Evaluation of preformed particle gels and polymer gels for conformance control in heterogeneous sandstone reservoirs

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Abstract. Enhanced oil recovery (EOR) through the combination of preformed particle gels (PPGs) and HPAM/Cr3+ polymer gels was proposed in this study. By conducting the homogeneous core displacement experiments, the recovery factors after HPAM/Cr3+ polymer gels treatment, PPGs treatment and HPAM/PPGs combination treatment are observed respectively. It is found that the combination of PPGs and HPAM/Cr3+ polymer gels can improve the oil recovery significantly. In addition, in order to simulate the development of heterogeneous reservoirs, the recovery factors in the case of different profile control methods are observed by the way of the heterogeneous core displacement experiments. Through the comprehensive analysis of these three experiments, it can be concluded that the combination of PPGs and HPAM/Cr3+ polymer gels exhibits an excellent conformance control performance in heterogeneous sandstone reservoirs.

1. Introduction

There are many natural fractures in the formation in the low-permeability sandstone reservoirs, which cause serious heterogeneity of the oil reservoir [1]. In addition, a series of formation damage phenomena (i.e., sand production, cementation material loss and so on) caused by the way of long terms of water injection, leading to many high-permeability channels and micro-fractures in the formation. These large pores and micro-fractures are always the seepage channels of oil and gas [2]. It often leads to water channeling, resulting in a sharp rise in water cut and a rapid decline in oil production [3]. Nowadays, various technologies have been developed to reduce the water cut of oil wells according to the field conditions, and the application of polymer gel has a good performance for profile control [4]. Besides, petroleum engineers have also used preformed particle gels (PPGs) to improve oil recovery in heterogenous reservoirs [5].

In view of the characteristics of serious heterogeneity in fractured reservoir, the polymer gel treatments have been proved to be an effective method on conformance control in low permeability fractured reservoir [6]. It is generally believed that the oil displacement mechanism of polymer (mainly partially hydrolyzed polyacrylamide) can be summarized as: the polymer improves the viscosity of displacement phase solution, improves the oil-water mobility ratio, overcomes the fingering phenomenon of water phase in heterogeneous reservoir, and improves the sweep volume of polymer solution in reservoir [7, 8]. On the other hand, PPGs can effectively block the high permeability pore throat of fractured reservoir, which can enhance oil recovery [9].
Preformed particle gels and polymer gel systems has been proved to be effective methods for plugging micro-fractures and large pores by a lot of researchers [10]. In order to further enhanced the conformance control performance, a combination system of PPGs and HPAM/Cr\textsuperscript{3+} polymer gel was put forward in this study. The combination system was made by combining the pre-crosslinked water absorbing microspheres into the three-dimensional network gel system. It not only has the overall network structure of weak gel, but also has the elastic expansion of water absorbing microspheres. The synergistic effect of polymer and microsphere may greatly enhance the oil recovery.

2. Experimental sections

2.1. Experimental instruments and drugs

Artificial core samples were purchased from China university of petroleum (Beijing), and the parameters of core samples are shown in Table 1.

| Core/# | Length/cm | Cross section/cm\(^2\) | Porosity/% | Liquid permeability/μm\(^2\) |
|--------|-----------|-------------------------|------------|-----------------------------|
| 1      | 7.514     | 5.011                   | 26.25      | 1.032                       |
| 2      | 6.934     | 5.027                   | 29.15      | 1.102                       |
| 3      | 7.232     | 5.016                   | 27.46      | 1.054                       |
| 4      | 7.405     | 5.031                   | 20.74      | 504.3                       |
| 5      | 7.524     | 5.086                   | 27.21      | 1002.2                      |
| 6      | 7.413     | 5.024                   | 23.15      | 498.7                       |
| 7      | 7.508     | 5.175                   | 27.43      | 1001.6                      |

The crude oil used in this study was collected from Yanchang oilfield, and its viscosity is 5.67 mPa·s at 30 °C. The PPGs and HPAM/Cr\textsuperscript{3+} polymer gel systems were homemade. The brine water with salinity of 10000mg/L was used for preparing polymer, microsphere polymer solution system and saturated core model to simulate formation salinity. The experimental apparatuses are shown in Figure 1.

![Experimental apparatuses](image)

Figure 1. Experimental apparatuses.

2.2. Experimental steps

2.2.1. Homogeneous core flooding experiments. Using HPAM, PPGs and the combination of HPAM and PPGs to carry out homogeneous core flooding experiment, the steps are as follows:

(1) The cylindrical core (core #1 shown in Table 1) was placed in the core holder, and the confining pressure of 3.5 MPa is added by hand pump, and then the brine water was saturated into the vacuumed core sample;

(2) The cores saturated with brine were placed in a 30 °C incubator for more than 12 hours;
(3) The prepared crude oil was injected into the core after saturated water at the pump speed of 0.2 ml/min until the pump pressure was stable. The volume of water expelled from the core was measured, and the volume of water expelled was the volume of saturated simulated oil. Then, the core was aged in a 30 °C incubator for 12 h;

(4) When the water cut reaches at 98% in the outlet of the core, the oil recovery by water flooding was calculated;

(5) After that, the HPAM solution with 1000 mg/L was injected into the core sample, and the injection volume of polymer solution was 0.15pv. Then, water flooding was carried out at the same injection rate until the water content at the outlet of the core was 98%.

(6) And then the 0.15PV PPGs solution with 1000 mg/L was injected to the core sample. Then, water flooding was carried out until the water content at the outlet end was 98%, and the final recovery was calculated;

(7) After repeating the procedures of (1)-(4) by using core #2, the 0.15PV PPGs solution was injected following with water flooding and then 0.15PV HPAM solution was injected following with water flooding. The final recovery was calculated when the water content at the outlet was 98%;

(8) After repeating the procedures of (1)-(4) by using core #3, 0.3PV of compound system (i.e., 0.15PV of HPAM solution and 0.15PV of PPGs solution) was used for profile control, and the final recovery factor was calculated after following water flooding.

2.2.2. Experiments of profile control in heterogeneous core samples. The experimental steps of heterogeneous core flooding by preformed particle gels (PPGs), HPAM/\text{Cr}^{3+} polymer gels and the compound system of PPGs and HPAM/\text{Cr}^{3+} polymer gels are as follows:

(1) The cylindrical cores (core #4 and #5) were placed in the core holder, and the confining pressure of 3.5Mpa was added by hand pump. Then the core was evacuated by vacuum pump for 2 h, and the artificial synthetic brine was saturated to measure the porosity;

(2) The cores saturated with synthetic brine were placed in a 30 °C incubator for more than 12 hours;

(3) The water permeability of core sample could be measured through water flooding;

(4) The simulated oil was injected into the core sample at the injection rate of 0.2 ml/min to calculate the volume of saturated oil, and then the core was aged in 30 °C incubator for 12 h;

(5) Two cores with different permeabilities were put into two parallel grippers, and water was driven at the pump speed of 0.2 ml/min until the water content at the outlet of the core reached at 98%;

(6) After that, 0.15PV of HPAM/\text{Cr}^{3+} polymer gel system was injected to core samples. And then the 0.15PV of PPGs solution was pumped into the core at the speed of 0.2 mL/min, and the recovery factor was calculated.

(7) Finally, the water was injected until the water cut reaches 98% at the core outlet, and the ultimate recovery could be calculated.

(8) After repeating the procedures of (1)-(5) by using core #6 and core #7, the 0.3PV compound system of PPGs and HPAM/\text{Cr}^{3+} polymer system was injected to the core samples. Then, water flooding was carried out until the water content at the outlet of core sample was 98%, and the recovery factor was calculated;
3. Results and discussions

3.1. Homogeneous core flooding experiments

The recovery curves of homogeneous core flooding experiments can be seen in Figure 2, Figure 3, and Figure 4.

![Figure 2. Curves of HPAM solution flooding following with PPGs flooding experiments.](image1)

![Figure 3. Curves of PPGs flooding following with HPAM solution flooding experiments.](image2)
Figure 4. Curves of compound system (the combination of HPAM and PPGs) flooding experiments.

It can be seen from the above three experimental curves that the oil recovery of composite system is higher, which indicates the compound system can yield a better performance on enhanced oil recovery (EOR) in homogeneous core. Comparing with HPAM flooding following with PPGs flooding method, the compound system can yield higher recovery factor. It is mainly due to the PPGs can block the fracture first to prevent the loss of polymer in the fracture channeling zone, improving the utilization rate of polymer. Comparing with PPGs flooding following with HPAM flooding method, the compound system can also yield higher recovery factor. It is mainly contributed to the synergistic effect of HPAM and PPGs, the PPGs can link to the polymer molecular chain and the intermolecular forces can improve the bulk viscosity significantly.

3.2. Heterogeneous core flooding experiments

After the heterogeneous core flooding experiments, the curves of recovery rate versus pore volume are shown in Figure 5.

System #1: polymer gel (i.e., 0.3%HPAM + 50 mg/L Cr^{3+}, 0.15PV) + PPGs (0.3%, 0.15PV).
System #2: compound system (i.e., 0.2% HPAM + 0.1% PPGs +50 mg/L Cr^{3+}, 0.15PV)
Figure 5. Experimental curves of heterogeneous core flooding with two different solutions.

As shown in Figure 5, with the continuous increase of the injection volume of system solution, the amount of oil expelled from the core is increasing both in 2 systems. At the same time, it can be seen that the oil recovery increases rapidly with the injection volume at the initial stage of injection, and then gradually tends to be stable. Through the comparison of recovery factor, it can be found that the recovery factor of composite system is slightly higher than that of single microspheres and weak gel flooding.

In the process of system #1 treatment, the weak gel was injected after water flooding. Because of low viscosity of bulk solution, weak gel mainly passed through the high-permeability core, leading to a high recovery factor in high-permeability rock and low recovery factor in low-permeability core. After the subsequent injection of microsphere, the microsphere mainly migrates through the low-permeability core, and recovery the crude oil from low-permeability core by its good elasticity. In the process of system #2 treatment, the bulk solution has higher viscosity due to the synergetic effect of HPAM/Cr\(^{3+}\) polymer gel and PPGs. This high viscosity solution can lead to a high oil washing efficiency in high-permeability core samples. After gelation of HPAM/Cr\(^{3+}\) polymer gel system, the injected water mainly migrates along the low permeability channel and drives most of the crude oil in the low permeability core. It finally got a higher recovery factor than system #1 treatment.

4. Conclusion
A series of studies on the PPGs and HPAM/Cr\(^{3+}\) polymer gel systems were carried out through the laboratory flooding experiments. And the main results can be summarized as follows:

(1) The combination of polymer and PPGs shows a good synergetic effect in core flooding experiment, which can be increased by 3% - 8% compared with the single flooding;

(2) According to the heterogeneous core flooding experiment, it is proved that the compound system of PPGs and HPAM/Cr\(^{3+}\) polymer gel systems has better performance on enhancing oil recovery.
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