Synergistic mechanism of well pattern adjustment and heterogeneous phase combined flooding on enhancing oil recovery in mature fault-block reservoirs

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Abstract
With the maturity of fault-block reservoirs, the water percolation channels are formed after long-term waterflooding, which leads to large amounts remaining oil unrecovered and low recovery efficiency. Thus, it is imperative to seek for enhancing oil recovery methods to improve the development performance of mature fault-block reservoirs. Well pattern adjustment and heterogeneous phase combined flooding are both feasible technologies for enhancing oil recovery in mature fault-block reservoirs. Nevertheless, both technologies have their limitations. Thus, a hybrid approach combining WPA and HPCF was proposed. In this study, the large-scale plate sand-pack model flooding experiments were conducted to investigate whether hybrid strategy has better EOR ability than the single WPA or HPCF. Thereafter, on the basis of incremental oil recovery and distribution of remaining oil, the mechanism of the synergistic effect of WPA and HPCF was illustrated. Finally, the influence of reservoir inclination on development performance was proposed. The results show that EOR of hybrid strategy is the highest, followed by single HPCF, and single WPA is the least. The HPCF mainly recovers remaining oil on both sides of main streamline after water flooding, and it prolongs the period of EOR validity. WPA can change the fluid flow direction and force the subsequent liquid enters the un-swept non-main streamline areas in the water flooding stage. Furthermore, by combining WPA and HPCF, the HPCF can enter the non-main streamline areas to expand sweep volume and improve oil displacement efficiency under the induction of WPA. Besides, the reservoir inclination has an obvious influence on the development performance of fault-block reservoir. With the increase of reservoir inclination, the incremental oil recovery of the single strategy or hybrid strategy decreases. Thus, these findings of this study can help for better understanding the synergetic effect of HPCF and WPA, which can provide a hybrid strategy for enhancing oil recovery in mature fault-block reservoir.

Keywords Mature fault-block reservoirs · Well pattern adjustment · Heterogeneous phase combined flooding · Synergistic mechanism

Abbreviations
EOR Enhance oil recovery
WPA Well pattern adjustment
HPCF Heterogeneous phase combined flooding
PPG Preformed particle gel
B-PPG Branch-preformed particle gel
PV Pore volume
OOIP Original oil-in-place

Introduction
Fault-block reservoir is one of the main reservoir types in Shengli Oilfield. The available reserves and annual oil production account for one third of the whole oilfield (Zhou 2008; Liu et al. 2014). However, after long-term waterflooding development, this type of reservoir has problems such as high comprehensive water cut, difficulty in producing remaining oil and stabilizing production (Cui et al. 2007). Fault-block reservoir has distinctive geological conditions of
fault development and large formation inclination (Li et al. 2018; Jiang et al. 2010). Owing to the influence of geological and development factors during high water cut period, the oil, gas and water distribution of mature fault-block reservoir are extremely complex (Liu et al. 2007; Ma et al. 2020; Wang et al. 2021), and it is difficult to further enhance oil recovery (EOR). Nevertheless, there are still extensive remaining oil trapped or locked in the pore and the potential remaining oil area of the reservoir is relatively large. Slightly improving the recovery of this part remaining oil also has high exploitation value (Dai et al. 2008). Therefore, the issue of how to effectively enhance oil recovery of mature fault-block reservoirs has attracted more and more attention. Many technologies have been proposed with the thinking of improving oil displacement efficiency and expanding the sweep volume, such as polymer flooding (Zhou et al. 2020; Alfaazizi et al. 2019; Sharafi et al. 2018; Saboorian et al. 2016), polymer gel (Bai et al. 2015; Qiu et al. 2022), polymer-surfactant binary combined flooding (Kamari et al. 2016; Yan et al. 2018; Xu et al. 2017; Dordzie et al. 2021) and so on. These tertiary oil recovery technologies based on polymer flooding has been proved by field application in improving the oil recovery and achieved remarkable economic value. However, there is one technology that works once and for all. Due to the limited profile control ability of polymer and binary flooding, the stable production of the oilfield will not be guaranteed. Therefore, how to further enhance oil recovery is an urgent problem to be solved.

Polymer gel has been developed on the basis of polymer flooding and field application, mainly used in profile control. This technology generally uses initiators and crosslinkers to realize the polymerization and crosslinking of polymer monomers under reservoir ambient to form a three-dimensional network structure. The network structure is similar to solid state in macro and unique fluid state in micro. Nevertheless, there are still some problems in the polymer gel system, especially the time of gelation is uncontrollable, which will lead to great uncertainty in the profile control (Karaoguz et al. 2007; Wu et al. 2011; Xu et al. 2018; Sun et al. 2021). In order to avoid these problems, preformed particle gel (PPG) has been researched and developed. PPG overcomes the inherent shortcoming of the traditional polymer gel, which can be crosslinked on the ground and injected in the form of particles (Mousavi et al. 2012; Majid et al. 2018; Song et al. 2018). PPG can block the large pores or high permeability zones and improve the heterogeneity. Moreover, PPG has strong stability and less affected by temperature, salinity, pH and shear action (Wang et al. 2019). In addition, PPG can swell in formation brine and have certain strength. The suspension of PPG shows a strong ability of profile control and significant EOR effect in mature reservoir (Goudarzi et al. 2015; Salehi et al. 2020; Wang et al. 2022). In recent years, based on the development status of Shengli oilfield, a novel branch-preformed particle gel (B-PPG) has been developed on the basis of PPG (Sang et al. 2014; Li et al. 2021). The viscosity of B-PPG suspension was improved by introducing branched chains into the main chain (He et al. 2018). After a long-term of repeated experimental exploration and summary, a heterogeneous phase combined flooding (HPCF) system composed of polymer, B-PPG and surfactant was proposed and received the attention of many oilfield experts (Bai et al. 2011; Zhao et al. 2018). The field test shows that the HPCF has a superior oil displacement efficiency and the ability of enlarge sweep volume compared to the polymer.

Another important measure to enhance oil recovery is well pattern adjustment (WPA) (Sayyafzadeh et al. 2010; Zhu et al. 2018; Guo et al. 2019; Wu et al. 2020). WPA technology can adjust change streamline distribution and reduce the streamline density in the original main streamline areas, which can improve the sweep efficiency and achieve the purpose of improving development performance (Choudhuri et al. 2015; Jia and Deng 2018). A field test of WPA technology has been implemented in WH5-917 and WH7-117 well groups of Shuanghe oilfield. Waterflooding was carried out until September 2016 after WPA in December 2014. The cumulative oil production of two well groups was $0.47 \times 10^4 \text{t}$ and $0.57 \times 10^4 \text{t}$, respectively. And the average water cut dropped by 1.21% and 1.14%, respectively (Bai et al. 2017).

The WPA technology has been applied in mature reservoirs and achieved good development efficiency. However, to the best of our knowledge, most of previous research focused on the single well pattern adjustment investigated by numerical simulation method. There is lack of physical simulation experimental method used to investigate the WPA technology applied in mature reservoirs. Moreover, the hybrid strategy of well pattern adjustment and HPCF has not been reported and the synergetic mechanism is still unclear. Thus, the objective of this study is to elucidate the synergistic mechanism of EOR in combining WPA and HPCF. The general sketch of this study is plotted in Fig. 1.

In this study, the large-scale plate sand-pack model (50 cm $\times$ 25 cm $\times$ 2 cm) was used to conduct displacement experiments. Then the large-scale plate sand-pack model flooding experiments were conducted to investigate whether hybrid strategy has better EOR ability than the single WPA or HPCF. On the basis of incremental oil recovery and distribution of remaining oil, the mechanism of the synergistic effect of WPA and HPCF was illustrated. Finally, the influence of reservoir inclination on development performance was proposed. We hope these findings in this study could provide the effective guidance for the development of mature fault-block reservoirs.
Experimental approach

Materials

(1) Particle gel: The branched-preformed particle gel (B-PPG) was applied in this study provided by Shengli oilfield. The elastic modulus of B-PPG was 10.3 Pa and the particle size before swollen was 100–150 mesh. The image of B-PPG before and after swollen is shown in Fig. 2. As can be seen from Fig. 2, the particles were irregular in shape and have angular edges after swollen.

The particle size distribution of 800 mg·L⁻¹ B-PPG suspension was measured by Bettersize 2600 laser particle size analyzer. The particle size of B-PPG suspension is mainly distributed in 100–1400 μm, and the median diameter (D₅₀) of B-PPG suspension can be determined as 542 μm.

(2) Surfactant: The surfactant used in this study was petroleum sulfonate (molecular formula: C₂₃H₃₈SO₃M).

(3) Polymer: In this study, the polymer was partially hydrolyzed polyacrylamide (HPAM) with molecular weight of 2.0×10⁷ and hydrolysis degree of 24%, which was provided by Shengli oilfield.

Fig. 2 The image of B-PPG sample: a dry powder; b after swollen
(4) Brine: The simulated formation brine was prepared and the total dissolved solids (TDS) of simulated formation brine were 21190.35 mg·L\(^{-1}\), and the type of brine was calcium chloride (CaCl\(_2\)).

(5) Oil: The simulated oil was prepared by kerosene and Paraffin oil in the ratio of 1:3. The viscosity of simulated oil was 28.5 mPa·s under the temperature of 25 \(^\circ\)C. Furthermore, in order to facilitate the calculation of the water cut of produced liquid, the simulated oil was dyed by Sudan III.

**Experimental apparatus**

The experimental apparatus includes ISCO pump, stirring intermediate container, large-scale plate sand-pack model, oil–water saturation detection system and six-way valve. The schematic diagram of experimental apparatus is plotted in Fig. 3. The image of large-scale plate sand-pack model is shown in Fig. 4. The dimension of model (length, width, depth) is 50 cm × 25 cm × 2 cm. Fifty pairs of saturation electrode probes are evenly distributed on the model, the change of remaining oil saturation in each flooding stage can be monitored at any time.

**Methods**

The 80–120 mesh quart sand was used to fill the large-scale plate sand-pack to simulate the reservoir. After sand-packing, the simulated formation brine was injected into the model, and adjust the position of injection well and production well several times to ensure that the air in the model is discharged as much as possible. Then the simulated oil was injected into the model to displace the water until the water cut of produced liquid is 0%. The displace experiment includes four different stages: initial water flooding, well pattern adjustment (WPA), HPCF flooding and subsequent water flooding. The experimental temperature (25 \(^\circ\)C) and injection rate (4 mL·min\(^{-1}\)) was remained the same in all experiments. The steps of large-scale plate sand-pack flooding experiment are shown in Fig. 5.
**Experimental scheme design**

Six experiments were designed in this study at different measure implementing and reservoir inclination. According to the actual well pattern of Xinlicun Yong8 block, Dongxin oil plant of Shengli oilfield, the experimental scheme was formulated. The position of injection well and production well before and after well pattern adjustment is shown in Fig. 6. The experimental scheme is illustrated in Table 1.

The composition of HPCF used in this study was 1600 mg·L⁻¹ polymer + 800 mg·L⁻¹ B-PPG + 0.3% surfactant.
and shown in Fig. 7. The oil recovery of each flooding stage water cut, injection pressure, and oil recovery is obtained strategies (WPA, HPCF) and hybrid strategy. Therefore, the rate the enhance oil recovery ability (EOR) of two single sand-pack flooding experiments were conducted to evaluate the experimental methods in 2.3, a series of large-scale plate flow direction of fluid needs to be changed. According to water flooding. In order to further improve oil recovery, the reservoir forms a water flow channel due to long-term experimental methods in 2.3, a series of large-scale plate sand-pack flooding experiments were conducted to evaluate the enhance oil recovery ability (EOR) of two single strategies (WPA, HPCF) and hybrid strategy. Therefore, the water cut, injection pressure, and oil recovery is obtained and shown in Fig. 7. The oil recovery of each flooding stage is illustrated in Table 2.

The results of above experiments (No.1 to No.6) shown that both well pattern adjustment (WPA) and HPCF can effectively improve remaining oil recovery. In addition, the value of EOR was decreased with the reservoir inclination increased. The 6.1%, 11.1% OOIP was obtained after the implementation WPA or HPCF in No.1, and No.2. Specifically, during initial water flooding period, with the injection of brine, after a short anhydrous oil production period, then the water cut increased and finally reaches 95%. The model entered high water cut period indicated that the percolation channels were formed. The oil around the main streamline was produced, and extensive remaining oil still exists in the unswept area. The oil recovery during initial water flooding was 48.4% and 47.8%, respectively. After WPA implemented, the water cut decreased from 95 to 84%, and the cumulative oil recovery increased by 6.1% OOIP because of the streamline adjustment. The ultimate oil recovery reached 54.5%.

In contrast, after HPCF implemented, the water cut decreased from 95 to 80%, the decrease degree of water cut is more than that of WPA (Fig. 7a and b). In addition, during the subsequent water flooding, the increase rate of water cut after HPCF implemented slower than that of WPA. Moreover, the cumulative oil recovery increased by 11.1% OOIP, which is higher than that of WPA. Due to the dynamic plugging of HPCF, the percolation resistance of initial streamline increased and force subsequent liquid to find a new percolation channel in unswept area, which expanded the swept area. Moreover, it is clearly observable that the time of enhance oil recovery is longer than that of WPA, which led to higher oil recovery.

Aiming at the limitations of single strategy, the hybrid strategy that combining HPCF and WPA was conducted and the results are shown in Fig. 7(c). Compared with the No.1 and No.2, the hybrid strategy has a better performance in EOR. After hybrid strategy implementing, the water cut decreased from 95 to 68%, which was significantly better than HPCF or WPA was implemented. The reason can be explained as a larger number of oil in unswept area was extracted by the formation of new streamline and high displacement efficiency. In addition, due to the dynamic plugging of HPCF, the swept volume will continue to expand and the water channeling is hard to formation. After injecting 1.32PV fluid, the water cut of model reached 98%. The time of enhance oil recovery was significantly prolonged. The oil recovery of hybrid strategy is increased by 21.3% OOIP, which is higher than the sum of the EOR of two single strategies. In other words, the combining of HPCF and WPA have synergistic effect on EOR.

Compared with the conventional reservoir, the fault-block reservoir has the characteristics of large formation inclination, which has a certain influence on the development of fault-block reservoir. Based on the results of above experiments (No.1 to No.3), the influence of reservoir inclination on enhance oil recovery was investigated and the results are shown in Fig. 7d–f. The cumulative oil recovery with different reservoir inclination is plotted in Fig. 8.

As can be seen from Fig. 7d–f, with the increases of reservoir inclination, the performance of oil production has the same trend. After implementing WPA, HPCF and hybrid strategy, the water cut decreased by 4%, 18% and 27%, respectively. Moreover, the peak pressures during measure implementing are 0.13 MPa, 0.22 MPa, 0.26 MPa, respectively. Due to the plugging effect and efficient oil displacement of HPCF, and the formation of new streamline, the sweep volume will be continually expanded and the remaining oil will be further extracted. When the water cut of model reach 98%, 0.61PV, 1.03PV and 1.12PV injection fluid was injected, respectively. Compare with No.1 to 3 experiments, the time of enhance oil recovery significantly decreased with the increases of reservoir inclination.

As can be seen from Fig. 8, with the increase of reservoir inclination, the performance of oil production has the same trend. After implementing WPA, HPCF and hybrid strategy, the water cut decreased by 4%, 18% and 27%, respectively. Moreover, the peak pressures during measure implementing are 0.13 MPa, 0.22 MPa, 0.26 MPa, respectively. Due to the plugging effect and efficient oil displacement of HPCF, and the formation of new streamline, the sweep volume will be continually expanded and the remaining oil will be further extracted. When the water cut of model reach 98%, 0.61PV, 1.03PV and 1.12PV injection fluid was injected, respectively. Compare with No.1 to 3 experiments, the time of enhance oil recovery significantly decreased with the increases of reservoir inclination.

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**Fig. 7** The water cut, pressure, and cumulative oil recovery of experiments: a No.1; b No.2; c No.3; d No.4; e No.5; f No.6

| No | Scheme   | Reservoir inclination | Cumulative oil recovery(%OOIP) | EOR(%OOIP) |
|----|----------|-----------------------|--------------------------------|------------|
|    |          |                       | After water flooding | After subsequent water flooding |
| 1  | WPA      | 15°                   | 48.4              | 54.5       | 6.1         |
| 2  | HPCF     |                       | 47.8              | 58.9       | 11.1        |
| 3  | WPA + HPCF |                   | 47.3              | 68.6       | 21.3        |
| 4  | WPA      | 30°                   | 43.1              | 46.3       | 3.2         |
| 5  | HPCF     |                       | 42.6              | 55.2       | 9.6         |
| 6  | WPA + HPCF |                   | 43.4              | 59.1       | 15.7        |
The distribution of remaining oil under different strategies

The percolation channels were formed in the reservoir after long-term water flooding. To further enhance oil recovery, it is essential to change the flow direction of fluid and expand the sweep volume. The distribution of remaining oil after implementing two single strategies or hybrid strategy with different reservoir inclination is shown in Figs. 9 and 10. The characteristics of the remaining oil distribution with different strategies under different reservoir inclination were analyzed.

As can be seen from Figs. 9 and 10, the percolation channels were formed in the lower part of the model during water flooding period. The sweep volume of the lower part of the model is significantly higher than that of the upper part of the model. In other words, the oil recovery in water flooding period was mainly contributed by the lower part of the model (Figs. 9a and 10a). After implementing WPA, the initial percolation channels were closed, and new flow direction of injected brine was found. The high saturation remaining oil existing in the un-swept area before WPA was extracted (Figs. 9b and 10b). Nevertheless, due to the injected liquid is still brine, the oil–water mobility ratio still exists. After the formation of new percolation channels, the water cut increased sharply and injection pressure decreased.

Fig. 8 EOR of different reservoir inclination

The distribution of remaining oil under different strategies

The percolation channels were formed in the reservoir...
After implementing HPCF, the liquid preferentially flows along the initial percolation channel, which formed in the water flooding period. Due to the prominent plugging performance of HPCF, the subsequent liquid was forced to enter the high saturation remaining oil area, which greatly expands the sweep volume. Moreover, owing to the viscosity of HPCF, the influence of gravity was overcoming and oil–water mobility ratio was improved, which prolong the period of EOR validity. In addition, although HPCF can effectively improve the oil recovery of model, compared with WPA, the flow direction of liquid has not been changed.

After implementing hybrid strategy, the peak pressure (Fig. 7) is significantly higher than that of two single strategies owing to the high displacement efficiency and flow direction. The HPCF was guided and flow direction by WPA from the initial streamline area to the high saturation remaining oil area (Figs. 9d and 10d). Therefore, the sweep volume has been greatly expanded. The HPCF can significantly prolong the period of EOR validity. Simultaneously, the WPA can immediately extract the remaining oil, which was poorly affected by water flooding. The hybrid strategy combines the advantages of the two single strategies.

**Mechanism of enhance oil recovery by hybrid strategy**

Based on the analyzing of cumulative oil recovery and the distribution of remaining oil, the mechanism of EOR by hybrid strategy is elucidated and shown in Fig. 11. The red arrow represents the initial streamline, and the yellow arrow represents the new streamline. As can been seen in Fig. 11, HPCF can effectively expand the sweep volume in fault-block reservoir and improve oil recovery in the areas on both sides of the initial streamline. During the subsequent water flooding period, driven by the brine flow, HPCF can migrate to the deep part of the reservoir and play the role of continuous plugging, which prolong the period of EOR validity. WPA can change the flow direction and force the liquid enter the areas that were not affected well. After implementing hybrid strategy, WPA can guide the HPCF...
enter the non-main streamline areas to expand sweep volume and improve oil displacement efficiency.

Summary and conclusions

In this study, a series of large-scale plate sand-pack flooding experiments with different strategies were conducted to investigate whether combining the WPA and HPCF can effectively enhance oil recovery in fault-block reservoir. Thereafter, the mechanism of enhance oil recovery by hybrid strategy was illustrated. Some conclusion can be drawn and as follows:

1) Based on the incremental oil recovery and water cut, no matter whether WPA or HPCF, the oil recovery can be effectively improved. The hybrid strategy combines the advantages of the two single strategies and achieves the effect of “1 + 1 > 2” in terms of EOR.

2) The reservoir inclination of fault-block reservoir has an obvious influence on enhance oil recovery by HPCF and WPA. The larger the reservoir inclination, the lower the ability of enhance oil recovery.

3) The mechanism of EOR by hybrid strategy is as follows: HPCF can effectively expand the sweep volume in fault-block reservoir and improve oil recovery in the areas on both sides of the initial streamline. During the subsequent water flooding period, driven by the brine flow, HPCF can migrate to the deep part of the reservoir and play the role of continuous plugging, which prolong the period of EOR validity. WPA can change the flow direction and force the liquid enter the areas that were not affected well. After implementing hybrid strategy, WPA can guide the HPCF enter the non-main streamline areas to expand sweep volume and improve oil displacement efficiency.

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Data availability The data used to support this study are available from the corresponding author upon request.
Declarations

Conflict of interest On behalf of all the co-authors, the corresponding author states that there is no conflict of interest.

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