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Study of the Chemical Flooding Effect in Gao-63 Reservoir

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Abstract: This article is aimed to discuss the impact of using two different kinds of surfactant in enhancing oil recovery in heterogeneous reservoirs. With the background of Jidong oilfield, Rui Feng surfactant which could reach ultra-low interfacial tension and combination surfactant RZ-JD80 with strong emulsifying property are chosen to do oil displacement and profile control-oil displacement experiment in homogeneous core and heterogeneous core respectively. The experiment is aimed to study the effect of oil displacement by injecting surfactant individually and the effect after injecting different profile control agent slug before surfactant flooding in heterogeneous cores. The results suggest that injecting Rui Feng surfactant and RZ-JD80 individually could enhance the oil displacement efficiency about 15 percentage points for homogeneous core. For strongly heterogeneous core, it is low efficiency by using either of these two surfactants individually. However, if injected a very little profile control agent slug before surfactant flooding, both of these two kinds of surfactant could enhance the oil recovery by different degree, especially, polymer microsphere plugging—RZ-JD80 flooding composite technology is more adaptable to Gao-63 reservoir. This technology could increase the recovery by 18.52 percentage points after surfactant flooding.

Key words: Low permeability, heterogeneous reservoir, surfactant flooding, emulsification, profile control.

1. Introduction

Most of Chinese oil fields belong to continental deposit, which are more heterogeneous than marine deposit. The Gao-63 reservoir of Jidong oilfield is a typical strongly heterogeneous reservoir [1, 2], and the permeability of some layers is low, however, in the low permeable layer, there always exists high permeable zone, which leads to seriously water channeling. In 2014, the composite water cut of produced fluid in Gao-63 reservoir has exceeded 90% and it has been in the development stage of extra high water cut stage [3, 4]. Long term water injection leads to intensified contradiction in oilfield development [5-8], so it is very urgent to research EOR (Enhanced Oil Recovery) technology adapted for the reservoir properties. Surfactant flooding, as a mature and effective EOR technique in chemical flooding, has been attracted more and more attention [9]. Its application extends from conventional medium-high permeable reservoir to high temperature and high salinity complex reservoir [10, 11]. Wang, Y., et al. [12] combined two kinds of surfactants to improve its salt resistance, obtaining good results in field test of high salinity reservoir in Zhongyuan oilfield. According to the reservoir conditions of Jin-90 block, Zhou, Q. and Liu, Y. [13] selected surfactant system to improve oil recovery in heavy oil reservoir. In recent years, the research and development of multi-functional surfactant has been the focus in China and abroad, especially the research and development of composite surfactant system is of great significance [14].

The temperature and salinity of Gao-63 reservoir are not very high, thus they are suitable for surfactant flooding. In this paper, two kinds of surfactant flooding experiments were conducted using homogeneous and heterogeneous core models to investigate the oil displacement effect of surfactant injection on homogeneous and heterogeneous core flooding. In view of heterogeneous core model, a short

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profile control agent slug is injected before surfactant flooding, and the displacement effect of profile control surface surfactant flooding technology is investigated. In addition, the plugging effect of self-developed polymer microspheres and conventional profile control agent-partially HPAM (Hydrolyzed Polyacrylamide) was compared to optimize the best development program for Gao-63 reservoir with low permeability and strong heterogeneity.

2. Material and Methods

2.1 Experimental Material

2.1.1 Experimental Equipment and Apparatus

There are many apparatus using in the experiments such as HAS-100HSB constant pressure and constant speed pump, thermostat, piston intermediate container, core holder (30 cm × 4.5 cm × 4.5 cm and 30 cm ×2.5 cm), high precision pressure sensor, Hitachi SU8010 field emission scanning electron microscopy, magnetic stirrer, ultrasonic oscillation device, RS6000 type high precision rheometer, liquid metering device, vacuum pump and some other devices.

2.1.2 Artificial Core Model

(1) Homogeneous cylindrical core model with the diameter of 2.5 cm and length of 30 cm, the permeability is 500 × 10^{-3} μm^2; (2) Heterogeneous core model (30 cm × 4.5 cm × 4.5 cm) with three layers, each thickness is 1.5 cm; permeability are 30 × 10^{-3} μm^2, 310 × 10^{-3} μm^2, 1,000 × 10^{-3} μm^2; permeability variation coefficient is 0.91. The physical parameters of core model are shown in Table 1.

2.1.3 Oil and Water Samples and Oil Displacement Agent

The experimental water is formation water of Gao-63 reservoir; total salinity is 3,260 mg/L; concentrations of Na^+/K^+, Mg^{2+}, Ca^{2+} were 1,070 mg/L, 27 mg/L and 20 mg/L; concentrations of Cl^-, HCO_3^-, SO_4^{2-} were 1,152 mg/L, 763 mg/L and 228 mg/L.

The experimental oil is a Gao-63 reservoir oil, with viscosity of 7.1 MPa·s at 77 centigrade.

Rui Feng surfactant: Light yellow, viscous liquid, soluble in water to form suspension, a kind of ultra-low interfacial tension surfactant. The oil-water interfacial tension is 7 × 10^{-3} mN/m of 0.3% mass concentration.

RZ-JD80 surfactant: in view of the target reservoir condition, with the strong emulsification ability, weak stability and the moderate low interfacial tension as the index, the compound multifunctional flooding regulation is optimized. The interfacial tension between oil and water is 6 × 10^{-2} mN/m of 0.3% mass concentration.

The high concentration polymer profile control slug is 3,000 mg/L HPAM solution.

Polymer microsphere: it can be prepared by emulsion polymerization, a certain amount of two vinyl benzene, acrylamide, Span80, azobisisobutyronitrile, AES surfactant and water [15].

2.2 Experimental Method

2.2.1 Experimental Condition

The experimental temperature of Gao-63 reservoir

Table 1 Physical parameters of core models.

Model type	Model number	Model size/cm	Permeability/× 10^{-3} μm^2	Displacement agent
Homogeneous-1	JZ-1	30 × Φ2.5	500	
Heterogeneous-1	FZJ-1	30 × 4.43 × 4.44	30/310/1000	Rui Feng surfactant
Heterogeneous-2 (HPAM)	FJZ-2 (HPAM)	30 × 4.44 × 4.45	30/310/1000	
Homogeneous-2	JZ-2	30 × Φ2.49	500	
Heterogeneous-3	FJZ-3	30 × 4.42 × 4.45	30/310/1000	RZ-JD80
Heterogeneous-4 (HPAM)	FJZ-4 (HPAM)	30 × 4.42 × 4.43	30/310/1000	
Heterogeneous-5 (Microspheres)	FJZ-5 (MP)	30 × 4.45 × 4.36	30/310/1000	

is 77 centigrade, and the displacement rate of homogeneous core is converted to 0.2 mL/min according to the oilfield development by 2.5 m/d. The displacement rate of heterogeneous core is converted to 0.5 mL/min according to the oilfield development by 1.19 m/d.

2.2.2 Emulsion Property Testing

The emulsion oil ratio is an important parameter to characterize the emulsifying properties of surfactant. The emulsifying property of surfactant is stronger and the emulsion oil ratio is higher. The mass fraction of 0.3% to measure the volume of surfactant aqueous solution and simulated oil read original oil (V_{oi}) according to the volume ratio of 1:1 added a special measuring cylinder, using ultrasonic oscillation device in 77 centigrade shocks for more than 20 minutes, the volume of residual oil (V_{or}) to readout oil-water interface stability. According to Eq. (1), the emulsion oil rate of the surfactant can be calculated:

$$R_E = \frac{V_{oi} - V_{or}}{V_{oi}} \times 100\% \quad (1)$$

wherein, R_E is emulsion oil rate; V_{oi} is initial oil volume; V_{or} is remaining oil volume.

2.2.3 Surfactant Flooding in Homogeneous and Heterogeneous Cores

For homogeneous cores and heterogeneous cores, the oil displacement experiments are carried out by using Rui Feng surfactant and RZ-JD80 surfactant, according to the program of water flooding—0.3 PV surfactant flooding—subsequent water flooding. The concrete steps are:

(1) The core is vacuumed by a vacuum pump and then the formation water and oil are saturated. At last, core is put in thermostat aging at 77 ^oC for more than 20 hours;

(2) Water flooding of displacement rates are 0.2 mL/min (homogeneous cores) and 0.5 mL/min (heterogeneous cores);

(3) When the water content reaches 98%, the 0.3 PV surfactant is injected;

(4) Subsequent water flooding is carried out until water content reaches 98%.

During the experiment, the injection pressure, oil and water volume, water content and recovery are recorded.

2.2.4 HPAM Profile Control—Surfactant Flooding in Heterogeneous Cores

HPAM profile control-oil displacement experiments of two kinds of surfactant are carried out according to the program of water flooding—0.1 PV 3,000 mg/L HPAM and 0.3 PV surfactant flooding—subsequent water flooding. The concrete steps are:

(1) The core is vacuumed by a vacuum pump and then the formation water and oil are saturated. At last, core is put in thermostat aging at 77 ^oC for more than 20 hours;

(2) Water flooding of displacement rate is 0.5 mL/min;

(3) When the water content reaches 98%, surfactant is injected until it reaches 100%;

(4) 0.1 PV 3,000 mg/L HPAM slug is injected into the core;

(5) 0.3 PV surfactant slug is injected and then subsequent water flooding is made until the water cut reaches 98%.

2.2.5 Microsphere Profile Control—RZ-JD80 Flooding in Heterogeneous Core

(1) The core is vacuumed by a vacuum pump and then the formation water and oil are saturated. At last, core is put in thermostat aging at 77 ^oC for more than 20 hours;

(2) Water flooding of displacement rate is 0.5 mL/min;

(3) When the water content reaches 98%, RZ-JD80 surfactant is injected until it reaches 100%;

(4) 0.1 PV polymer microspheres slug is injected into the core and temperature maintains aging for 12 hours;

(5) 0.3 PV RZ-JD80 surfactant slug is injected and then subsequent water flooding is made until the water

cut reaches 98%.

3. Results and Discussion

3.1 Emulsion Property Evaluation

Emulsification between oil and water can be realized in a variety of ways, such as oscillation, agitation, etc.. Its essence is to emulsify oil and water through the shearing action between fluid molecules. The emulsifying capacity of two kinds of surfactant and crude oil were tested by ultrasonic oscillation device, as shown in Fig. 1. For Rui Feng surfactant, there is no change between the oil-water interfaces in the initial stage of shock. A little emulsion appears near the oil-water boundary layer and the oil-water interface gradually becomes blurred after 10 minutes. With the vibration time increasing, emulsion band becomes wider and then tends to be stable and the maximum emulsion oil ratio reaches 30%. From the time of emulsion production and the final emulsion rate, the surfactant is only a weak emulsifier, which is generally emulsified. However, for RZ-JD80 surfactant, the emulsion began to produce in the early stage of vibration, and the emulsion oil ratio reached 70% at 210 seconds, then slowly increased to reach 75% at 890 seconds and remained stable. It can be seen that RZ-JD80 is a strong emulsifying agent which emulsifying capacity is very strong. Emulsification photo of two kinds of surfactant is shown in Fig. 2.

3.2 Influence of Core Heterogeneity on Surfactant Flooding

3.2.1 Surfactant Flooding in Homogeneous Cores

For homogeneous cores, Rui Feng and RZ-JD80 surfactant flooding were carried out and the oil displacement curves are shown in Fig. 3. The water displacement efficiencies of these two experiments were 50.56% and 48.71%. With injection of two kinds of surfactant, the water content of produced liquid decreased in different degrees and the water content by Rui Feng surfactant flooding decreased to 80%. After injection of surfactant, the displacement pressure

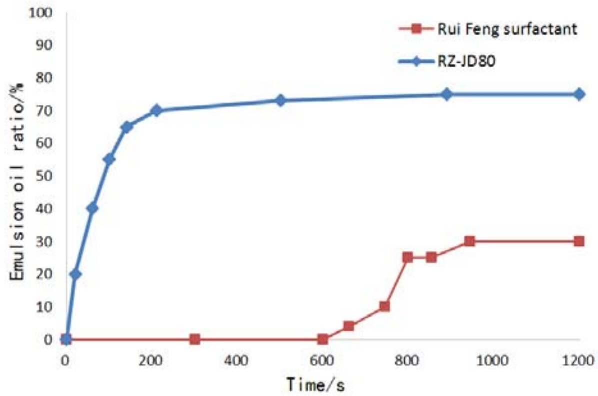


Fig. 1 Curve of emulsified oil rate.

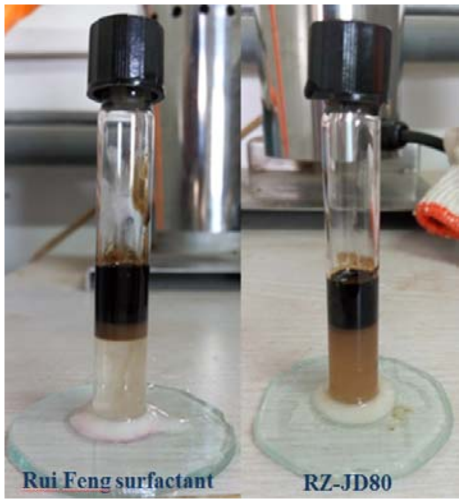
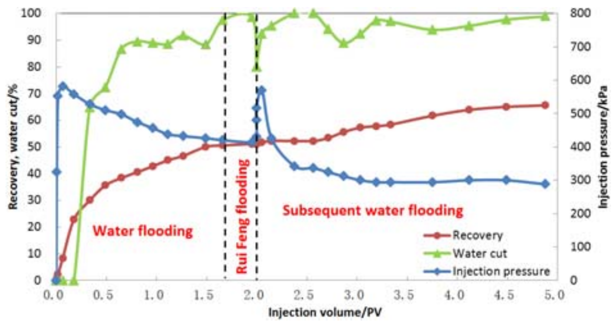
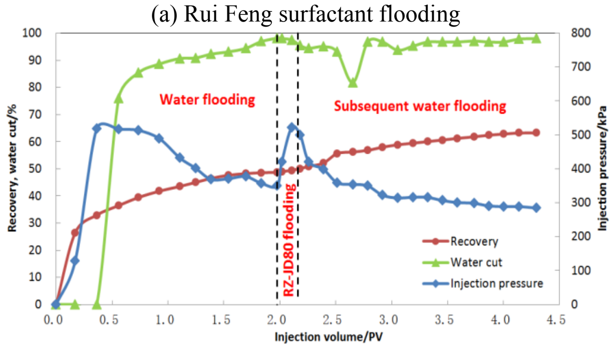


Fig. 2 Emulsification photo of crude oil.



(a) Rui Feng surfactant flooding



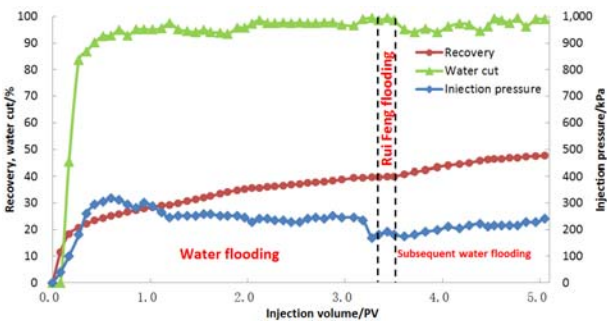
(b) RZ-JD80 surfactant flooding

Fig. 3 Curve of oil displacement in homogeneous core.

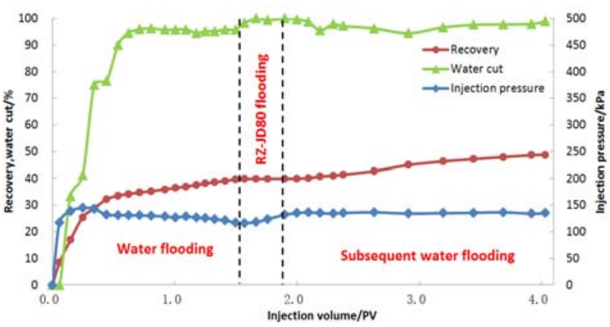
increased slightly and decreased at once, indicating that the injectivity of these two kinds of surfactant are both good. The final oil displacement efficiencies are 65.56% and 63.24% by injecting Rui Feng and RZ-JD80 surfactant. These two kinds of surfactant can increase the recovery by 15 and 14.53 percentage points respectively on the basis of water flooding. It indicated that in the homogeneous core, Rui Feng surfactant (ultra-low interfacial tension displacement agent) and RZ-JD80 surfactant (interfacial tension is not ultra-low) can basically improve the micro displacement efficiency after water flooding. The difference between the two surfactants should be reflected by improving the sweep efficiency in heterogeneous cores.

3.2.2 Surfactant Flooding in Heterogeneous Cores

The displacement effect of surfactant flooding in heterogeneous cores is shown in Fig. 4. Rui Feng surfactant can increase the recovery by 8% on the basis of water flooding and the final recovery is 47.56%. RZ-JD80 surfactant can increase the recovery by 8.95% on the basis of water flooding and the final recovery is 48.78%. It can be seen that the injection



(a) Rui Feng surfactant flooding



(b) RZ-JD80 surfactant flooding

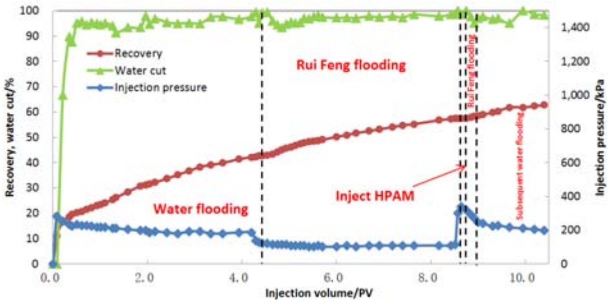
Fig. 4 Curve of oil displacement in heterogeneous core.

pressure of either Rui Feng or RZ-JD80 surfactant, had not significantly increased after water flooding if surfactant solution was injected directly. Only very small amounts of emulsion could be observed in produced liquid after RZ-JD80 injection. Obviously, injected surfactant migrates mainly in water channeling or flowing channel after water flooding. It is difficult to enter the area of remaining oil with high oil saturation. In the area of low oil saturation, these two kinds of surfactant cannot make full use of its high efficiency oil displacement characteristics, especially RZ-JD80 cannot make full use of its "profile-helping" function in strong water flow area with low oil saturation. Therefore, these two types of surfactant flooding could enhance the recovery basically the same if surfactant slug is injected directly after water flooding.

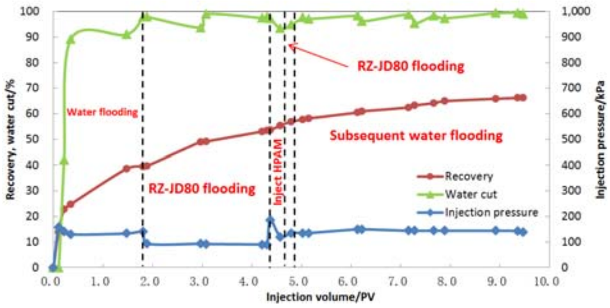
3.3 Evaluation of HPAM Profile Control—Surfactant Flooding in Heterogeneous Cores

The permeability variation coefficient of heterogeneous core is 0.91. The profile control slug is 0.1 PV 3,000 mg/L HPAM solutions. Experiments were carried out by the program of HPAM profile control—0.3 PV surfactant flooding after water flooding, obtaining the oil displacement characteristic curve (Fig. 5). After profile modification, these two kinds of surfactant slug have a great difference in EOR. Rui Feng surfactant can enhance recovery by 5.39% based on surfactant flooding; however, RZ-JD80 can even enhance the recovery by 12.78% on the basis of surfactant flooding which is 2.4 times higher than Rui Feng surfactant flooding.

In the experimental scheme of profile control—surfactant flooding, the main function of surfactant slug is oil displacement and "profile-helping". Rui Feng surfactant as oil displacement agent with ultra-low interfacial tension, its main mechanism is to improve the micro displacement efficiency in swept area but the "profile-helping" function is weak. RZ-JD80 is a complex



(a) HPAM profile modification—Rui Feng flooding

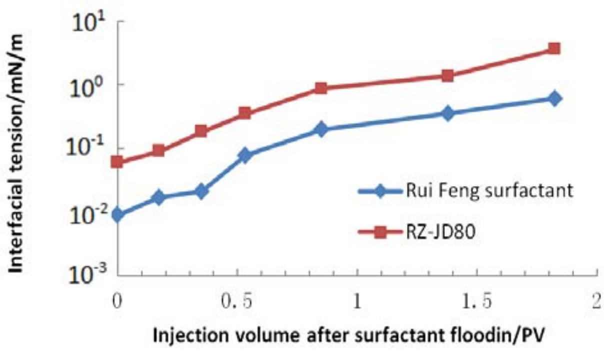


(b) HPAM profile modification—RZ-JD80 flooding

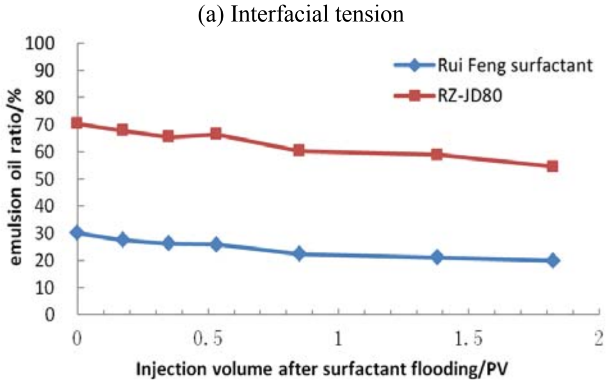
Fig. 5 Curve of HPAM plugging—oil displacement in heterogeneous core.

multifunctional flooding oil displacement—profile control agent with strong emulsifying ability, weak stability and moderate low interfacial tension. As a minute profile control slug, RZ-JD80 contact with and residual/remaining oil then generate profile control system, in situ, real-time in the process of oil migration and fine-tuning, spontaneously adjust water flooding profile, the main auxiliary slug blocking relatively small flow channel and expand the scope of the water flow channel plugging, also proving the above observed phenomenon in liquid emulsion. By contrast, Fig. 4 shows that surfactant can enter the remaining oil area as long as a small profile control slug (0.1 PV) is injected before the surfactant slug. The strong emulsified RZ-JD80 surfactant contacts with the remaining oil during the displacement process to form emulsion slug and gradually enlarges the profile control range of action. Because the strong emulsified RZ-JD80 has dual function of oil washing and profile-helping, in the experiment of HPAM profile control—surfactant flooding, utilizing RZ-JD80 as the surfactant slug can improve the recovery rate much higher than that by Rui Feng surfactant slug.

In order to research which surfactant property influences EOR the greatest, each liquid samples outlets were taken from the beginning moment of the profile after surfactant flooding. The samples of oil-water interfacial tension and emulsifying performance were tested. Test results curve as shown in Fig. 6. It can be seen that the interfacial tension of the produced liquid gradually increases with the experiment. The interfacial tension of Rui Feng increased from 9 × 10^{-3} mN/m to 6.02 × 10^{-1} mN/m while RZ-JD80's rose from 8 × 10^{-2} mN/m to 3.55 mN/m. The interfacial tension of Rui Feng surfactant has always been about an order of magnitude lower than that of RZ-JD80 throughout the whole experiment; the emulsion oil ratio of two kinds of surfactant flooding decreased gradually with experiment went on but decreased slightly. The emulsion oil ratio of Rui Feng decreased from 30.11% to 19.95% while RZ-JD80's decreased from 70.33% to 54.43%. During the whole experiment, the emulsion oil ratio of RZ-JD80 was far higher than that



(a) Interfacial tension



(b) Emulsion oil ratio

Fig. 6 Property curve of produced liquid.

of Rui Feng surfactant (about 2.5 times higher). According to the experimental results of profile control—oil displacement in heterogeneous cores, the enhanced recovery rate by RZ-JD80 flooding is 2.4 times higher than that by surfactant flooding. It is indicated that for Gao-63 reservoir (heterogeneous reservoir), the emulsion properties of surfactant flooding play a major role after profile control [16-19] while ultra-low interfacial tension only plays a supporting role in EOR. It also confirms the scientific design of Gao-63 reservoir flooding scheme with compound surfactant in accordance with the principle of strong emulsifying capacity and moderate low interfacial tension.

3.4 Evaluation of Polymer Microspheres Profile Control—RZ-JD80 Flooding in Heterogeneous Core

According to the experiment of RZ-JD80 flooding—0.1 PV microspheres profile control—0.3 PV RZ-JD80 flooding scheme, the displacement curve was shown in Fig. 7. Compared with the polymer slug, injection pressure can be improved significantly by microspheres plugging and maintain about 800 KPa for a long time. It could be observed the concentration of emulsion is higher in the produced liquid. It demonstrates that polymer microspheres have strong plugging ability for high permeable layer. Then the strong emulsifying agent—RZ-JD80 would be injected into medium and low permeable layers. It emulsified with residual oil in place and a profile-helping solution system with blocking capacity is generated in real time. It has played a greater role in process of oil displacement and it helps to improve both oil displacement efficiency and sweep efficiency. Compared with HPAM plugging, microspheres could increase recovery by 18.52% on basis of surfactant flooding. It shows that the adaptability of polymer microspheres plugging—RZ-JD80 flooding is better for Gao-63 reservoir (heterogeneous reservoir) with higher recovery. Summarizing Figs. 3-5 and 7, for reservoirs with less heterogeneity, improving oil displacement efficiency is the key to promote recovery; for reservoirs with more heterogeneity, improving sweep efficiency is the first step to promote recovery.

After drying the experimental core, cutting core slices (thickness is 3 mm) perpendicular to the axis of each 5 cm of the core and then scanning electron microscopy were performed. It can be observed the injected microspheres mainly concentrated within 5 cm from the entrance in high permeable layer. There are also parts of microspheres migrating to the central area of high permeable layer. However, in the middle permeable layer, only a handful of microspheres are attached to the end face. Microspheres cannot be found in low permeable layer. Photos taken by SEM (Scanning Electron Microscopy) of the high permeable layer (Fig. 8) can be clearly seen. At the core throat, the polymer microspheres with a diameter of 1-10 μm can achieve coalescence and bridging,

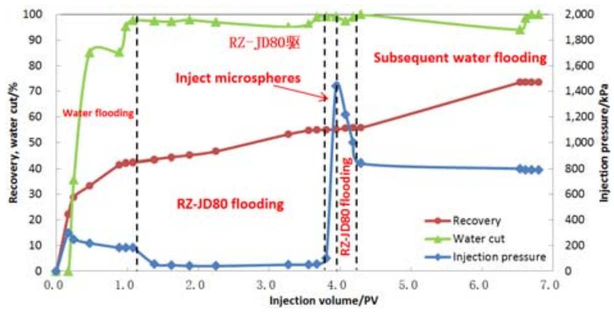


Fig. 7 Curve of microsphere plugging—oil displacement in heterogeneous core.

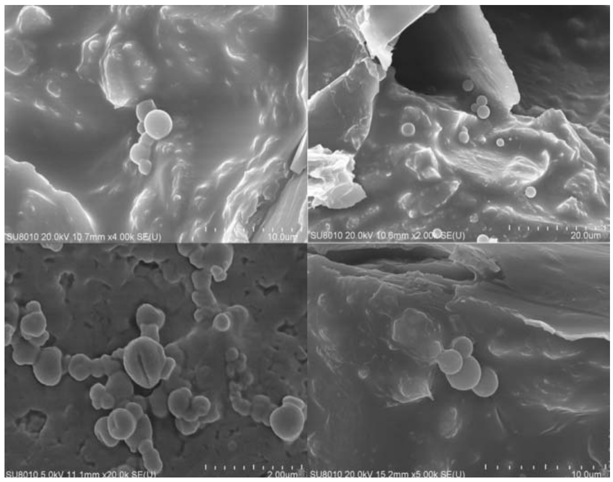


Fig. 8 SEM photographs of microspheres in core.

effectively blocking the channeling of water, enabling subsequent injection liquid diversion and entering the lower permeable layer to drive the remaining oil. It can be seen that for the heterogeneous reservoir condition of Gao-63 reservoir, profile control capacity of polymer microsphere is better and the sweep efficiency can be greatly improved as well.

4. Conclusions

For homogeneous cores, the oil displacement efficiency can be greatly improved by both of Rui Feng surfactant flooding and RZ-JD80 flooding without a profile modification slug.

For strong heterogeneous cores, enhanced oil recovery ability by only injecting two kinds of surfactant is poor. However, as long as a small profile control agent slug is injected before surfactant flooding, these two kinds of surfactant can enhance the oil recovery by different degrees.

For Gao-63 reservoir with high heterogeneity, it is not necessary to pursue ultra-low interfacial tension of surfactant for EOR. In fact, emulsifying properties play a major role, while moderate low interfacial tension can also work effectively for EOR.

The main factor restricting oil recovery in strong heterogeneous reservoirs is sweep efficiency. Profile control—surfactant flooding composite technology can greatly improve the recovery, especially the polymer microspheres—strong emulsifier flooding composite technology is very suited for Gao-63 reservoir.

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