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Study of the mechanisms of streamline-adjustment-assisted heterogeneous combination flooding for enhanced oil recovery for post-polymer-flooded reservoirs

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Abstract

Streamline-adjustment-assisted heterogeneous combination flooding is a new technology for enhanced oil recovery for post-polymer-flooded reservoirs. In this work, we first carried out a series of 2D visualization experiments for different chemical flooding scenarios after polymer flooding. Then, we explored the synergistic mechanisms of streamline-adjustment-assisted heterogeneous combination flooding for enhanced oil recovery and the contribution of each component. Test results show that for single heterogeneous combination flooding, the residual oil in the main streamline area after polymer flooding is ready to be driven, but it is difficult to be recovered in the non-main streamline area. Due to the effect of drainage and synergism, the streamline-adjustment-assisted heterogeneous combination flooding diverts the injected chemical agent from the main streamline area to the non-main streamline area, which consequently expands the active area of chemical flooding. Based on the results from the single-factor contribution of the quantitative analysis, the contribution of temporary plugging and profile control of branched preformed particle gels ranks in the first place and followed by the polymer profile control and the effect of streamline adjustment. On the contrary, the surfactant contributes the least to enhance the efficiency of oil displacement.

Keywords Plate sand-pack model · Heterogeneous combination flooding · Streamline adjustment · Polymer flooding · Displacement

1 Introduction

Polymer flooding is an important enhanced oil recovery (EOR) method (Renouf 2014). China's oil reserves are some 1.5 billion tonnes. There is still 40%–50% of the crude oil left in the formation after polymer flooding (Chang et al. 2006; Hou et al. 2009; Maghzi et al. 2014). Moreover, the remaining oil is much dispersed and is difficult to exploit (Hou 2007; Muhammed et al. 2012; Urbissinova et al. 2010; Zhang et al. 2014; Zhou et al. 2013). Therefore, researchers and engineers have developed many post-polymer-flooding EOR methods (Al-Ibadi and Civan 2013; Choi et al. 2010; Han et al. 2014; Lin et al. 2003; Pirayesh et al. 2014; Ranganathan et al. 1998; Sang et al. 2014; You et al. 2011; Wang et al. 2003; Wever et al. 2013), including alkali–surfactant–polymer (ASP) flooding, weak gel flooding and colloidal dispersion gel or bulk gel flooding. These EOR methods have been successfully implemented, but further applications are limited due to the complex geological properties and high risk of destructive blockage.

Cui et al. (2011) in Shengli Oilfield designed a novel suspended chemical flooding system according to the interaction of chemical agents. The suspended chemical, which is a heterogeneous combination flooding system, was developed for further enhancing oil recovery of reservoirs under more harsh and complicated conditions after polymer flooding.

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The suspended system consisted of the branched preformed particle gels (B-PPG) (Coste et al. 2000; Goudarzi et al. 2014) and a homogeneous solution contained polymer and surfactant. So it has heterogeneous characteristics due to the coexistence of solid and fluid. Owing to the viscoelastic properties of B-PPG, the suspended particles can deform and pass the pore throats, which were able to control the dynamic profile effectively (Bai et al. 2007; Elsharafi and Bai 2012; Shi et al. 2011). In addition, the suspended system could also lead to a lower interface tension in the presence of surfactant. Consequently, the suspended system achieved high sweep efficiency and displacement efficiency. Core flooding tests proved that the heterogeneous combination flooding system could improve oil recovery significantly after polymer flooding.

Streamline adjustment methods play an important role in the streamline-adjustment-assisted heterogeneous combination flooding. One of the streamline adjustment methods is well-pattern infill and transformation. A pilot test of this new hybrid strategy has been carried out in the Zhongyi part of the Gudao reservoir, and it has achieved remarkable development performance. Its reservoir parameters are representative of post-polymer-flooding reservoirs. The initial well spacing is 270 m, and the row spacing is 300 m. After the well pattern was adjusted by well infilling, the well spacing is 135 m, and the row spacing is 150 m. The field trial included two injection slugs. The first slug is a 0.05-PV pre-protection slug, 1500 mg/L B-PPG + 1500 mg/L polymer solution. The second slug is the main slug of 0.3 PV solution consisting of 1200 mg/L B-PPG, 1200 mg/L polymer solution, 0.2% anionic surfactant and 0.2% nonionic surfactant. The pilot field trial has shown that it improves the oil recovery effectively. The injection pressure increased from 7.0 to 10.1 MPa. The resistance factor of the pilot field trial reached 2.20. The flow resistance increased significantly. Also, a significant water-cut reduction and oil-production enhancement were achieved. The water-cut curve of the pilot test decreased from 97.5% to 76.9%. The incremental oil recovery was estimated to be 8.5%, and the final recovery could reach 63.6% OOIP.

However, the EOR mechanisms of this hybrid strategy are very complex, since it involves the synergistic effect between chemical agents, the complex interactions between the continuous fluid phase and the dispersed particle phase and well-pattern adjustment.

Researchers have conducted extensive studies of the use of hybrid technologies for enhanced oil recovery. For example, Wang et al. (2009) analyzed the applications of surfactant–polymer (SP) flooding in the Shengli Oilfield and proposed that the synergistic effect of surfactant and polymer is the key to good development performance. Hou et al. (2013) studied the distribution characteristics of additional extracted oil displaced by SP flooding and analyzed

the respective EOR mechanisms of surfactant, polymer and synthetic effects. Muhammed et al. (2012) studied the interaction between super-absorbent polymer gel and surfactants by physical experiments. He also proved that PPG treatment is a cost-effective profile control method. Chemical methods mainly improve the sweep efficiency and displacement efficiency in main streamline area between the injectors and producers. Well-pattern adjustment (Cipolla and Kyte 1992; Gould and Sarem 1989; Wu et al. 1989) can further enhance the development performance of the non-main streamline area because the streamlines can be totally changed. According to the studies by Flores et al. (2006), Sayyafzadeh et al. (2010) and Rose et al. (2011), well-pattern adjustment can induce the injected fluid to take effect in non-main streamline areas and further enlarge the sweeping area.

Though there are many studies concerning the synergistic effect of polymer and surfactant, the EOR mechanism of streamline adjustment is still unclear. There are a few studies conducted on the driving remaining oil mechanism of B-PPG, polymer, surfactant and streamline adjustment in heterogeneous combination flooding after polymer flooding. Studies of the synergistic mechanism between each chemical and streamline adjustment technology are still limited, which hinders the application of the hybrid strategy in more post-polymer-flooding reservoirs. Therefore, this work conducts experiments reflecting the injection–production relationships based on small-scale models. And more importantly, the streamline can be changed during the displacement process, so the experiments can reflect the effect of streamline adjustment. On this basis, we investigate the EOR mechanisms of the hybrid strategy and quantitatively analyze the relative contributions of B-PPG, polymer, surfactant and streamline adjustment in the hybrid strategy.

2 Experimental section

2.1 2D visualization experimental equipment

As shown in Fig. 1, the 2D visual physical equipment is composed of a fluid drive system (syringe pump), a 2D transparent sand-pack model, an effluent fluid separation and metering device, a HD macro- and micro-integrated zoom camera with large zoom ratio, a LED light source, a computer control and acquisition system and a spectral analysis of saturation system. Through the image and data acquisition system, computers can record the dynamic experimental process.

Figure 2 shows the top view of a 2D sand-pack model, which includes three injection wells, three production wells, six wellhead switches, a cruciform joint, a high transmittance plate and a sand-pack model. The cruciform

Fig. 1 Equipment for visual displacement
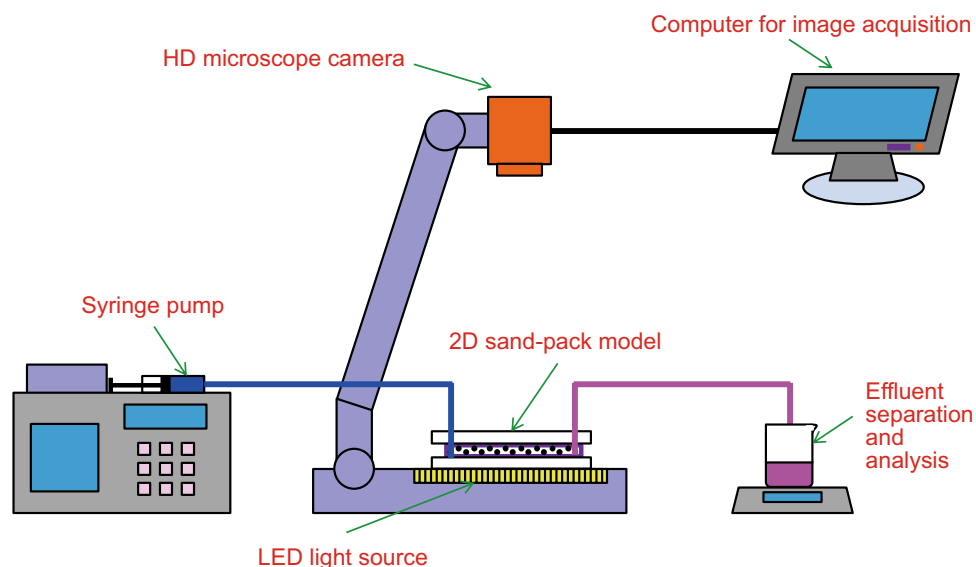
joint connects the syringe pump, sand-pack model and the effluent fluid separation and metering device. Different fluids can be injected through the conversion of well-head switches without interrupting the experiment. The sand-pack model consists of two pieces of transparent plate filled with sand. The transparent plates, with a size of 200.0 mm × 150.0 mm × 4.0 mm, were bonded together with epoxy resin (a sealant), and the size of the sand-pack space was 174.0 mm × 120.0 mm × 2.0 mm. The specially designed 2D physical model can simulate the effect of an infilling well pattern on the displacement oil by turning on (or off) the wellhead switches. There were six boreholes distributed uniformly in the sand-pack model, which were used to simulate injection wells and production wells. One injection well and one production well were open at the initial state. After the well-pattern infilling, three injection wells and three production wells were open. The well pattern changed from staggered well pattern to regular rectangular well pattern. The wells were perforated and covered with metal screens to guard against any flow of sand. The distance between wells of the same type was fixed at 86.0 mm, and the distance between the line of injection wells and production wells was set as 116.0 mm.

Fig. 2 Top view of 2D sand-pack model. The blue solid circle with arrow line refers to the injection well in the open state, and the blue hollow circle with arrow line represents the closed state. The pink solid circle refers to the production well in the open state, and the pink hollow circle is in the closed state
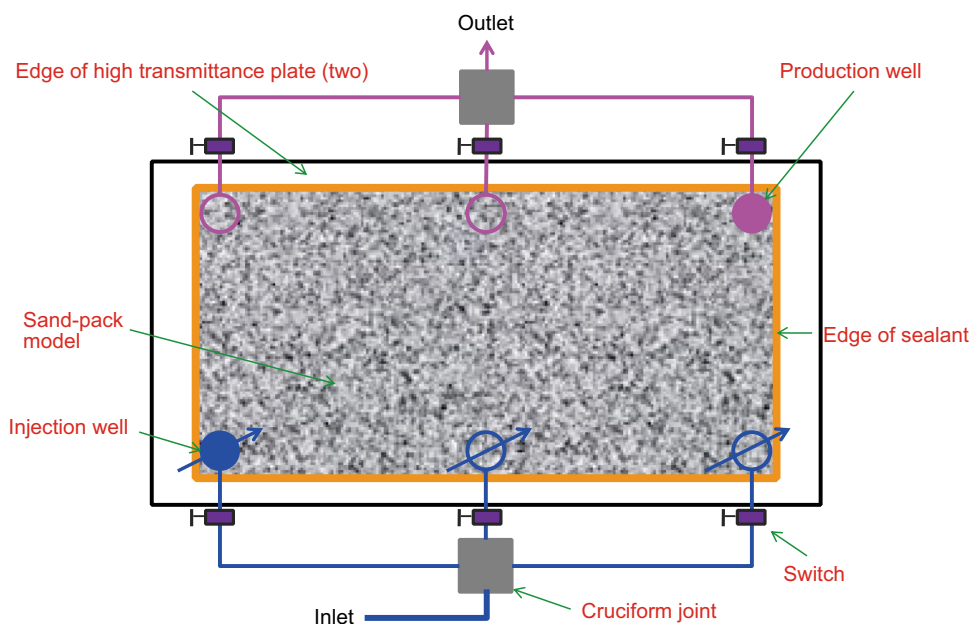
2.2 Sand-pack model

In the experiments, quartz sand supplied by Shengli Oilfield was used. The size of 80% of the sand ranged from 45 to 50 mesh. In order to ensure the same wettability, fresh sand was packed at 20 °C in every test. The air permeability of the sand-pack models was 1.5–2.5 μm^2. Brine water with a NaCl concentration of 2.5 wt% was injected to saturate sand-pack models to calculate their porosity. The porosity of the sand-pack models was about 35.0%–37.0%. The sand-pack models were saturated with brine, and this was then followed by injecting oil through three injection wells and three production wells to set up the initial oil saturations of sand-pack models. The whole oil saturation process of each experiment was recorded by the HD camera to ensure that all the sand-pack models had a uniform oil distribution in the initial state.

2.3 Experimental materials

A degassed crude oil was used for all the displacement experiments. The viscosity and density of this crude oil were 70 mPa·s and 0.8 g/cm^3 at 20 °C, respectively. NaCl solution with a concentration of 2.5 wt% was used as injection water; such brine was also used to prepare all solutions in this study.

Polyacrylamide used in this work had an average molecular weight of 15 MDa. The viscosity of this polymer solution was 12.4 mPa·s at 1500 mg/L and 10.3 mPa·s at 1200 mg/L. The surfactant was sodium dodecyl benzene sulfonate (SDBS). B-PPG particles were provided by the Shengli Oilfield, China. The properties of these chemical agents are summarized in Table 1.

2.4 Experimental procedures

All experiments were conducted at 20 °C. The rate of water flooding, chemical flooding and the following water flooding were fixed at 0.60, 0.35 and 0.60 mL/min, respectively. The detailed steps are as follows: (1) connect the experimental device as shown in Fig. 1 and open the camera; (2) saturate the sand-pack model with brine after vacuum pumping, then displace the brine with crude oil, and finally stop the displacement after reaching the irreducible water saturation; (3) water flooding: start the displacement with brine at a rate of 0.60 mL/min until the water cut at the outlet reached 90% in the initial well pattern; (4) polymer flooding: inject the polymer solution into the model with a slug of 0.4 PV, a concentration of 1800 mg/L at an injection rate of 0.35 mL/min; (5) post-polymer water flooding: inject brine at a rate of 0.60 mL/min and stop when the water cut at the outlet reached 98%; (6) displacement using different development strategies: change the initial well pattern to regular rectangular well pattern by converting wellhead switches when the streamline adjustment technology was included; inject the chemical slug into the model at an injection rate of 0.35 mL/min when the chemical technology was included; (7) post-chemical water flooding; inject brine at an injection rate of 0.60 mL/min and stop when the water cut at the outlet reached 98%; (8) analyze the oil recovery percent at different displacement stages; (9) image treatment; capture images from the recorded video and analyze the effect at different displacement stages.

2.5 Scheme design

Table 2 presents the seven experimental schemes designed in this study. The first three schemes were used for combination strategy investigations, while the remaining schemes were used for single strategy investigation in streamline adjustment.

3 Results and discussion

3.1 Conversion of residual oil saturation

Different experiments have different remaining oil saturation due to the non-reproducibility of physical models. To reduce the influence of the remaining oil saturation difference, it is necessary to adjust the remaining oil saturation of different experiments to the same level. The "conversion factor" Z is used to convert the oil saturation of different experiments to the same level. The "conversion factor" Z_n

Table 1 Basic properties of the chemical agents

Sample	Viscosity*, mPa·s	Salinity, wt%	Particle size range, μm	Average particle size, μm
Brine	0.5	2.5		
Polymer	12.4 (at 1500 mg/L) 10.3 (at 1200 mg/L)	2.5		
Surfactant	0.53 (at 4000 mg/L)	2.5		
B-PPG	810 (at 1200 mg/L)	2.5	49–872	561

*Viscosity was measured at a shear rate of 7.3 s^{-1} and 20 °C

Table 2 Design of 2D visual experiments

No.	Abbreviation	Design of experiments[**]	Injection parameters	Injection volume
1	/	W + P + PPW	/	/
2	HCF	W + P + PPW + HCF + PCW	① 1500 mg/L B-PPG + 1500 mg/L P	0.05 PV
			② 1200 mg/L B-PPG + 1200 mg/L P + 4000 mg/L S	0.3 PV
3	SA/HCF	W + P + PPW + SA/HCF + PCW	① 1500 mg/L B-PPG + 1500 mg/L P	0.05 PV
			② 1200 mg/L B-PPG + 1200 mg/L P + 4000 mg/L S	0.3 PV
4	SA	W + P + PPW + SA + W	/	/
5	SA/S	W + P + PPW + SA/S + PCW	4000 mg/L S	0.3 PV
6	SA/P	W + P + PPW + SA/P + PCW	① 1500 mg/L P	0.05 PV
			② 1200 mg/L P	0.3 PV
7	SA/B-PPG	W + P + PPW + SA/B - PPG + PCW	① 1500 mg/L P	0.05 PV
			② 1200 mg/L P	0.3 PV

[**]W, water flooding; P, polymer flooding; PPW, post-polymer water flooding; SA, streamline adjustment; HCF, heterogeneous combination flooding; PCW, post-chemical water flooding; S, surfactant flooding; B-PPG, branched preformed particle gel flooding

of the nth experiment is defined as the ratio of remaining oil saturation of the nth to the first experiment at the end of the water flooding after polymer flooding. The conversion value of residual oil saturation is expressed as follows.

$$Z_n = \frac{S_{on}}{S_{o1}} \tag{1}$$

$$S_o' = S_o \times Z_n \tag{2}$$

where S_{on} and S_{o1} represent the residual oil saturation of the nth experiment and the first experiment, respectively; S_o represents the residual oil saturation at different stages of any experiment; S_o' represents the conversion value of the residual oil saturation.

The cumulative recovery percent is the ratio of the cumulative volume of the produced oil to the volume of the initial saturated oil. The process recovery percent is the ratio of the volume of the produced oil to the volume of the initial saturated oil. The residual oil saturation, the conversion value, and the oil recovery percent (R, %) of the seven experiments are shown in Table 3. We can observe that the saturation of the initial oil for each experiment is close, but it is quite different at the subsequent water flooding stage of polymer flooding, and the minimum value is 48.9%, the maximum value is 57.2%. After the conversion according to Eq. (2), the oil saturation is 55.8%. The oil recovery of streamline-adjustment-assisted heterogeneous combination flooding is highest, reaching 76.3%. Next comes the recovery of heterogeneous

Table 3 Remaining oil saturation of different stages of each experiment

Displacement process		Experiment 1		Experiment 2		Experiment 3		Experiment 4		Experiment 5		Experiment 6		Experiment 7	
		S_o, %	R, %	S_o, %	R, %	S_o, %	R, %	S_o, %	R, %	S_o, %	R, %	S_o, %	R, %	S_o, %	R, %
Initial condition		98.1	0.0	98.1	0.0	98.9	0.0	99.1	0.0	99.5	0.0	99.4	0.0	99.1	0.0
Water flooding		64.7	34.0	64.7	34.0	70.2	29.0	76.6	22.7	66.4	33.3	65.0	34.6	74.0	25.3
Polymer flooding		59.5	39.3	59.5	39.3	60.6	38.7	62.4	37.0	60.1	39.6	62.3	37.3	63.1	36.3
Following water flooding	Experimental value	55.8	43.1	55.8	43.1	48.9	43.6	55.6	43.7	55.3	43.9	56.3	43.9	57.2	43.7
	Conversion value	55.8		55.8		55.8		55.8		55.8		55.8		55.8	
Chemical flooding	Experimental value	/		54.6		43.6		50.4		50.8		53.6		55.5	
	Conversion value	/		54.6	44.3	49.8	49.7	50.6	49.0	51.3	48.5	53.1	46.6	54.1	45.4
Following water flooding	Experimental value	/		32.1		20.5		49.4		44.4		43.1		40.7	
	Conversion value	/		32.1	67.3	23.4	76.3	49.6	50.0	44.8	55.0	42.7	57.0	39.7	59.9

combination flooding with 67.3%, but the main effect is on the subsequent water flooding stage. Experiments 4–7 show the effect of single chemical agent in the composite system.

3.2 Mechanisms of the hybrid strategy for enhanced oil recovery

3.2.1 Remaining oil distribution after polymer flooding

Experiment 1 reflected the polymer flooding development process, which included a water flooding stage and a polymer flooding stage. The remaining oil distribution at the end of water flooding and polymer flooding is shown in Fig. 3. From Fig. 3a, it can be seen that a large quantity of oil still remained after water flooding. There was a main streamline area (near the channel of water channeling) with a poorer oil accumulation and non-main streamline area (away from the channel of water channeling) with a richer oil accumulation between the injection and production wells. During the early period of water flooding, the injection water displaced oil to the production well in a fingering manner, since the viscosity of oil is higher than that of water. When the water front reached the production well, a main streamline would form between the injection and production wells. The remaining oil distributed discontinuously as an isolated island state due to the viscous fingering and high oil–water interfacial tension. In the non-main streamline area, the remaining oil distributed as a continuous state. This is because the viscosity of oil is higher than that of water and the oil in non-main streamline area cannot be readily driven by the injected water.

Polymer flooding has been proven to be an effective EOR method for high water-cut reservoirs. The viscosity of the polymer solution in reservoir conditions is higher than that of the injection water, which contributes to the increase in the sweep efficiency of the injected fluid. As shown

in Fig. 3b, the main streamline area increased obviously, while the non-main streamline area decreased after polymer flooding with some oil driven out. Increasing the injected fluid viscosity is one aspect of the polymer flooding mechanisms, and another is the diversion caused by the formation of residual resistance. Compared with water flooding, the area of remaining oil as the continuous state decreased after polymer flooding, and some amount of remaining oil as the continuous state around the production well changed to the isolated island state. Several new thief channels emerged, and oil distribution became more complex.

3.2.2 Restart mechanisms of recovering remaining oil after polymer flooding

Figure 4 shows the distributions of residual oil at different stages in experiment 2. From Fig. 4a, it can be seen that the distribution of the remaining oil in the plane was more complex after polymer flooding. Polymer flooding extended the sweep range near the injection well. However, because the blocking effect of the polymer was weak, a significant channel was still formed between the injection and production wells, and a large amount of isolated island oil was formed.

The residual oil distribution in pre-slug, main slug and the subsequent water flooding stages is shown in Fig. 4b–f. The pre-slug was composed of highly concentrated B-PPG particles and polymer solution. From Fig. 4b, during the process of injection, the pre-slug mainly flowed along thief channels formed during polymer flooding. The pre-slug had good effect in plugging the thief channels due to its high particle concentration.

The main slug solution was composed of B-PPG particles, polymer and surfactant. As shown in Fig. 4c, fluid diversion occurred during the process of injection and another two streamlines took shape. The injected fluid moved divergently, and the displacement front was more balanced. Besides, the surfactant agent reduced the interfacial
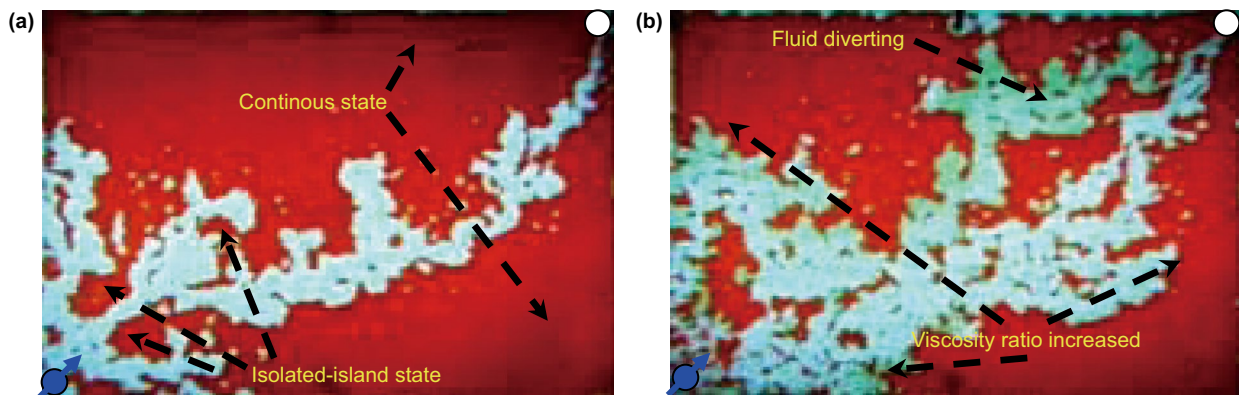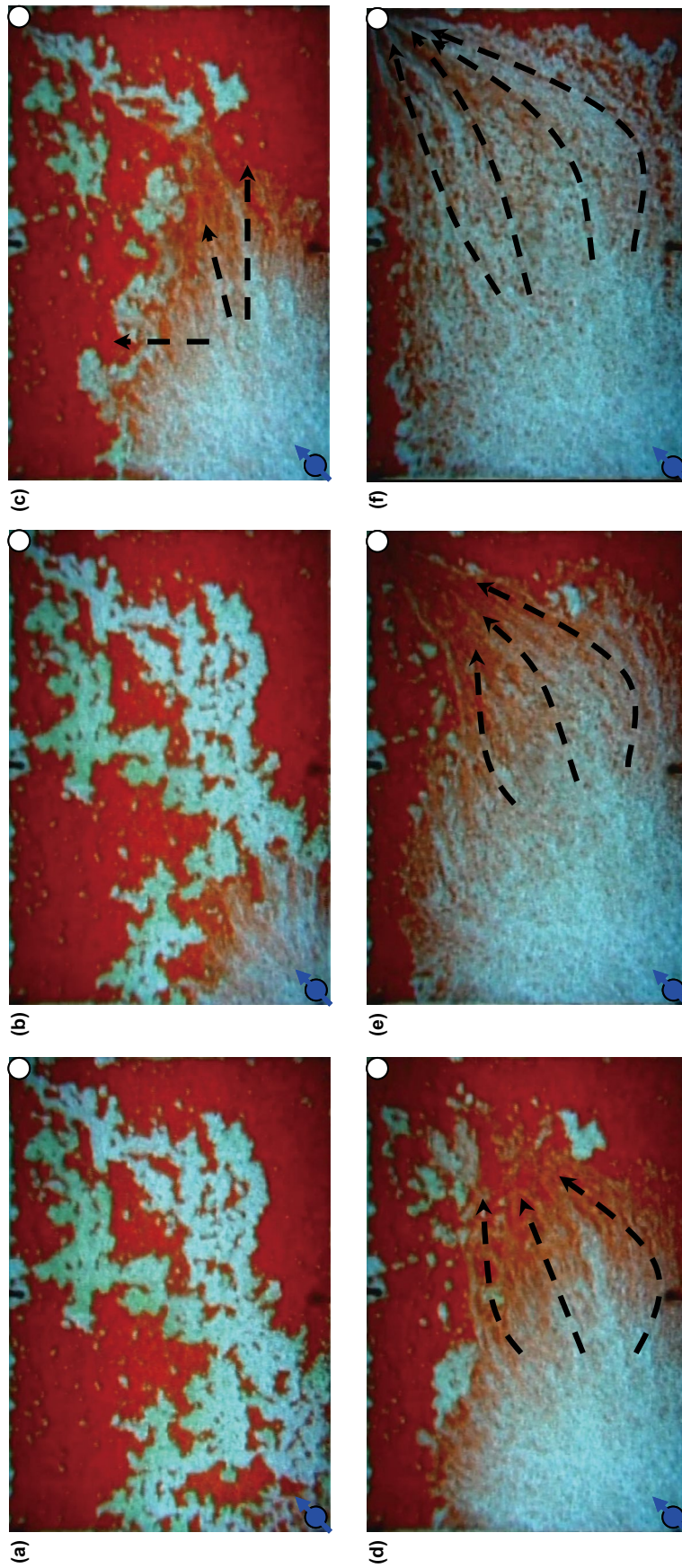

Fig. 3 Images of remaining oil distribution after water flooding (**a**) and polymer flooding (**b**) (red part is the remaining oil)

Fig. 4 Images of remaining oil distribution during heterogeneous combination flooding. **a** After polymer flooding. **b** Heterogeneous combination flooding, pre-slug 0.05 PV. **c** Heterogeneous combination flooding, main slug 0.15 PV. **d** Heterogeneous combination flooding, main slug 0.3 PV. **e** Followed by water flooding. **f** After heterogeneous combination flooding

tension of the oil–water system to 0.0037 mN/m, resulting in little oil remaining around the injection well. From Fig. 4d, the injected solution diverted again to the channeling at the end of the main slug injection. Compared with Fig. 4a, the sweep area enlarged and indicated that B-PPG particles had flowed into the deep positions of the physical model. The polymer agent increased the solution viscosity and enhanced the carrying ability, making B-PPG particles flow through the porous media more easily. Surfactant in the polymer solution plays a skidding role during the transport of B-PPG particles. Polymer and surfactant in the suspended chemical solution help B-PPG transport in the porous media. That is to say, the polymer and surfactant assist B-PPG particles to fulfill deep profile control. During the heterogeneous combination flooding, chemical agents work together and change the distribution of remaining oil from the isolated island state to the continuous state, displacing oil into the production well.

The effect of in-depth fluid diversion became more significant during the following water flooding stage (see Fig. 4e–f). Heterogeneous combination flooding had greatly improved the sweep efficiency around the injection wells. The injection water was divided into several branches in the middle of the physical model, which resulted in several flow channels taking shape near the production well where the remaining oil was rich. Only a small amount of isolated island state remaining oil was located around the production well in the main streamline area.

3.2.3 Induced effect of streamline adjustment

After polymer flooding, heterogeneous combination flooding could only increase the sweep area of the main streamline area, but continuous residual oil still existed in the non-streamline area. This part of the remaining oil may be moved by further streamline transformation. Figure 5 shows the remaining oil distribution of experiment 3. As depicted

in Fig. 5a, it can be seen that the distribution characteristics after polymer flooding were consistent with the above analysis. That is, the main streamline area was dominated by the isolated island state, and the continuous state form dominated the non-main streamline area. As observed from Fig. 5b, it can be seen that after well-pattern adjustment and heterogeneous combination flooding, the sweep area was further improved. The remaining oil was mainly distributed in the non-main streamline. Most of the remaining oil was in the isolated island state, and there was no contiguous state oil. The difference between experiments 3 and 2 shows the superiority of the heterogeneous combination flooding with streamline adjustment. Streamline adjustment plays a major role in an "induced effect"; that is, it changes the direction of fluid flow, leading the chemical agents to the non-main streamline area.

3.2.4 Comparison of the recovery percent

In order to identify the development effect under different strategies, the cumulative recovery percent and process recovery percent of each experiment were statistically
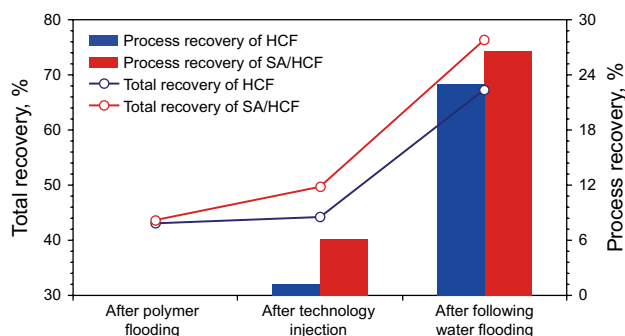

Fig. 6 Recovery percent curves of heterogeneous combination flooding (HCF) with and without streamline adjustment (SA)
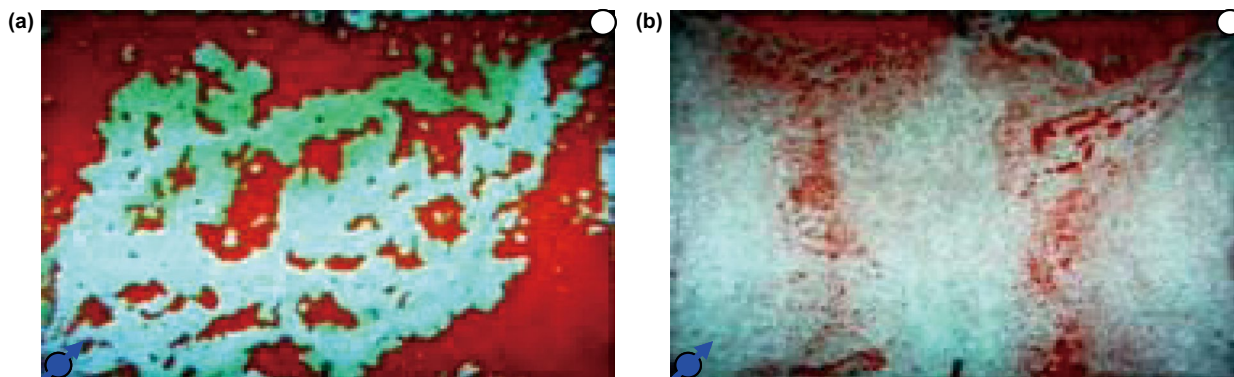

Fig. 5 Images of remaining oil distribution after polymer flooding and after well-pattern adjustment and heterogeneous combination flooding (red part refers to remaining oil). **a** After polymer flooding. **b** After well-pattern adjustment and heterogeneous combination flooding

analyzed, as shown in Fig. 6. The moment after polymer flooding was selected as the starting point for study, from which the cumulative recovery percent gradually increased. The cumulative recovery percent of SA/HCF scheme was 9.0% higher than that of HCF scheme, where the induced effect of streamline adjustment could enhance the acting area of the HCF system. For either the SA/HCF scheme or the HCF scheme, water flooding is the main strategy for further oil recovery.

3.3 Contributions of different factors in the hybrid strategy

In order to quantitatively characterize the contributions of the four factors in the hybrid strategy, single-factor comparison experiments were conducted. Experiments 4, 5, 6 and 7 were used for single-factor comparison.

3.3.1 Contribution of streamline adjustment

Figure 7 shows the remaining oil distribution of experiment 4 at the end of polymer flooding and water flooding after streamline adjustment, respectively. It can be seen that new main streamlines took shape, and the remaining oil became more dispersed, and the amount of isolate-island state oil increased significantly. It indicated that the streamline adjustment in hybrid development strategy has the induced effect for the injected fluid to displace the potential remaining oil. Moreover, the EOR effect of streamline adjustment was more obvious for actual post-polymer flooding reservoirs with strong vertical heterogeneity. Based on the results obtained from experiment 4, with the single method of streamline adjustment, the injected fluid still flows along the channel formed after the polymer flooding. So, the polymer and other chemicals are required to increase the viscosity of the injected fluid and thus improve the displacement efficiency for further enhanced oil recovery for post-polymer reservoirs.
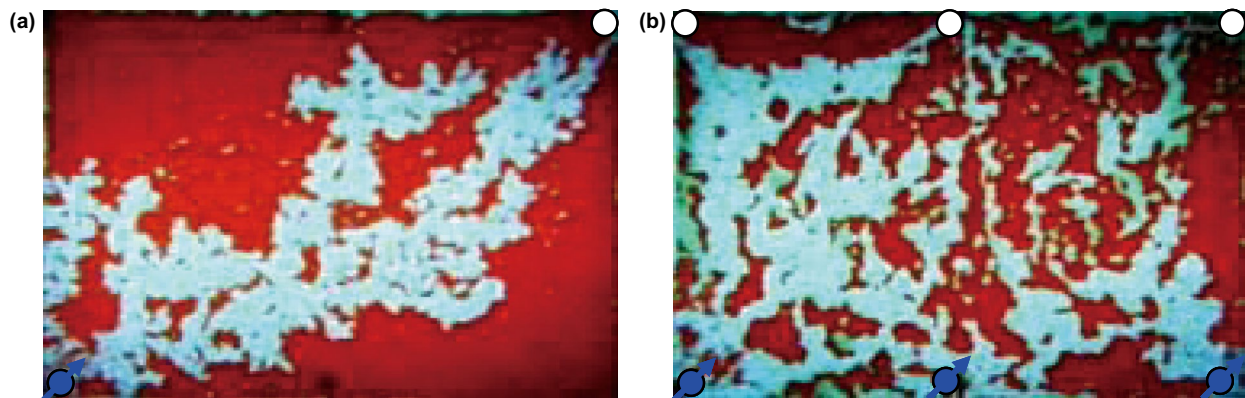
Fig. 7 Images of remaining oil distribution of experiment 4. **a** After polymer flooding. **b** After streamline adjustment and followed water flooding
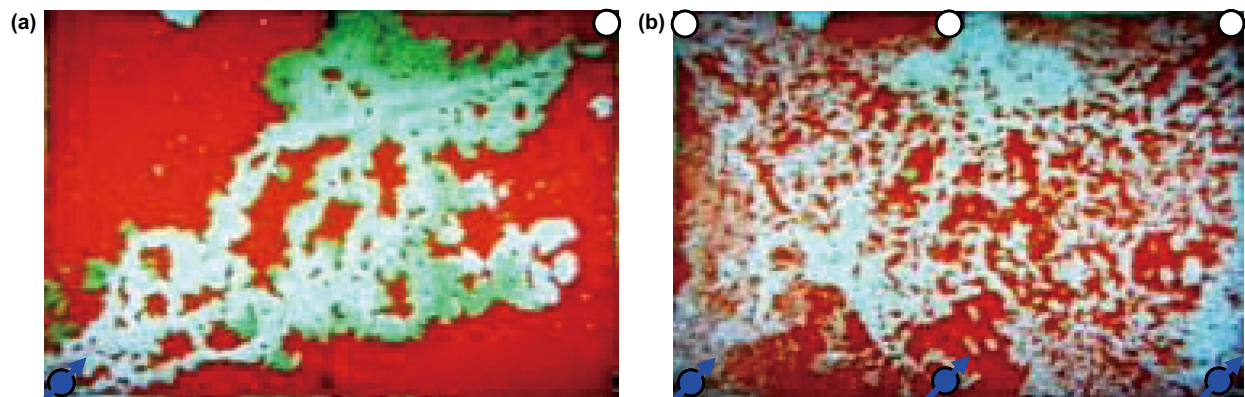
Fig. 8 Images of remaining oil distribution of experiment 5. **a** After polymer flooding. **b** After streamline-adjustment-assisted surfactant flooding

3.3.2 Contribution of surfactant

Figure 8 shows the remaining oil distribution of experiment 5 at the end of polymer flooding and water flooding after streamline-adjustment-assisted surfactant flooding, respectively. Surfactant could reduce residual oil in the swept area and improve the displacement efficiency. As shown in Fig. 8b, the remaining oil became more dispersed and the remaining oil area was decreased. That is because the injected surfactant solution is miscible with oil, causing an emulsion to be formed around the edge of remaining oil area. Due to low viscosity, the surfactant solution can readily flow through the highly permeable channels and cannot displace the oil efficiently, which results in the wide distribution of isolated island state oil between the injection and production wells. Besides, the skidding mechanism of surfactant strengthens the channeling velocity. The surfactant can increase the displacement efficiency, but has no positive impact on the sweep efficiency improvement. Thereby, profile control agents should be added to increase the viscosity of the injected fluid by improving the sweep efficiency.

3.3.3 Contribution of polymer and B-PPG particles

B-PPG particles and polymer are profile control agents in the hybrid strategy. Figure 9 shows the remaining oil distribution after streamline adjustment combined with secondary polymer flooding (see experiment 6). Figure 10 shows the remaining oil distribution after streamline adjustment combined with B-PPG flooding (see experiment 7). The remaining oil distribution of the two experiments is similar. As observed in Figs. 9b and 10b, both the polymer solution and the B-PPG suspension system achieved good displacement efficiency in the swept area. Compared with experiments 4 and 5, the amount of remaining oil in an isolated island state had been decreased significantly in experiments 6 and 7. Both the polymer solution and the B-PPG suspension system had the ability to divert fluid, and the diverted fluids prefer to flow toward the production wells in channels with smaller resistance formed during previous first polymer flooding, which resulted in the occurrence of some oil as continuous state locating in the newly formed non-main
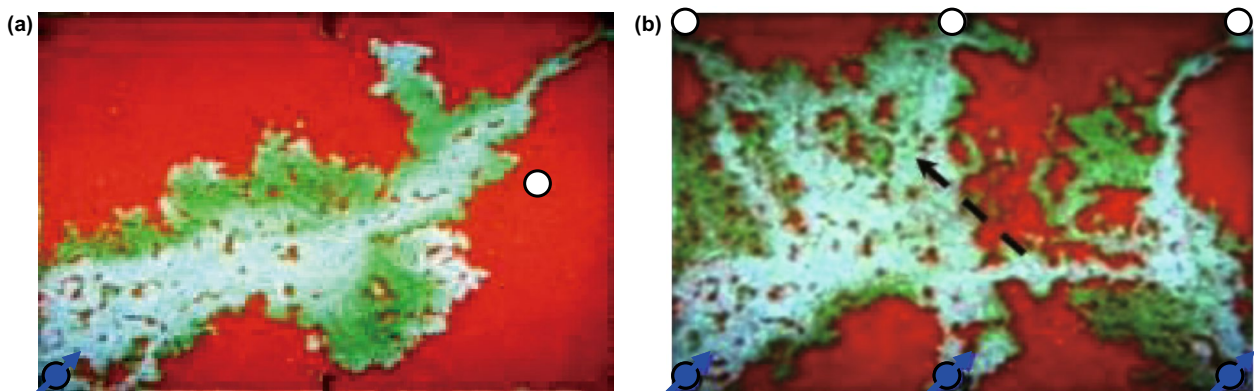

Fig. 9 Images of remaining oil distribution of experiment 6. **a** After polymer flooding. **b** After streamline-adjustment-assisted polymer flooding
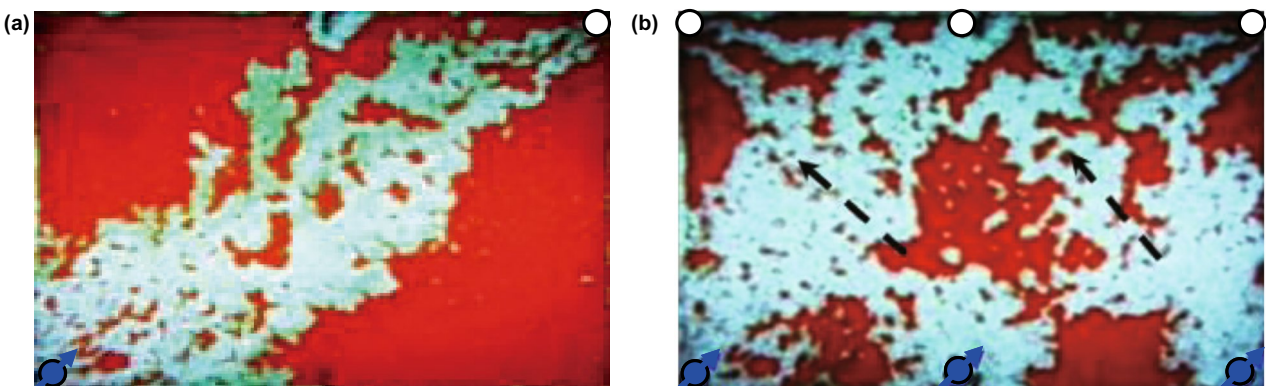

Fig. 10 Images of remaining oil distribution of experiment 7. **a** After polymer flooding. **b** After streamline-adjustment-assisted B-PPG flooding

streamline area. The distribution characteristics of the remaining oil indicate that it is difficult for the profile control system to travel through the porous medium due to its residual resistance mechanism. Therefore, a surfactant is required in the polymer solution and the B-PPG system to improve the transport ability, avoiding destructive blockage and thus enhancing the sweep efficiency. From the above analysis, it is concluded that the synergistic effect of B-PPG particles, polymer and surfactant can achieve good development effect.

Different factors in the hybrid strategy have different EOR mechanisms. Thus, the four factors in the hybrid strategy can be combined and used to further enhance the oil recovery of post-polymer flooding reservoirs.

3.3.4 Comparison of the degrees of contribution

In order to identify the development effect of different methods, EOR values of different experiments and the relative contributions of different factors were statistically analyzed. The effect of streamline-adjustment-assisted heterogeneous combination flooding on EOR is divided into four factors, i.e., streamline adjustment synergism (SA), surfactant synergism (S), polymer synergism (P) and B-PPG synergism (B-PPG). Quantitative value of the contribution degree of four factors is calculated as:

$$X_i = \frac{R_i}{\sum\limits_{i=1}^{4} R_i} \times 100 \tag{3}$$

where X_i represents the contribution degree of factor i, i=1, 2, 3, 4 (representing SA, S, P and B-PPG). R_1 represents the increased recovery percent of the streamline adjustment factor, which is the difference of recovery percent between experiment 4 and experiment 1. R_2 represents the increased recovery percent of the surfactant factor, which is the difference of recovery percent between experiment 5 and experiment 4. R_3 represents the increased recovery percent of the polymer factor, which is the difference of recovery percent between experiment 6 and experiment 4. R_4 represents the increased recovery percent of the B-PPG factor, which is the difference of recovery percent between experiment 7 and experiment 4.

The difference of recovery percent between experiment 4 and experiment 1 was 6.9%. Compared with experiment 4, the recovery degree of experiment 5, experiment 6 and experiment 7 increased by 5.0%, 7.0%, and 9.9%, respectively. The increased values of different experiments and contributions of different factors are shown in Fig. 11. Based on the experiments, the contribution degree of
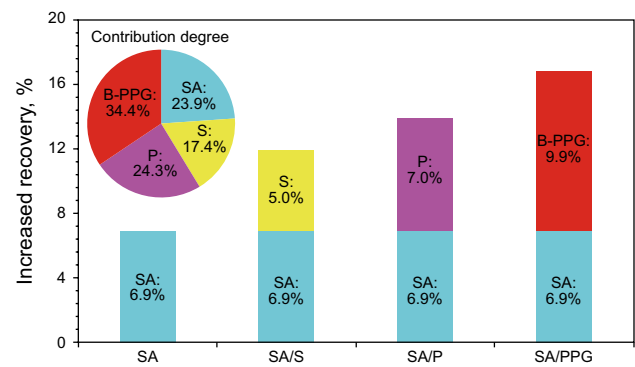

Fig. 11 Increased values of different experiments and relative contributions of different factors

branched preformed particle gels (B-PPG), polymer and surfactant was 34.4%; 24.3% and 17.4%, respectively; the contribution degree of streamline adjustment was calculated as 23.9%.

4 Conclusions

1. After the polymer flooding, the remaining oil was distributed discontinuously in an isolated island state in the main streamline area and as a continuous state in the non-main streamline area. Compared with water flooding, polymer flooding dispersed more residual oil, and more thief seepage channels were observed.

2. During the heterogeneous combination flooding, the distribution of remaining oil in the main streamline area was obviously changed from an isolated island state to a continuous state because of the synergistic effect among chemicals. As the solid phase possessing viscoelastic properties, B-PPG particles suspended in the solution could deform and flow in the physical model to play a role in fluid diversion. Fluid diversion happened all over the process and expanded the sweep coefficient significantly. As the liquid phase in heterogeneous combination flooding, polymer increased the system viscosity and surfactant improved the displacement efficiency. Besides, polymer and surfactant helped B-PPG travel through the porous medium and avoid destructive blockages. The heterogeneous combination flooding without streamline adjustment could improve the sweep efficiency and displacement efficiency in the main streamline area between the injection and production wells, but the development performance was not so good in the non-main streamline area.

3. After the hybrid strategy including streamline adjustment and heterogeneous combination flooding, there was hardly any remaining oil distributed in the main

streamline area and only a small amount of remaining oil located in the non-main streamline area mainly in an isolated island state. Streamline adjustment could guide the suspended chemical solution to the non-main streamline area, which was beneficial for the chemicals to fully play the role for displacing remaining oil into larger areas after polymer flooding. Compared with the heterogeneous combination flooding without streamline adjustment, the hybrid strategy had better sweep efficiency and displacement efficiency for post-polymer flooding reservoirs. The cumulative recovery percent of the SA/HCF scheme was 9.0% higher than that of the HCF scheme.

4. In the hybrid strategy, the fluid diverting mechanism of B-PPG had the biggest contribution of 34.4%. The profile control of polymer and the induced effect of streamline adjustment had the contribution of 24.3% and 23.9%, respectively. The surfactant had the smallest contribution of 17.4% in improving oil displacement efficiency.

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