam Properties of Aromatic Side Chained N-Acyltaurate Amphiphiles. Colloids Surf., A 2012, 396, 317–327.

(37) Sun, H. Q.; Zhang, L.; Li, Z. Q.; Zhang, L.; Luo, L.; Zhao, S. Interfacial dilational rheology related to Enhance Oil Recovery. Soft Matter 2011, 7, 7601–7611.

(38) Li, Y.; Zhang, L.; Zhang, L.; Zhao, S.; Yu, J. Y. Effect of Oxyethylene Numbers on Surface Dilational Properties of Alkyl Secondary Alcohol Ethoxylates. J. Dispersion Sci. Technol. 2011, 32, 490–497.
(39) Ma, B. D.; Gao, B. Y.; Zhang, L.; Gong, Q. T.; Jin, Z. Q.; Zhang, L.; Zhao, S. Influence of Polymer on Dynamic Interfacial Tensions of EOR Surfactant Solutions. *J. Appl. Polym. Sci.* 2014, 40562.