



Temperature-resistant and salt-tolerant mixed surfactant system for EOR in the Tahe Oilfield

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Abstract

A new temperature-resistant and salt-tolerant mixed surfactant system (referred to as the SS system) for enhancing oil recovery at the Tahe Oilfield (Xinjiang, China) was evaluated. Based on the analysis of the crude oil, the formation water and rock components in the Tahe Oilfield, the long-term thermal stability, salt tolerance and the ability to change the wettability, interfacial activity and oil washing efficiency of the mixed surfactant system were studied. The system contains the anionic surfactant SDB and another cationic surfactant SDY. When the total mass concentration of the SS solution is 0.15 wt%, m(SDB)/m(SDY) ratio is 1 to 1, and excellent efficiencies are achieved for oil washing for five kinds of Tahe Oilfield crude oils (more than 60%). In addition, after adding cationic surfactant, the adsorption capacity of the surfactant is further reduced, reaching 0.261 mg/g. The oil displacement experiments indicate that under a temperature of 150 °C and a salinity of 24.6×10^4 mg/L, the SS system enhances the oil recovery by over 10% after water flooding. The SS anionic–cationic surfactant system is first presented in the open literature that can be successfully applied to obtain predictions of Tahe Oilfield carbonate reservoirs with a high temperature and high salinity.

Keywords Mixed surfactant system · Temperature resistance · Salt tolerance · Carbonate reservoir · Enhanced oil recovery

1 Introduction

With increasing energy demand around the global, production of oil from unconventional reservoirs using enhanced oil recovery technology is becoming increasingly important.

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As the main component of enhanced oil recovery technology, advancement in chemical methods helps to alleviate the energy problems of the world (Yang et al. 2019). The use of surfactants can reduce the interfacial tension or change the wettability, thereby increasing the amount of oil recovered from the reservoir after water flooding (Banat 1995; Hirasaki et al. 2008; Hosseininasab et al. 2016). Oil recovery from the fractured carbonate reservoirs of the Tahe Oilfield using water flooding is very low, and the amount of residual oil is high. The main chemical methods for enhancing oil recovery in Tahe Oilfield include surfactants flooding, alkaline flooding and polymer flooding (Yang et al. 2020a, b). Compared with alkaline flooding and polymer flooding, surfactant flooding as a tertiary oil displacement method can remarkably improve oil recovery. Research on temperature-resistant and salt-tolerant surfactants in oilfields has received much attention (Das et al. 2018; Pal et al. 2018; Zhao et al. 2000), but most of the studies have focused on sandstone reservoirs. In contrast, there have been no successful reports to date on temperature-resistant and salt-tolerant surfactant systems in the Tahe Oilfield carbonate reservoirs.

Tertiary oil recovery in high-temperature and high-salinity reservoirs is very important, especially to improve the

heat resistance and salt tolerance of the surfactant system. In fact, two common approaches to obtain surfactants with both temperature resistance and salt tolerance are the modification of conventional surfactants and the combination of different kinds of surfactants (Zhang et al. 2005). Currently, there are many temperature-resistant and salt-tolerant surfactants, but most of them are anion-nonionic surfactants (Wang et al. 2000; Zhang et al. 2005). Chen Xin et al. synthesized two kinds of anionic–nonionic surfactants, palmitic acid diethanolamine polyoxyethylene ether sulfonate sodium (PDES) and oleic acid diethanolamine polyoxyethylene ether sulfonate sodium (ODES), which show good performance at 110 °C and with 4 g/L brine (Chen et al. 2016). Wang Jinshu et al. formulated an anionic–nonionic surfactant for use in the Liaohe Oilfield of China (Wang et al. 2019). Its viscosity reduction rate can reach 91.06%, which can meet the field application requirements of the Liaohe Oilfield, but their study did not evaluate the effect of the surfactant at high temperatures. Compared with the application of anionic–nonionic surfactants in high-temperature and high-salt oil reservoirs, the number of applications of anionic–cationic surfactants are few. Han Xia studied anionic–cationic surfactants in the Shengli Oilfield in China (Han et al. 2012). The results showed that the surfactant still had a very good ultralow interfacial tension after 48 h of adsorption on quartz sand, but they did not report the experimental temperature. In summary, research on the application of anionic–cationic surfactants in high-temperature and high-salt oil reservoirs can help to further enhance oil recovery.

Based on the research on crude oil and formation water at the Tahe Oilfield, we propose a new mixed surfactant system that can sustain a high temperature (150 °C) and high salinity (24.6×10^4 mg/L). An anionic surfactant SDB (Guo et al. 2014) (synthesized by author) with another cationic surfactant, SDY, is contained in this system, which can not

only reduce the dosage of surfactants but also improve the oil washing efficiency.

2 Experimental

In this study, the interfacial activity, long-term aging performance, salt tolerance and temperature resistance, oil washing efficiency, adsorption and oil displacement efficiency properties of the SS system are evaluated.

2.1 Materials

Bromododecane, diphenylether, chlorosulfuric acid, petroleum sulfonate and the cationic surfactant SDY were purchased from Beijing Modern Eastern Fine Chemical Co. Ltd. and were used as received. Sodium chloride ($\text{NaCl} \geq 98\%$), calcium chloride ($\text{CaCl}_2 \geq 98\%$) and sodium hydroxide ($\text{NaOH} \geq 98\%$) were provided by Beijing North Fine Chemicals Co., Ltd. Oil samples, core samples, formation water and marble samples were all taken from the Tahe Oilfield, Xinjiang, China. The SARA (saturated fraction, aromatic fraction, resin and asphaltene) results of the oil sample are shown in Table 1.

As shown in Table 2, mineral ions in the Tahe Oilfield Formation water contain various anions (Cl^- , CO_3^{2-} , SO_4^{2-} , HCO_3^- , etc.) and cations (Ca^{2+} , Mg^{2+} , K^+ , Na^+ , etc.); the total salinity is 24.6×10^4 mg/L, and the total concentration of Ca^{2+} and Mg^{2+} is 14,484 mg/L, which are higher than those in conventional oilfields in China.

2.2 Preparation of the SS system

SDB is synthesized with diphenylether and bromododecane in the presence of chlorosulfuric acid as a sulfonating

Table 1 SARA results of crude oil in the Tahe Oilfield

| Sample | Saturated, % | Aromatic, % | Resin, % | Asphaltene, % | Recovery, % |
|---------|--------------|-------------|----------|---------------|-------------|
| YQ5 | 8.28 | 25.17 | 13.47 | 53.08 | 100.00 |
| TH12245 | 12.26 | 32.69 | 23.89 | 31.16 | 100.00 |
| TH12238 | 12.43 | 30.56 | 24.62 | 32.39 | 100.00 |
| TH12340 | 10.69 | 24.34 | 27.04 | 37.93 | 100.00 |

Table 2 Content of ions and suspended matter of formation water at the Tahe Oilfield

| Items | Na^+ | K^+ | Ca^{2+} | Mg^{2+} | SO_4^{2-} | Cl^- | HCO_3^- | Fe^{3+} | CO_3^{2-} | Suspended matter |
|-----------------|-------------------|--------------|-------------------|------------------|--------------------|-------------------|------------------|------------------|--------------------|------------------|
| Content, mg/L | 6.4×10^4 | 426 | 1.4×10^4 | 784 | 450 | 1.6×10^5 | 95.7 | 7.2 | <0.1 | 141 |
| Content, mmol/L | 2800.0 | 10.9 | 342.5 | 32.7 | 4.7 | 4742.9 | 1.6 | 0.004 | – | – |

agent, and then, sodium hydroxide is used to neutralize the intermediate product (Guo et al. 2014). The molar ratio of diphenylether to bromododecane is 1 to 1. After synthesizing SDB, it was mixed with the cationic surfactant SDY in a mass ratio of 1 to 1, thus obtaining the SS, which was then diluted to 0.15 wt% with formation water for subsequent use. The molecular formulas of anionic surfactant SDB and cationic surfactant SDY are shown in Fig. 1.

2.3 Formation water quality measurement

The ionic compositions and contents in the Tahe Oilfield Formation water were measured by a PIC-10A ion chromatograph (Qingdao Puren Instrument Co., Ltd, China) according to the standard of the People’s Republic of China SY/T 5523–2006 (Practice for analysis of oilfield waters) (Gao et al. 2018).

2.4 Carbonate rock measurement

The mineral species and clay contents in the Tahe Oilfield carbonate and marble are measured by the standard method SY/T5163-2010 (Analysis method of clay minerals and ordinary nonclay minerals in sedimentary rocks by X-ray diffraction) (Xue et al. 2018). The instrument used in this experiment was a D/Max2500 X-ray diffractometer (Rigaku, Japan).

2.5 Interfacial tension measurement

The oil–water interfacial tension meter used in this experiment is an SVT20N manufactured by the German company Dataphysics. This instrument calculates the interfacial tension by measuring the shape of low-density oil droplets in high-density liquids (Ibrahim et al. 2006). The experimental temperature is 40 °C, and the interfacial tension used is defined according to formula (1).

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

where σ is the interfacial tension (N/m); $\Delta\rho$ is the liquid density difference (g/cm^3); r is the cylindrical radius (mm); and ω is the rotation speed (r/mm).

2.6 Long-term thermal stability measurement

Under a temperature of 150 °C, a 0.15 wt% SS solution and a 0.15 wt% petroleum sulfonate solution were aged for 30 d. By measuring the change in interfacial tension between the surfactant and crude oil before and after high-temperature aging, the long-term thermal stability was evaluated.

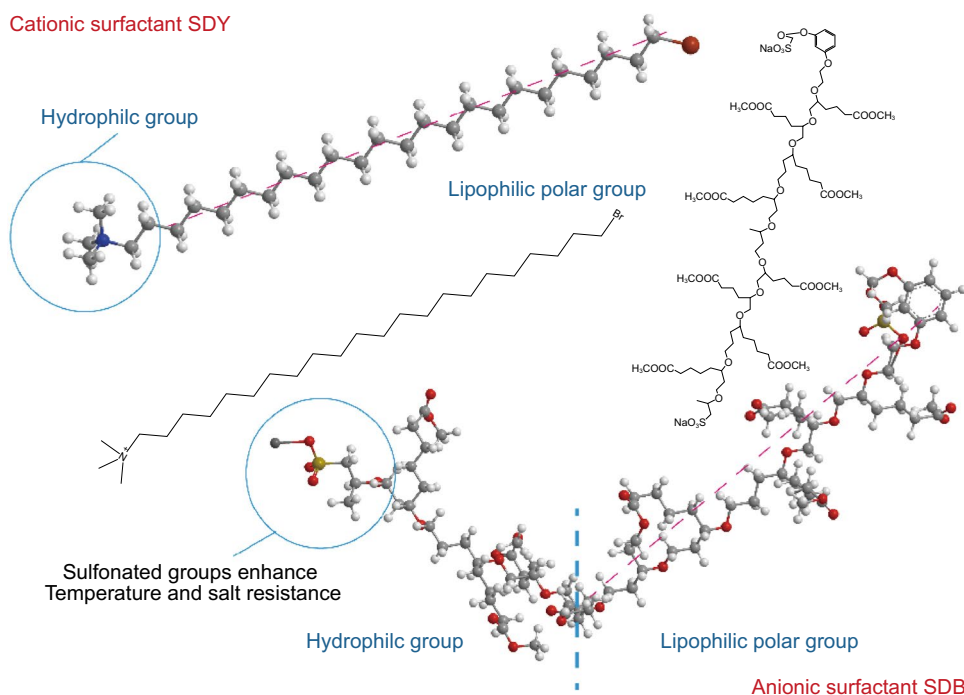


Fig. 1 Molecular formula of cationic surfactant SDY and anionic surfactant SDB

2.7 Salinity tolerance measurement

Deionized water was used to prepare a 0.15 wt% surfactant solution, and NaCl or CaCl₂ at different concentrations (100–200,000 mg/L) was added to it. The mixed solution was stirred evenly and was centrifuged at 2000 r/min for 10 min. Precipitation occurred as the amount of solute in the solution increased. At this time, the concentration of NaCl or CaCl₂ is the limit of the salt tolerance of the surfactant (Xin et al. 2008).

2.8 Wettability measurement

An E5637-C high-temperature and high-pressure interfacial tension tester (Sanchez Technologies, French) was used to determine the wettability of the Tahe Oilfield carbonate reservoirs according to the standard of SY/T5153-2007 (reservoir rock wettability determination method) (Zhang et al. 2016). Experimental rock slices were prepared from the Tahe Oilfield cores, and changes in the contact angle before and after 0.15 wt% SS solution treatment were separately measured.

2.9 Adsorption performance measurement

In the process of oil washing and flooding, oil sand adsorbs some surfactants, which reduces the efficiency of surfactants. It should be noted that for anionic–cationic surfactants, there is no suitable method that can effectively detect its adsorption performance at the same time. In this study, since the oil sands used are positively charged, the adsorption loss of cationic surfactants is very low compared with anionic surfactants. Therefore, in this study, only the adsorption performance of anionic surfactants was studied. Using a UV-2100 ultraviolet spectrophotometer (Unico Instrument Co., Ltd., China) to measure the difference in surfactant concentration in the solution before and after reaching rock adsorption equilibrium, the amount of adsorption can be calculated by formula (2) (Wang et al. 2002).

$$\Gamma = \frac{(C_0 - C) \times M}{m} \times 100\% \quad (2)$$

where Γ is the adsorption capacity (%); C_0 is the initial mass fraction of adsorbate solution (%); C is the instantaneous mass fraction of adsorbate solution (%); M is the mass of the adsorbate solution (g); and m is the mass of oil sand (g).

2.9.1 Oil washing efficiency measurement

The traditional method of the oil washing of sandstone cannot be used to construct and simulate carbonate reservoir

structures with many fissures and karst caves. Therefore, we used marble fragments and crude oil to make marble oil sands, and the oil content was 6.0%. The mass ratio of the SS solution to oil sands is 1 to 1, both of which are put into a ZR-2 container (Haian County Oil Scientific Instrument Co., Ltd., China) and studied at 150 °C for 1 h. After 1 h, the changes in oil sand quality were recorded, and the washing efficiency was calculated.

$$A = \frac{m_1 + m_2 - m_3}{m_1} \times 100\% \quad (3)$$

where A is the washing efficiency (%); m_1 is the mass of oil; m_2 is the mass of marble; and m_3 is the mass of oil sand after the washing experiment.

2.9.2 Oil displacement efficiency measurement

Core displacement equipment (Jiangsu Huaan Scientific Research Equipment Co., Ltd., China) was used to measure the displacement of different surfactants at 150 °C and calculate the corresponding displacement efficiency. The surfactant displacement experimental procedure is as follows.

- 1) Assemble the displacement experimental device as shown in Fig. 2 and carefully check the tightness of all valves and connections.
- 2) Put the core into a drying oven at 80 °C and fully dry for 24 h. After the sample is weighed, a Vernier caliper is used to measure its diameter and length.
- 3) Put the dried core into a holder and inject N₂ and then calculate the core permeability by measuring the inlet pressure.
- 4) The core is evacuated for 6 h and then saturated with the Tahe Oilfield Formation water for 12 h. After weighing the core, the core porosity and pore volumes are calculated.
- 5) Injecting Tahe crude oil TH12238 into the core to displace the saturated formation water in the core requires 20 pore volumes (PVs) to fully saturate the crude oil. The oil needs to be saturated for 24 h, and then, the volume (V) of water expelled from the core is recorded.
- 6) Water flooding: Inject the Tahe Oilfield Formation water into the core of fully saturated crude oil until no oil escapes and record the volume of crude oil (V_1) at this time.
- 7) Surfactant flooding: after the first water flooding, the surfactant used for flooding is injected until no crude oil escapes, and the volume of crude oil displaced (V_2) is recorded.
- 8) Second water flooding: Inject the Tahe Oilfield Formation water again until no crude oil escapes and then record the volume of crude oil (V_3).

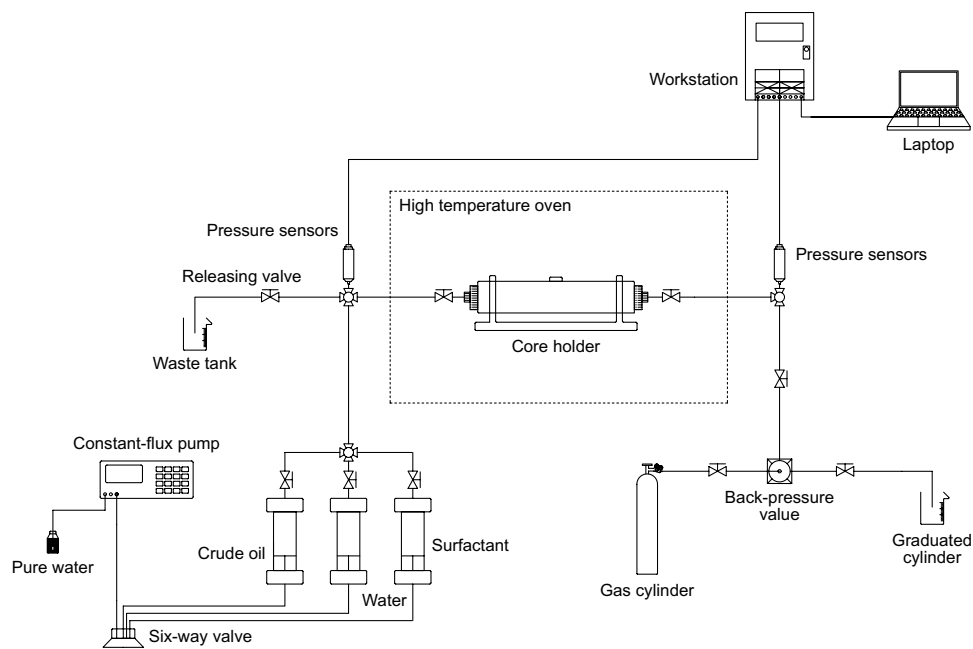


Fig. 2 Flooding device

The oil displacement efficiency by water flooding is calculated as:

$$\eta_1 = \frac{V_1}{V} \times 100\% \tag{4}$$

The oil displacement efficiency by the surfactant and subsequent flooding is calculated as:

$$\Delta\eta = \frac{V_2 + V_3}{V} \times 100\%$$

The total oil displacement efficiency is calculated as:

$$\eta = \eta_1 + \Delta\eta$$

2.9.3 Microscopic visualization model for the flooding experiment

The microscopic visualization model can directly represent the microscopic percolation characteristics of the displacement medium. The pore structure and size of carbonate rocks were simulated by etching on glass. Magnifying the microstructure through a camera can reveal the effect of the surfactant. The experimental device was installed according to Fig. 3, and sufficient crude oil was injected at 25 °C. After 24 h, the crude oil was replaced with water. Finally, 0.1% SDY surfactant was used to displace the oil. All processes require the use of a camera to record the displacement effects.

3 Results and discussion

3.1 Carbonate rock

The XRD results of carbonate and marble are shown in Fig. 4 and Table 3. We find that carbonate and marble have similar mineral species and contents. Their main components are calcite with proven lipophilicity, which also determines whether the wettability of carbonate rocks is oil-wet or mixed (Biswas 1987; Thomas et al. 1993). Therefore, marble fragments can be used to conduct oil washing experiments instead of using Tahe Oilfield carbonate, which is difficult to obtain, and compared with the sandstone oil evaluation method, marble fragments can be used to construct many fissures and caves, similar to the real reservoir conditions. A series of hydrolysis equilibria under formation water exist in carbonate reservoirs, which affect the zeta potential of carbonate, and equilibrium equations are shown in formula (7). When the pH of the formation water is low, the zeta potential of carbonate is positive; in contrast, it was found that the zeta potential is negative. Kh. Jarrahan and O. Seidib confirmed that when the pH value is 8–9.5, carbonate exhibits a zero potential; when the pH is higher than 9.5, the zeta potential is negative; and when it is lower than 8, the zeta potential is positive (Jarrahan et al. 2012). By testing the Tahe Oilfield Formation water, we find that the pH value is 6.7, so the zeta potential of the Tahe Oilfield carbonate is positive. Surfaces of carbonate adsorb carboxylic acid from oil and cause the surface to be oil-wet. The cationic surfactant the SS solution

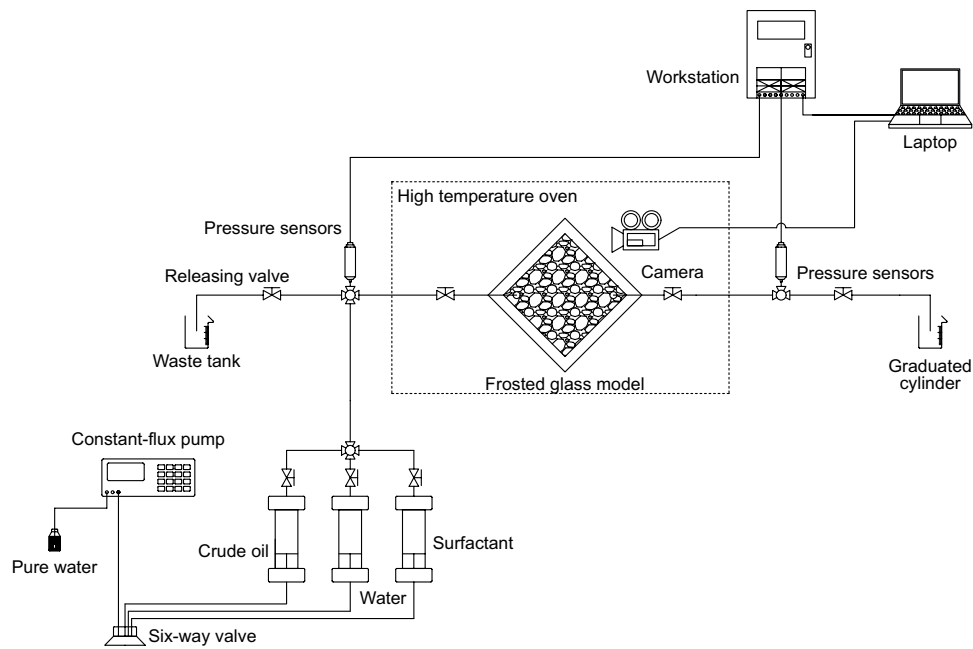


Fig. 3 Experimental device for the microscopic visualization model

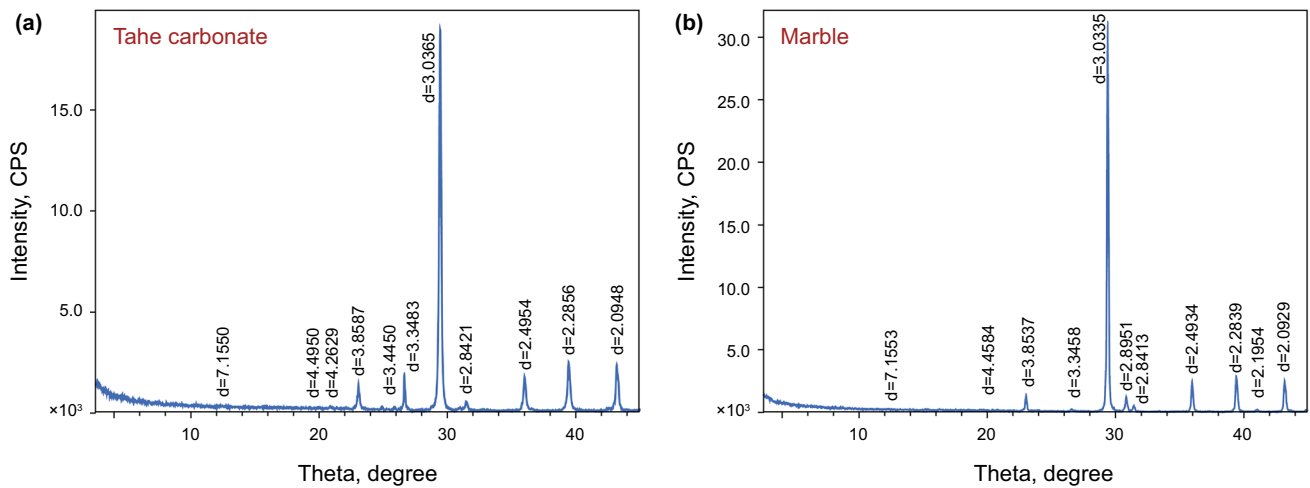
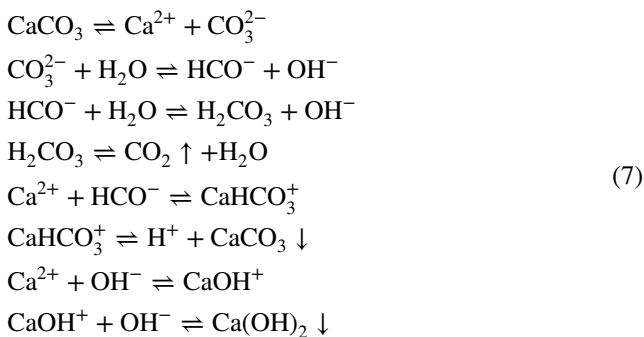


Fig. 4 XRD of the Tahe Oilfield carbonate and marble

Table 3 Mineral types and contents of the Tahe Oilfield carbonate and marble

| The types and contents of minerals, % | | | | | | | |
|---------------------------------------|--------|------------|--------|---------|----------|--------|------|
| Items | Quartz | Orthoclase | Albite | Calcite | Dolomite | Barite | Clay |
| Tahe carbonate | 3.2 | – | – | 93.8 | 0.9 | 0.8 | 1.3 |
| Marble | 1 | – | – | 93 | 5 | – | 1 |

irreversibly desorbs carboxylic acid from the carbonate surface by the formation of ion pairs between the cationic heads of the surfactant molecules and the acidic components of crude oil adsorbed on the carbonate rock surface, so the wettability of the carbonate surface becomes water-wet, which is a favorable condition to enhance oil recovery by surfactant flooding.



3.2 Interfacial tension

As shown in Fig. 5, the SS system can lower the oil–water IFT from 26.506 mN/m to 0.445 mN/m after adding 0.15 wt% SS solution because hydrophilic groups between the cationic surfactant SDY and the anionic surfactant SDB in

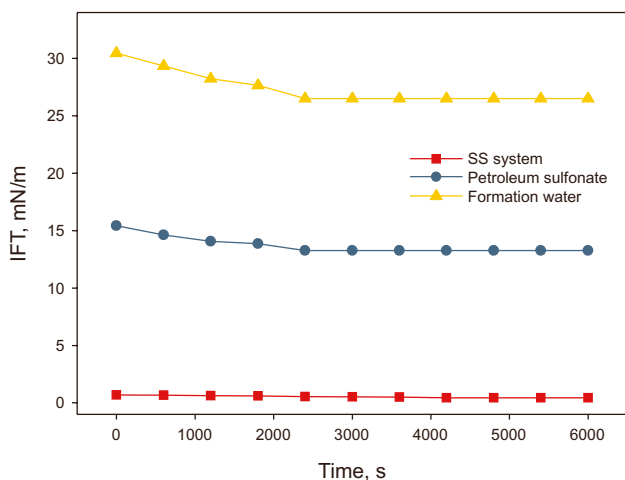


Fig. 5 IFT of different surfactants

the system exhibit strong electrostatic attraction and cause the surfactant molecules to arrange closely at the oil–water interface, which is helpful to obtain ultralow interfacial tension (Robertson et al. 1998; Zhao et al. 2014). Compared with petroleum sulfonate solution, the SS system obtains a lower IFT value due to strong interfacial activity. The adhesive work formula between oil and rock is used to determine the difficulty of the falling off of crude oil from rocks, where the adhesive work $W = \sigma_{ow} (1 - \cos\theta)$ (Yao et al. 2008). Therefore, the lower the ITF value is, the higher the oil washing efficiency. Table 4

3.3 Long-term temperature-resistance performance

As shown in Fig. 6, after aging the SS surfactant and petroleum sulfonate at 150 °C for 30 days, the oil–water interfacial tension of petroleum sulfonate increased significantly, but the oil–water interfacial tension hardly changed after SS aging. This shows that SS surfactants have good heat resistance and can withstand a high temperature of 150 °C. China’s Tahe Oilfield is a high-temperature oilfield with many areas reaching a temperature of 150 °C, which is suitable for using SS surfactants to enhance oil recovery.

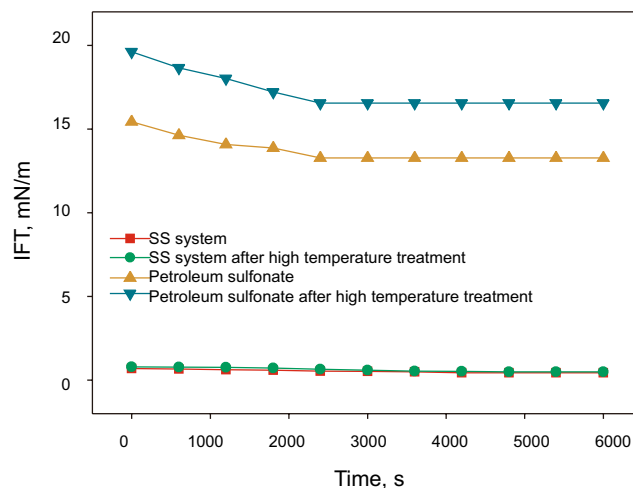


Fig. 6 Interfacial tension variations in the SS system and petroleum sulfonate after high-temperature aging

Table 4 Washing efficiency for different crude oils with the SS system

| Oil | TH12245 | TH122338 | YQ5-1 (mixed thin oil rate 1.5:1) | YQ5-2 (mixed thin oil rate 1.3:1) | TH12340 |
|-----------------------|---------|----------|-----------------------------------|-----------------------------------|---------|
| Viscosity, mPa·s | 34.3 | 39.4 | 47.9 | 65.5 | 99.1 |
| Washing efficiency, % | 95.5 | 92.8 | 85.0 | 70.4 | 61.4 |

3.4 Salt-resistance performance

The salt resistance of the SS system is determined, and the salinity tolerance of the system (190,000 mg/L for sodium salts, 20,000 mg/L for calcium salts) is significantly better than that of petroleum sulfonate (14,000 mg/L for sodium salts, 80 mg/L for calcium salts). At same time, we found that the system solution prepared by using formation water as the solvent was clear and transparent. We consider that the system of the cationic surfactant SDY and the anionic surfactant SDB is neutral and has excellent resistance to calcium and magnesium ions. Hence, we can use the system in oilfield environments of high salinity, such as the Tahe Oilfield in China.

3.5 Altering the wettability performance

Figure 7 shows that the Tahe Oilfield oil–water–rock contact angle is 129.7° , which demonstrates that the rock surface is lipophilic. This is an important reason why the residual oil content is high after water flooding. Generally, when the lipophilicity of the rock surface is greater than the hydrophilicity, its recovery degree is lower, which shows that changing the wettability of the rock is significant for enhancing the recovery (Cao et al. 2014). After 0.15% SS solution treatment, we find that the contact angle changes from 129.7° to 56.2° , which can effectively alter the wettability of carbonate rocks. We conclude that SS molecules adsorbed on the surface of rock and reduced the interfacial energy, and then as the oil on the rock surface was stripped, the wettability of the rock changed. It is well known that if the rock surface is hydrophilic, then its oil washing efficiency is better than that of the rock surface. The SS system lowered the adhesion work by 99.67% by reducing the oil–water interfacial tension and transformation.

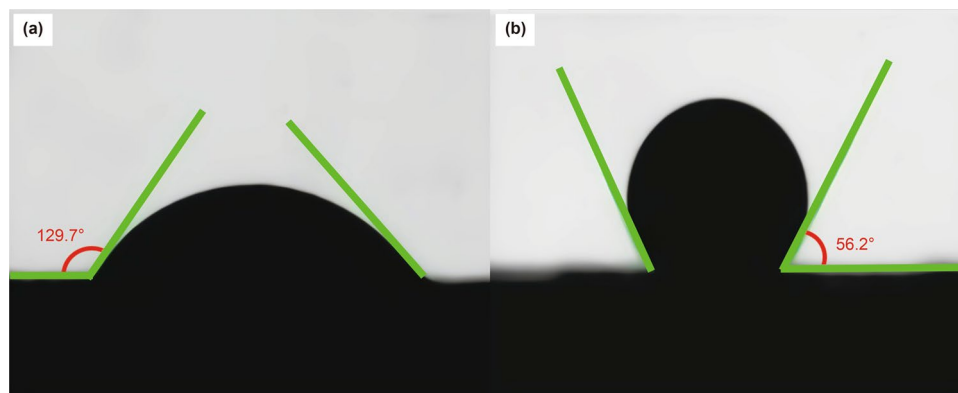


Fig. 7 Change in contact angle before and after SS solution treatment: **a** before SS handling; **b** after SS handling

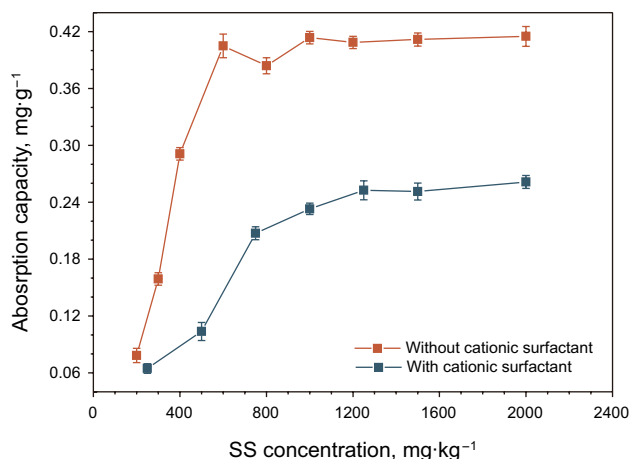


Fig. 8 Adsorption isothermal curve of oil sands

3.6 Adsorption performance

At 150°C , marble oil sand was used to absorb different concentrations of SDB surfactant (without cationic surfactant) and SS surfactant (with cationic surfactant) solution for 24 h. Then, the supernatant was centrifuged, and the absorbance value was measured to calculate the static adsorption capacity of the oil sand surface.

As shown in Fig. 8, the adsorption capacity of the SS and the SDB solution is less than 1 mg/g oil sands, thus meeting the requirements for the adsorption performance of surfactants for EOR (Cardoso et al. 2007). However, the adsorption capacity of SS with cationic surfactant (0.261 mg/g oil sands) is less than that of SDB (0.418 mg/g oil sands) without cationic surfactant. This is due to the presence of the cationic surfactant SDY in the SS surfactant, which prevents the adsorption of the anionic surfactant SDB to carbonate. Without the cationic surfactant, the anionic surfactant will adsorb onto the surface of carbonate and form two layers.

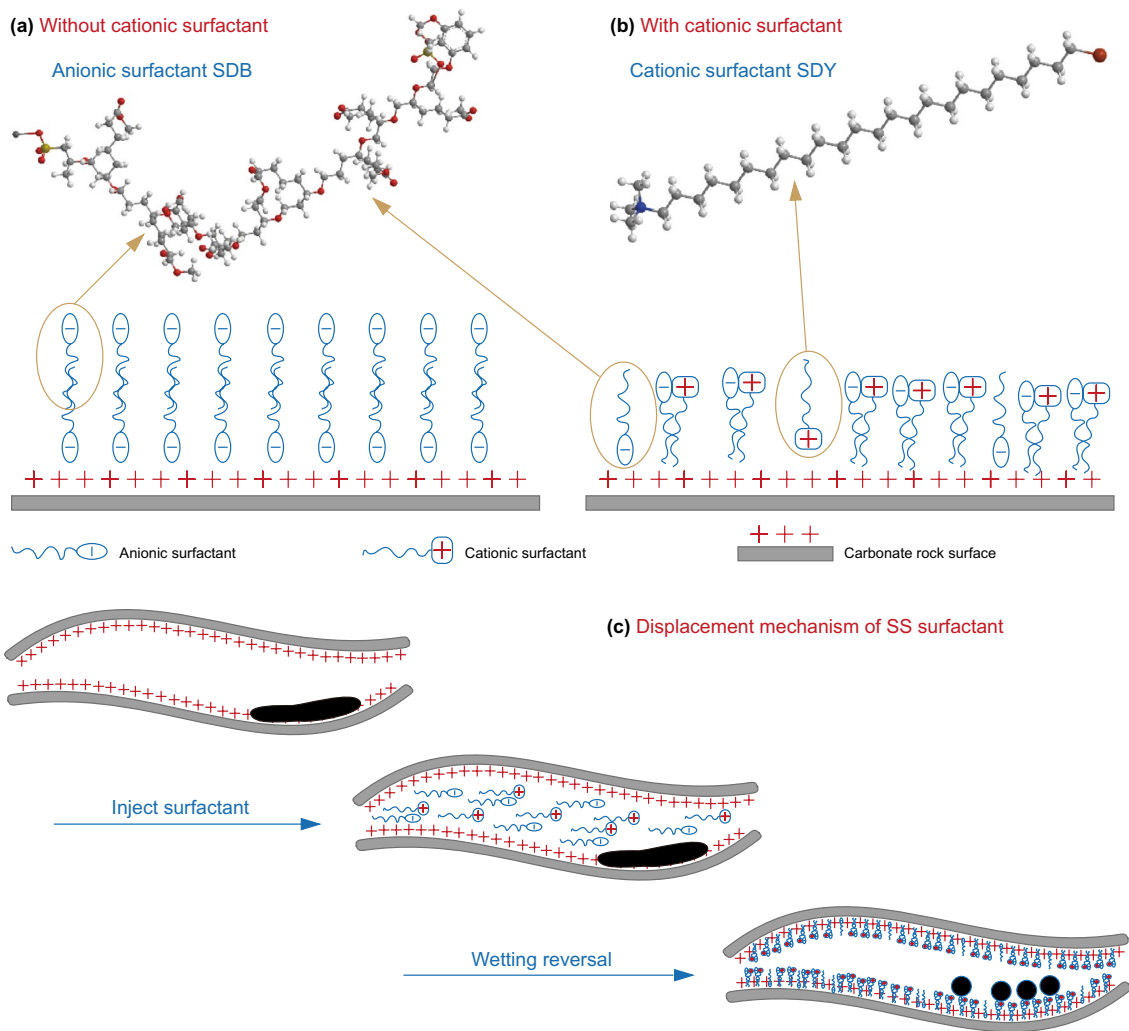


Fig. 9 a Schematic illustration of the adsorption of anionic surfactant without cationic surfactant on a positively charged surface; b schematic illustration of the adsorption of anionic surfactant with cationic surfactant; and c displacement mechanism of SS surfactant

The first layer forms on the surface, and the second layer of surfactant may be adsorbed by surfactant tail–tail hydrophobic interactions at high anionic surfactant concentrations (Shamsijazeyi et al. 2014; Somasundaran et al. 1966; Yeskie et al. 1988). However, the SS system contains anionic and cationic surfactants, which may damage the structure through interactions between ions. The mechanism is shown in Fig. 9. There are many types of surfactant adsorption on solid surfaces, including ion adsorption and hydrophobic interaction adsorption. In our research in this paper, the rock surface is positively charged. When only SDB anionic surfactant is used, the surfactant will be adsorbed on the rock surface due to the electrostatic force between two different charges. When the concentration of anionic surfactants is further increased, their hydrophobic groups will adsorb together, thereby changing the wettability of the rock surface (Fig. 9a). When the SDB cationic surfactant is added, the

anionic surfactant and the cationic surfactant are adsorbed together due to electrostatic force, and it is electrically neutral at this time. Therefore, there is no electrostatic force between the rock surface and SS surfactant. The rock surface is hydrophobic. Due to the hydrophobic effect, the hydrophobic group of SS surfactant will be adsorbed on the rock surface, thereby changing the wettability of the rock surface (Fig. 9b). Before the surfactant is injected, the crude oil is adsorbed on the rock surface and is not easily separated. After the surfactant is injected, the wettability of the rock surface changes, and the crude oil is easily separated from the rock surface, thereby enhancing the recovery (Fig. 9c).

3.7 Efficiency of oil washing

We examined the oil washing efficiency of the 0.15 wt% formation water solution and the 0.15 wt% petroleum sulfonate

deionized water solution, and the results showed that the washing efficiency of the SS system (92.8%) was higher than that of petroleum sulfonate (13.5%) and that of formation water without surfactant (5.0%). In addition, the SS system has excellent adaptability to five kinds of Tahe Oilfield crude oils, with washing efficiencies greater than 60%. As shown in Table 3, when the viscosity is below 50 mPa·s at 150 °C, the washing efficiency is higher than 80%. Some researchers (Li et al. 2006; Sheng 2010; Yao et al. 2008; Zhao et al. 2000) have suggested that the washing efficiency of agents is associated with the adhesion work of crude oil in the rock surface; the lower the adhesive work is, the higher the washing efficiency. The SS system can lower the adhesive work by reducing the interfacial tension and changing the wettability of rock. Based on the results, we conclude that there are three ways to increase the washing efficiency: (1) reduce the oil–water interfacial tension; (2) reduce the viscosity of crude oil; and (3) change the wettability of the rock surface.

3.8 Oil displacement efficiency

The oil displacement efficiencies of the SS system and petroleum sulfonate solutions were evaluated using TH12238 at 150 °C. The experimental results are presented in Table 5. The oil recovery is approximately 32% by water flooding,

and the value increases by 10% after 0.15 wt% SS surfactant flooding, which is higher than that of petroleum sulfonate (0.9%). The results demonstrate that the SS system can significantly improve the oil recovery of the Tahe Oilfield. We also speculate that the SS system synthesized by the authors can improve the oil recovery of other domestic and overseas oilfields with broad or even worse reservoir conditions.

3.9 Flooding effect of the surfactant in the microstructure model

As shown in Fig. 10, after saturating the crude oil, the pores of the microstructure model are filled with dark crude oil. After the water flooding ended, most of the crude oil was displaced. However, a large amount of crude oil remained in the fine pores. After the water flooding, the surfactant was used for a second flooding event, and the crude oil in the pores was displaced by the surfactant. Compared with that at the end of water flooding, the recovery after surfactant flooding is significantly improved. This is because the surfactant can effectively reduce the oil–water interfacial tension and change the wettability of the surface model, thereby reducing the adhesion work of crude oil adsorbed on the model surface. The reduction in adhesion work will increase the oil washing efficiency so

Table 5 Results of the displacement experiment

| No. | Diameter, cm | Length, cm | Porosity, % | Permeability, $\times 10^{-3} \mu\text{m}^2$ | Temperature, °C | Injected system | Water flooding, η_1 , % | EOR M_1 , $\Delta\eta$, % |
|-------|--------------|------------|-------------|--|-----------------|-----------------|------------------------------|------------------------------|
| M_1 | 2.48 | 6.16 | 16.1 | 95.7 | 150 | A | 32.6 | 0.9 |
| M_2 | 2.51 | 5.62 | 15.6 | 126.1 | 150 | B | 32.1 | 11.6 |
| M_3 | 2.52 | 6.83 | 14.3 | 73.5 | 150 | B | 32.5 | 10.2 |
| M_4 | 2.61 | 6.65 | 16.8 | 89.3 | 150 | B | 32.6 | 10.6 |

¹Water flooding and subsequent water flooding using the Tahe Oilfield Formation water;

²Injected system A: water flooding with 0.15 wt% petroleum sulfonate solution in deionized water and subsequent flooding;

³Injected system B: water flooding and with 0.15 wt% SS solution in the Tahe Oilfield Formation water and subsequent flooding after SS handling

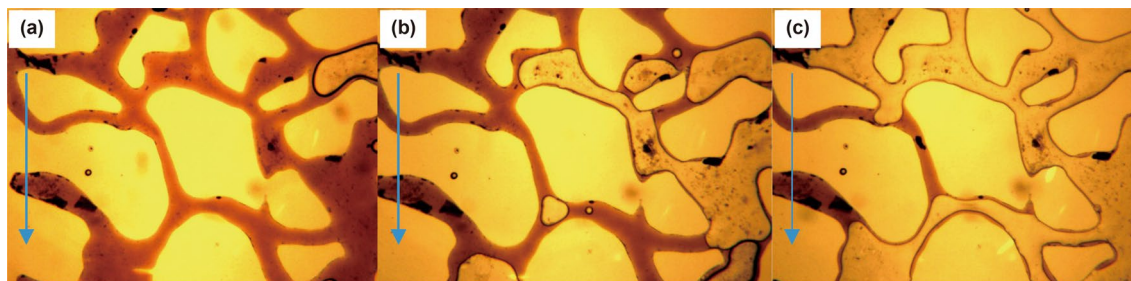


Fig. 10 Channels in the microstructure model: **a** after saturated crude oil is added, **b** after water flooding, and **c** after surfactant flooding

that a large number of crude oil droplets will be stripped. Crude oil droplets will collide with each other and merge together during the flow, and this process will continue to develop to help the remaining oil flow to the outlet.

4 Conclusions

It has been shown that the surfactant SDB has favorable properties that work with SDY, and the temperature resistance (to 150 °C) and salt tolerance (to 24.6×10^4 mg/L) of the SS system are much better than those of petroleum sulfonates, which indicates that the SS system can be used to improve the oil recovery in high-temperature and high-salinity reservoirs, such as the Tahe Oilfield and Tarim Oilfield in China. The adsorption loss of the SS system is 0.261 mg/g oil sands, which is below the standard because the cationic surfactants in the SS system damage the structure of the two layers of anionic surfactants via interactions between the ions. This helps to reduce the adsorption of anionic surfactants on carbonate rocks and further improve its oil displacement effect.

The SS system can lower the oil–water interfacial tension from 26.506 mN/m to 0.445 mN/m, change the oil formation water–rock contact angle from 129.7° to 56.2°, and has excellent washing efficiency of more than 60% for five kinds of Tahe Oilfield crude oils. When the viscosity of oil is below 50 mPa·s, the washing efficiency is more than 80%. The keys to improving the washing efficiency are to reduce the oil viscosity, reduce the oil–water interfacial tension, and change the wettability of the rock surface.

The results of core displacement experiments (temperature of 150 °C, salinity of 24.6×10^4 mg/L) show that the SS system can improve the oil recovery to approximately 10% and has excellent properties for high-temperature and high-salinity reservoirs.

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