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ORIGINAL PAPER

Research into polymer injection timing for Bohai heavy oil reservoirs

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Abstract Polymer flooding has been proven to effectively improve oil recovery in the Bohai Oil Field. However, due to high oil viscosity and significant formation heterogeneity, it is necessary to further improve the displacement effectiveness of polymer flooding in heavy oil reservoirs in the service life of offshore platforms. In this paper, the effects of the water/oil mobility ratio in heavy oil reservoirs and the dimensionless oil productivity index on polymer flooding effectiveness were studied utilizing relative permeability curves. The results showed that when the water saturation was less than the value, where the water/oil mobility ratio was equal to 1, polymer flooding could effectively control the increase of fractional water flow, which meant that the upper limit of water/oil ratio suitable for polymer flooding should be the value when the water/oil mobility ratio was equal to 1. Mean while, by injecting a certain volume of water to create water channels in the reservoir, the polymer flooding would be the most effective in improving sweep efficiency, and lower the fractional flow of water to the value corresponding to

ΔJ_{\max} . Considering the service life of the platform and the polymer mobility control capacity, the best polymer injection timing for heavy oil reservoirs was optimized. It has been tested for reservoirs with crude oil viscosity of 123 and 70 mPa s, the optimum polymer flooding effectiveness could be obtained when the polymer floods were initiated at the time when the fractional flow of water were 10 % and 25 %, respectively. The injection timing range for polymer flooding was also theoretically analyzed for the Bohai Oil Field utilizing relative permeability curves, which provided methods for improving polymer flooding effectiveness.

Keywords Heavy oil reservoir · Mobility ratio · Polymer injection timing · Injection timing range · Timing optimization

1 Introduction

Heavy oils account for about 69 percent of the total of about $17.8 \times 10^8 \text{ m}^3$ original oil in place discovered in offshore reservoirs in the Bohai Oil Field. For water flooding in heavy oil reservoirs, the swept volume by water during a pilot flood turns out to be very limited due to an excessively high water/oil mobility ratio and serious fingering. The average oil recovery of the overall development program is 20.2 percent in the Bohai Oil Field (Zhou 2009). Therefore, specific measures should be taken for most conventional heavy oil reservoirs to improve oil displacement efficiency during different oil production stages (Levitt et al. 2013). As for the Bohai Oil Field even if the oil recovery is improved by only 1 %, it will in effect result in obtaining the equivalent of another major oil field of hundreds of millions of tonnes without any exploration

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and development investment. Among different EOR techniques, polymer flooding, as a relatively mature technique (Chang 2011; Abu-shiekh et al. 2012; Delamaide et al. 2013), has been proven to be very effective in increasing oil recovery and decreasing water cuts in different scales of on-site polymer flood pilots conducted in the Bohai Oil Field (Ye et al. 2010; Zhang et al. 2011a, b; Kang and Zhang 2013; Shi et al. 2013).

In the course of water flooding in conventional heavy oil reservoirs, with an increase in water saturation, the water/oil mobility ratio will increase as well, resulting in a much higher increase in the water cut in heavy oil reservoirs than in light oil reservoirs (Kumar et al. 2005; Asghari and Nakutnyy 2008; Aktas et al. 2008; Mogbo 2011; Morelato et al. 2011; Liu et al. 2012). Influenced by such factors as reservoir heterogeneity, the polymer flood was initiated when the water cut of the produced fluids reached 60 % for the SZ36-1 oil field, and the oil recovery factor increased by only 5–7 % due to polymer floods (Zhang et al. 2007, 2009, 2013; Jiang et al. 2010; Kang et al. 2011), which was lower than that in the onshore light crude reservoirs (Asghari and Nakutnyy 2008). Meanwhile, the largest difference between onshore and offshore oil production is that the design service life of an offshore platform is less than 30 years (Rivas and Gathier 2013). Therefore, it is extremely important for offshore oil fields to select an optimum injection timing to initiate polymer floods in heavy oil reservoirs (Zhang et al. 2013) for better ultimate oil recovery.

Field tests show that the earlier the polymer flooding is performed, the better the water/oil mobility control is maintained with polymer solutions. This means that the injection timing of polymer solutions has a significant influence on the ultimate recovery factor (Ma 1995; Hu 2004; Alzayer and Sohrabi 2013). Therefore, appropriate polymer injection timing would be helpful to effectively enhance oil recovery, lower the risks in polymer flooding in heavy oil reservoirs, and displace more oil during the service life of offshore platforms. In this paper, the effect of the water/oil mobility ratio on the efficiency of polymer flooding is studied at different fractional flows of water in heavy oil reservoirs using relative permeability curves, and then the polymer injection timing is optimized.

2 Experimental

2.1 Materials

Hydrophobically associating polyacrylamide (HAP2010, industrial purity) was commercially available, with a relative molecular weight of 1.0×10^7 , degree of hydrolysis of 20 percent, and a hydrophobic group content of 1.0 percent. Injection water used in all tests had a total salinity of

9,047 mg/L, in which the mass concentrations of Na^+/K^+ , Ca^{2+} , Mg^{2+} , SO_4^{2-} , HCO_3^- , and Cl^- were 2,552, 569, 229, 37, 191, and 5,471 mg/L, respectively. The types of oils used, namely oil A and B, were the mixtures of diesel and dehydrated crude from the Bohai Oil Field, with viscosities of 70 and 123 mPa s, respectively, at 65 °C. The oil viscosity was measured with a DV-III Brook-field viscometer.

2.2 Experimental procedures and data processing method

Natural cores were taken from the Bohai oil reservoirs, with a dimension of 2.5 cm in diameter and 7 cm in length. These cores had a gas permeability of about $2,000 \times 10^{-3} \mu\text{m}^2$ and porosity of about 30 %.

Water–oil/polymer solution–oil relative permeability curves were measured by an unsteady state method according to oil and natural gas industrial specifications SY/T 5435-2007, P.R. China. The experimental procedures are as follows (Crotti and Rosbaco 1988; Bakhitov et al. 1980): (a) The core was cleaned with solvent and dried with hot nitrogen and then evacuated; (b) Permeability was measured with gas; (c) The core was saturated with injection water, then the core porosity and permeability to water were calculated; (d) Oil was injected into the core at a rate of 0.1 mL/min up to 3 PV (pore volume) in order to reach the irreducible water saturation. Oil was injected into the core by an ISCO Model 260D pump; (e) The oil permeability was measured at irreducible water saturation; (f) The injection water was injected into the core at a rate of 1 mL/min up to 10 PV in order to reach the irreducible oil saturation; (g) The water permeability was measured at residual oil saturation; (h) The core was cleaned with solvent and dried with hot nitrogen and evacuated. Then steps from b to e were repeated; (i) The polymer solution (polymer concentration was 1,750 mg/L) was injected into the core at a rate of 1 mL/min up to 10 PV in order to reach the residual oil saturation; and (j) The permeability to polymer solution was measured at irreducible oil saturation. The volumes of oil and water produced were measured dynamically.

The water saturation at different periods was calculated by the material balance method, and the modified “J·B·N” method (Dou et al. 2007; Shi et al. 2001; Zhou et al. 2010; Delgado et al. 2013) was used to calculate the water–oil/polymer solution–oil relative permeability. The effective viscosity μ_{eff} of the polymer solution was calculated with Eq. (1).

$$\mu_{\text{eff}} = \frac{RF}{RRF} \mu_w, \quad (1)$$

where RF is the resistance factor, dimensionless; RRF is the residual resistance factor, dimensionless; and μ_w is the viscosity of water solution, mPa s.

3 Results and discussion

3.1 Relative permeability curves during water flooding and polymer flooding

In experiments, the viscosity of the injection water and the polymer solution was 0.60 and 1.05 mPa s, respectively, at 65 °C. The relative permeability of the displaced and displacing phases (oil and water during water flooding, oil and polymer solution during polymer flooding) was measured, and the relative permeability curves are shown in Fig. 1.

In Fig. 1, K_{ro} and K_{rw} are the oil and water relative permeability, respectively, during water flooding; and K_{rpo} and K_{rp} are the oil and polymer solution relative permeability, respectively, during flooding; S_w is the water saturation.

With an increase in oil viscosity, the residual oil saturation increased in the relative permeability curves, which demonstrated that the performance of the displacing phase dropped (Jiang et al. 2008). Under the same water saturation, the relative permeability of cores to the polymer phase was far lower than that to the water phase, while the relative permeability of cores to the oil phase changed slightly; and the residual oil saturation decreased in the relative permeability curve during polymer flooding. This showed that polymer flooding could control the water/oil mobility and improve the oil displacement efficiency for heavy oil reservoirs (Shi et al. 2010).

3.2 Effect of the fractional flow of water on injection timing of polymer floods

According to the relative permeability curves during water flooding and polymer flooding, the mobility ratio (M), the fractional flow of water (f_w), and the rate of increase of fractional water flow with water saturation (df_w/dS_w) could be obtained in the fractional flow equation

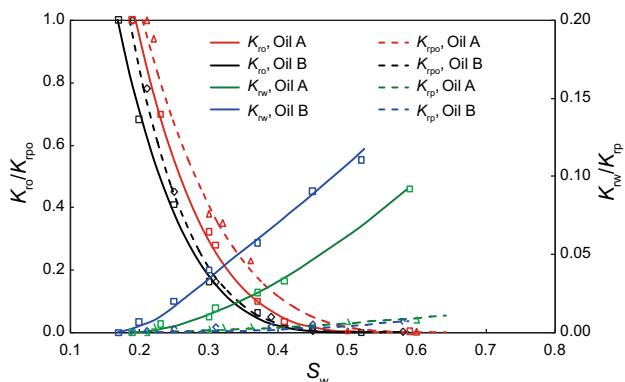


Fig. 1 Relative permeability curves during water flooding and polymer flooding

(Romero-Zeron et al. 2009; Torabi et al. 2013). During water flooding, the curves of the mobility ratio versus water saturation are shown in Fig. 2, and the fractional water flow curves and the rate of increase in the fractional water flow with water saturation are demonstrated in Fig. 3

Figure 2 indicates that at a water saturation of 0.35, the water/oil mobility ratio is typically very unfavorable for oil B; and a similar tendency is present for oil A when the water saturation is about 0.38. During polymer flooding, the polymer solution/oil mobility ratio would be reduced to just slightly above 1.0. The injection of polymer solutions may increase the viscosity of the water phase and decrease the water mobility, indicating that improved sweep efficiency can be expected from polymer flooding.

As shown in Fig. 3, when the oil viscosity was relatively high, the fractional flow of water increased rapidly and reached its maximum levels at low water saturations. As a result, water channels may be formed in a short time due to serious viscous fingering, causing early water breakthrough and poor oil displacement efficiency.

The water/oil mobility ratio and the fractional flow of water increased quickly when the water saturation (S_w) increased. Therefore, oil recovery can be improved by injecting polymer solutions before the rate of increase of fractional water flow reached its maximum level. This was helpful to control mobility for stabilizing the water front, improve sweep efficiency and to increase displacement efficiency.

For oil B and A, when the water saturation was 0.186 and 0.252, respectively, the rate of increase of fractional water flow reached its maximum, as soon as the water/oil mobility ratio was higher than 1. The mobility ratio would increase dramatically when the water saturation was higher than 0.186 and 0.252. At high mobility ratios viscous fingering occurred, leading to a poor sweep efficiency (Shi et al. 2012). A frontal-advance velocity cutoff would be established for mobility control with polymer floods

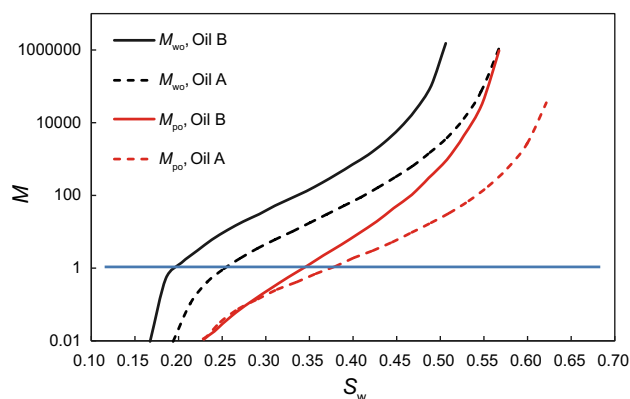


Fig. 2 Mobility ratios for crude oils of different viscosity

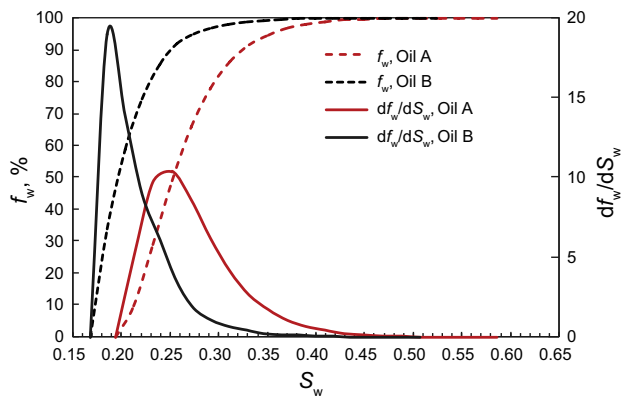


Fig. 3 The curves of fractional water flow and the rate of increase of fractional water flow

(Lee 2010), but the mobility control of polymer solution could become limited when the mobility ratio was too high during water flooding, leading to a poor polymer flood sweep efficiency in high viscosity reservoirs.

It was favorable to perform polymer flooding at relatively low water/oil mobility ratio when the polymer solution had enough ability to control flow mobility. Injection of polymer solutions would decrease the rate of increase of fractional water flow and extended the stable production period, so good displacing efficiency would be achieved. The upper water saturation limit of polymer flooding should be the saturation (S_{wu}) when the rate of increase of fractional water flow reached its maximum level. When $S_w \leq S_{wu}$, the ability of polymer floods to control flow mobility ratio has appeared to be affected significantly by the water saturation in the heavy oil reservoirs. While $S_w > S_{wu}$, polymer floods could not control flow mobility, finally resulting in poor displacement efficiency.

Thus, it was favorable to perform polymer floods before the rate of increase of fractional water flow reached its maximum level. The suitable water saturation for polymer floods should be less than 0.186 and 0.252, respectively, for oil B and A. The water saturation was 0.186 and 0.252, the rates of increase of fractional water flow was 34 % and 50 %, respectively.

3.3 Effect of dimensionless productivity index on injection timing of polymer floods

The objective of mobility control is to improve the volumetric sweep efficiency of polymer floods. The oilfield responses are observed through an increase in injection pressure and reduced water cut (Mahani et al. 2011). The polymer solution slug would improve the volumetric sweep efficiency, resulting in a decrease in water cut; on the other hand, the polymer solution slug would lower the water

injection capacity and the liquid producing capacity. The reduction of the liquid producing capacity generally took place in the initial stage of the polymer flooding process, and decreased slowly thereafter.

Figure 4 indicates that the water saturation of oil reservoirs increased during polymer flooding when the fractional flow of water was the same. Figure 5 shows that the dimensionless productivity index in the polymer flooding process was less than that in the water flooding process.

The difference between the dimensionless productivity indexes in the water flooding and polymer flooding processes are defined as follows:

$$\Delta J = J_{orw} - J_{orp}, \quad (2)$$

where J_{orw} is the dimensionless productivity index in the water flooding process; J_{orp} is the dimensionless productivity index in the polymer flooding process.

Figure 5 shows that ΔJ increased at first and then decreased as the water saturation increased. The water/oil mobility ratio was low when the water saturation was relatively low. The water front was relatively stable, injection water could connect the flow channels in oil reservoirs, and thus J_{orw} was relatively high. If the polymer solution was injected at this moment, the polymer mobility should be less than the oil mobility, resulting in an excessive pressure increase and lowering the dimensionless productivity index. This showed that the flow channels for initial water were connected together in oil reservoirs when the water saturation was relatively low. ΔJ reached its maximum level (ΔJ_{max}) as the water saturation increased, which indicated that flow channels were formed in oil reservoirs due to water injection and the oil was displaced by injection water. After that, the injection water would preferentially flow through the high permeability channels, the fractional flow of water increased rapidly, water breakthrough was very fast and the volumetric sweep efficiency was low, so it was desirable to inject polymer solution to control the flow resistance in flow channels, which ultimately enhanced the displacement efficiency.

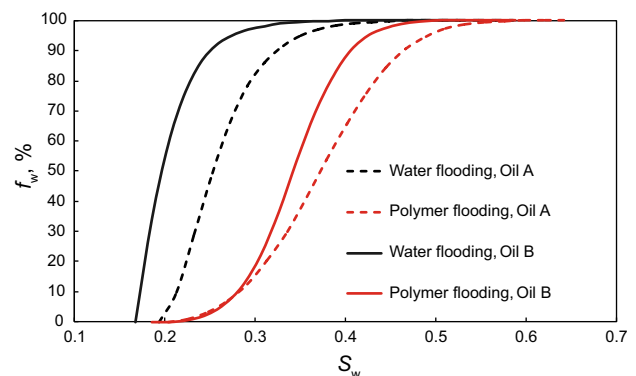


Fig. 4 The fractional water flow curves

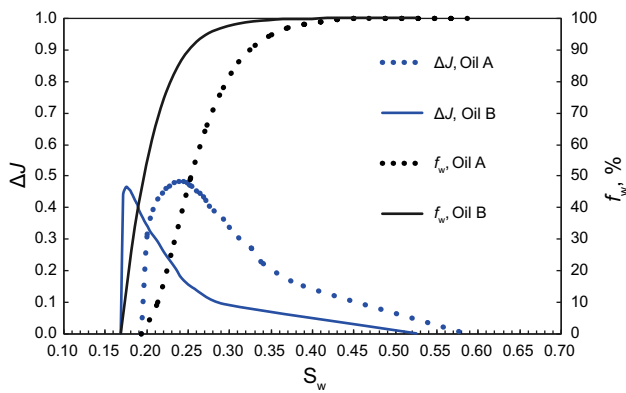


Fig. 5 Dimensionless productivity index during water flooding and polymer flooding

When $S_w \leq S_{wL}$ (where S_{wL} is the water saturation when ΔJ reached its maximum level), the displacement effect of the polymer flood was similar to water flood. The main function of polymer floods was to form flow channels. The displacement efficiency of polymer floods would be below the desired level if the polymer solution was only used to build up flow channels. S_{wL} should be the water saturation lower limit for polymer floods. A certain amount of water is recommended to be injected into heavy oil reservoirs to create or connect flow channels before polymer flooding. Then the polymer solution is injected to modify the oil/water mobility, improve the volumetric sweep efficiency, and to enhance success rate of polymer floods. Therefore, when ΔJ reaches maximum (ΔJ_{max}), the corresponding water saturation should be the lower limit of injection timing, which is also the start for polymer slug injection in heavy oil reservoirs.

When $S_w \geq S_{wL}$, the injection of a polymer solution slug would improve the volumetric sweep efficiency and oil recovery. For oil B and A, the corresponding suitable water saturation should be higher than 0.179 and 0.240, respectively, for polymer flooding. When the water saturations were 0.179 and 0.240, the rates of increase of fractional water flow were 10 % and 25 %, respectively.

By analyzing the displacement mechanism of water flooding and polymer flooding, the injection timing for heavy oil B was in the range of 10–34 % of the fractional flow of water; and the injection timing for oil A was in the range of 25–50 % of the fractional flow of water. During the service life of the offshore platform, the optimum injection timing for polymer flooding should be selected as S_{wL} in order to maximize the improvement of the oil recovery for the Bohai heavy oil reservoirs. Normally, under consideration of the mobility control ability of polymer solution, the higher the crude oil viscosity is, the earlier the polymer flooding injection timing should be. It could be realized that the polymer injection timing should

be a little later if the ability of the polymer solution to control flow mobility is high enough, which also could achieve good displacement efficiency.

4 Conclusions

- (1) For polymer solutions of the same mobility control ability, the polymer flood may be injected at relatively low water saturation to stabilize the water front and decrease the water cut when the oil viscosity is higher.
- (2) The injection timing for polymer floods is when the upper limit of water saturation is less than S_{wu} . Before the fractional flow of water reaches the maximum value, the injection polymer solution can effectively control the increase of fractional water flow.
- (3) The injection timing for polymer floods is when the lower limit of water saturation is greater than S_{wL} . A certain amount of water injected before polymer flooding may effectively connect the flow channels in heavy oil reservoirs, cut the polymer cost and ensure the displacement efficiency of polymer flooding.
- (4) Influenced by the service life of offshore platforms in Bohai heavy oil reservoirs, the injection timing should be selected at S_{wL} . When the oil viscosity is 123 mPa s, the optimum injection timing for polymer floods should be 10 % of the fractional flow of water; and when the oil viscosity is 70 mPa s, the optimum injection timing for polymer floods should be 25 % of the fractional flow of water. Meanwhile, for polymer solutions with different mobility control capabilities, the optimum injection timing for polymer flooding should be varied as well.

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