Experimental Study on Enhanced Oil Recovery Method in Tahe High-Temperature and High-Salinity Channel Sand Reservoir: Combination of Profile Control and Chemical Flooding

Fa-yang Jin,* Qi-hang Li, Yan He, Qiang Luo, and Wan-fen Pu

ABSTRACT: On account of the intralayer and interlayer heterogeneity, high temperature (110 °C), and high salinity (224,919 mg/L) of Tahe channel sand reservoir, single profile control or chemical flooding cannot greatly enhanced oil recovery. The goal of the current research was to optimize a polymer gel formula that was suitable for high-temperature and high-salinity reservoirs, screen an appropriate chemical flooding method, and determine the efficiency of the combination of profile control and chemical flooding. Experimental results indicated that the formed polymer gel could maintain relatively high strength after aging for 30 days. Moreover, the combination of profile control and surfactant flooding could result in an enhanced oil recovery of 17.9%, and the combination of profile control and foam flooding could result in an enhanced oil recovery of 23.0%, which was ascribed to the improvement of sweeping efficiency and displacement efficiency. All the results indicated that the formed polymer gel and the combination of profile control and chemical flooding have great application potential in Tahe high-temperature and high-salinity channel sand reservoir.

1. INTRODUCTION

At present, excess water production and low recovery factor are the main problems faced by Tahe high-temperature (110 °C) and high-salinity (224,919 mg/L, containing 8895 mg/L Ca²⁺ and 821 mg/L Mg²⁺) channel sand reservoir, which are caused by the existence of evident water channeling in the middle of the channel and the difficult activation of remaining oil in both sides of the channel. How to effectively control water production and consolidate oil production is the main task.

Commonly, chemical flooding technologies are applied to water control and oil production boost, such as polymer flooding, surfactant flooding, alkaline flooding, polymer/surfactant (PS) flooding, alkaline/surfactant/polymer (ASP) flooding, and foam flooding. Different chemical flooding technologies are suitable for different reservoir conditions. For example, polymer flooding and polymer-based flooding technologies are applicable in medium–low-temperature and low-salinity reservoirs due to the limited temperature resistance and salt tolerance properties of polymers. Alkaline flooding will cause serious scaling, which will damage low permeability formation. Although foam flooding can be implemented at high-temperature and high-salinity reservoirs, its sealing performance is poor in strong heterogeneity reservoirs, and foam will be output along high permeability channels. Some novel surfactants can effectively improve displacement efficiency under high-temperature and high-salinity reservoirs, while the viscosity of surfactant solution is similar to that of formation water, and channeling occurs during the displacement process under the condition of strong heterogeneity.

To effectively expand sweep efficiency and further enhance oil recovery, polymer gel treatment is proposed to reduce water cut by sealing the thief zone and diverting injection fluid. Many polymer gels are developed including in situ monomer gel, in situ polymer gel, and particle gel. For in situ monomer gel, the initial viscosity of monomer and cross-linker solution is similar to that of formation water, and it can access into the in-depth reservoir theoretically. However, the gelation time is uncontrollable in high-temperature reservoirs for monomer gelation is a free-radical initiated process. Also, the system contains high monomer concentration (4−10%) to maintain gel strength under high-temperature and high-salinity conditions, leading to high operation cost. Moreover, the...
penetration of the system into low permeability causes low permeability formation damage. For in situ polymer gel, since it was proposed by Philips in the 1970s, it has been widely applied for conformance control. The commonly used polymers include polyacrylamide (PAM), partially hydrolyzed polyacrylamide (HPAM), xanthan and guar, and so on. These polymer molecules are connected by cross-linkers to form three-dimensional (3D) networks with a unique liquid-like characteristic on a molecular length scale and liquid-like characteristic on a macroscopic scale. However, due to the single repetitive unit and linear structure of PAM and HPAM, their antishearing properties, temperature tolerance, and salt resistance properties are poor, which may reduce gel strength and even lead to failure of gelation after the system enters into porous media. Due to the biodegradation of xanthan and guar, the long-time stability of gels is poor. The main objective of this study is to prepare a novel anti-high-temperature and high-salinity polymer gel and select a suitable chemical flooding method to improve sweep efficiency and displacement efficiency. First, the functional polymer was optimized according to polymer performances, such as temperature tolerance, salt tolerance, antishearing performance, and gelling properties. Then, the optimal polymer formula was determined according to gel properties. Then, the effect of salinity, temperature, pH, and aging time on gel performance was evaluated. Subsequently, core flooding experiments were conducted to evaluate the effect of profile control combined with chemical flooding on enhanced oil recovery (EOR) under Tahe channel sand reservoir conditions.

2. RESULTS AND DISCUSSION

2.1. Optimization of Gel Formula. 2.1.1. Optimization of Polymer Type. The gel that was prepared using a functional polymer is suitable for high-temperature and high-salinity conditions and has good economic benefits; therefore, it is essential to screen polymers with favorable salt resistance and temperature tolerance properties, antishearing properties, and gelling properties.

2.1.1.1. Temperature Endurance. The temperature endurance of polymers in fresh water is shown in Figure 1. The viscosity of polymer solution decreased with the increase in temperature. For KY-SSH, due to the mutual repulsion between hydrophilic and lipophilic groups, the curl and entanglements among intramolecules and intermolecules weakened, and polymer chains arrayed in a comb shape in aqueous solution, which enhanced the rigidity of molecular chains and regularity of the molecular structure. When the temperature was increased to 95 °C, the viscosity of KY-SSH solution was 285.1 mPa·s with a viscosity retention ratio of 59.9%; the highest viscosity of HY-SSH was ascribed to the highest molecular weight and hydrolysis, while the flexible molecular chains indicated poor temperature tolerance. For polymers that were supplied by the SNF group, the introduction of 2-acrylamido-2-methylpropane sulfonic acid (AMPS) in molecular chains enhanced the molecular hydrodynamic volume at high temperatures, resulting in the enhancement of temperature endurance. Moreover, with the increase in molecular weight, the viscosity of polymer solution increased at high temperatures with higher viscosity retention ratio. AN391 and AN125SH exhibited favorable temperature resistance with viscosity retention values of 70.2 and 70.4%, respectively at 95 °C.

2.1.1.2. Salt Resistance. Brine was prepared by mixing formation water and deionized water in different proportions. The effect of salinity on polymer viscosity is illustrated in Figure 2. With the increase in salinity, viscosity decreased sharply first and then tended to be constant. In deionized water, the repulsive forces among negatively charged polymer chains endowed polymers with favorable thickening ability. With the increase in salinity, the diffused double layer was compressed by metal cations, negative electricity of polymer chains was reduced, and polymer molecules curled to form compact random cluster; thus, polymer solution viscosity was reduced. When salinity was 11 × 10^4 mg/L, AN391 and AN125SH exhibited favorable salt tolerance with viscosity retention values of 12.9 and 12.3%, respectively.

2.1.1.3. Antishearing Performance. The antishearing performance of polymer solution was determined by the change in viscosity after shearing at 3000 rpm for different times using a Wuyin agitator, and the results are shown in Figure 3. When the polymer solution was subjected to mechanical shearing, molecular chains were broken and molecular weight and mechanics volume decreased, resulting in the decrease in solution viscosity. Meanwhile, the longer the shearing time, the greater the loss of polymer viscosity. After comparison, it was found that the viscosity retention ratio of

---

**Figure 1.** Apparent viscosity of polymer as a function of temperature (c = 3000 mg/L).

**Figure 2.** Effect of salinity on viscosity (c = 3000 mg/L).
result are tabulated in Table 2. The strength of gel that formed by formaldehyde and AN125SH was weak and its long-

time stability was poor. After aging for 10 days, the gel strength was reduced to B, which was ascribed to the C–N bonds that formed by the interaction between formaldehyde and acylamino group was easily destroyed at high temperature conditions, resulting in the decrease in gel strength. FQ-1 and FQ-2 not only had part of formaldehyde cross-linking effect but also had a polyhydroxymethyl phenol cross-linking reaction. Moreover, the introduction of benzene ring in gel enhanced covalent bonds’ strength and provided better temperature tolerance than the formaldehyde system. While the phenol content in FQ-1 was higher than that of FQ-2, resulting in better performance of the FQ-1 system than FQ-2. For the FEI system, the gel strength was high, while both of them were dehydrated after 20 days. Ultimately, FQ-1 was optimized as a cross-linker.

2.1.3. Optimization of Polymer Concentration. The AN125SH concentration was optimized under the conditions of a stabilizer concentration of 50 mg/L and FQ-1 concentration of 1000 mg/L, and the results are tabulated in Tables 3 and 4. With the increase in AN125SH concentration, gelation time decreased and gel strength was enhanced. The increase in polymer concentration increased reaction active points, and the more polymer molecules were cross-linked in the same time, macroscopically manifesting the shorter gelation time and stronger gel strength.22 After aging for 60 days, the gel strength slightly decreased while no dehydration

Table 2. Effect of Cross-Linker Type on Gel Strength

| cross-linker type | aging time (day) 0.5 1 2 3 5 10 20 | formaldehyde | FQ-1 | FQ-2 | FEI |
|-------------------|-----------------------------------|-------------|------|------|-----|
|                   |                                   | A           | A    | A    | E   |
|                   |                                   | B           | A    | A    | G   |
|                   |                                   | C           | A    | A    | H   |
|                   |                                   | D           | B    | B    | D   |
|                   |                                   | E           | E    | D    | H   |
|                   |                                   | F           | C    | C    | B   |
|                   |                                   | G           | D    | D    | G   |
|                   |                                   | H           | E    | E    | G   |
|                   |                                   | I           | F    | F    | H   |
|                   |                                   | J           | G    | G    | I   |
|                   |                                   | K           | H    | H    | J   |
|                   |                                   | L           | I    | I    | K   |
|                   |                                   | M           | J    | J    | L   |
|                   |                                   | N           | K    | K    | M   |
|                   |                                   | O           | L    | L    | N   |
|                   |                                   | P           | M    | M    | O   |
|                   |                                   | Q           | N    | N    | P   |
|                   |                                   | R           | O    | O    | Q   |
|                   |                                   | S           | P    | P    | R   |
|                   |                                   | T           | Q    | Q    | S   |
|                   |                                   | U           | R    | R    | T   |
|                   |                                   | V           | S    | S    | U   |
|                   |                                   | W           | T    | T    | V   |
|                   |                                   | X           | U    | U    | W   |
|                   |                                   | Y           | V    | V    | X   |
|                   |                                   | Z           | W    | W    | Y   |
|                   |                                   | A           | X    | X    | Z   |
|                   |                                   | B           | Y    | Y    | A   |
|                   |                                   | C           | Z    | Z    | B   |
|                   |                                   | D           | A    | A    | C   |
|                   |                                   | E           | B    | B    | D   |
|                   |                                   | F           | C    | C    | E   |
|                   |                                   | G           | D    | D    | F   |
|                   |                                   | H           | E    | E    | G   |
|                   |                                   | I           | F    | F    | H   |
|                   |                                   | J           | G    | G    | I   |
|                   |                                   | K           | H    | H    | J   |
|                   |                                   | L           | I    | I    | K   |
|                   |                                   | M           | J    | J    | L   |
|                   |                                   | N           | K    | K    | M   |
|                   |                                   | O           | L    | L    | N   |
|                   |                                   | P           | M    | M    | O   |
|                   |                                   | Q           | N    | N    | P   |
|                   |                                   | R           | O    | O    | Q   |
|                   |                                   | S           | P    | P    | R   |
|                   |                                   | T           | Q    | Q    | S   |
|                   |                                   | U           | R    | R    | T   |
|                   |                                   | V           | S    | S    | U   |
|                   |                                   | W           | T    | T    | V   |
|                   |                                   | X           | U    | U    | W   |
|                   |                                   | Y           | V    | V    | X   |
|                   |                                   | Z           | W    | W    | Y   |
|                   |                                   | A           | X    | X    | Z   |
|                   |                                   | B           | Y    | Y    | A   |
|                   |                                   | C           | Z    | Z    | B   |
|                   |                                   | D           | A    | A    | C   |
|                   |                                   | E           | B    | B    | D   |
|                   |                                   | F           | C    | C    | E   |
|                   |                                   | G           | D    | D    | F   |
|                   |                                   | H           | E    | E    | G   |
|                   |                                   | I           | F    | F    | H   |
|                   |                                   | J           | G    | G    | I   |
|                   |                                   | K           | H    | H    | J   |
|                   |                                   | L           | I    | I    | K   |
|                   |                                   | M           | J    | J    | L   |
|                   |                                   | N           | K    | K    | M   |
|                   |                                   | O           | L    | L    | N   |
|                   |                                   | P           | M    | M    | O   |
|                   |                                   | Q           | N    | N    | P   |
|                   |                                   | R           | O    | O    | Q   |
|                   |                                   | S           | P    | P    | R   |
|                   |                                   | T           | Q    | Q    | S   |
|                   |                                   | U           | R    | R    | T   |
|                   |                                   | V           | S    | S    | U   |
|                   |                                   | W           | T    | T    | V   |
|                   |                                   | X           | U    | U    | W   |
|                   |                                   | Y           | V    | V    | X   |
|                   |                                   | Z           | W    | W    | Y   |
|                   |                                   | A           | X    | X    | Z   |
|                   |                                   | B           | Y    | Y    | A   |
|                   |                                   | C           | Z    | Z    | B   |
|                   |                                   | D           | A    | A    | C   |
|                   |                                   | E           | B    | B    | D   |
|                   |                                   | F           | C    | C    | E   |
|                   |                                   | G           | D    | D    | F   |
|                   |                                   | H           | E    | E    | G   |
|                   |                                   | I           | F    | F    | H   |
|                   |                                   | J           | G    | G    | I   |
|                   |                                   | K           | H    | H    | J   |
|                   |                                   | L           | I    | I    | K   |
|                   |                                   | M           | J    | J    | L   |
|                   |                                   | N           | K    | K    | M   |
|                   |                                   | O           | L    | L    | N   |
|                   |                                   | P           | M    | M    | O   |
|                   |                                   | Q           | N    | N    | P   |
was observed. With the increase in polymer concentration, the decomposition of molecular chains slowed down, resulting in the enhancement of gel stability. In order to realize long-time profile control, 4000−8000 mg/L AS125SH was optimized due to the benign fluidity.

2.1.4. Optimization of Cross-Linker Concentration. Cross-linker concentration was an important evaluation index for gel performance. When cross-linker concentration was too low, the gel strength was too weak and even no cross-linked networks were formed. Meanwhile, the gelation time was too short and even dehydration occurred when the cross-linker concentration was too high. FQ-1 concentration was optimized under the conditions of an AS125SH concentration of 6000 mg/L and stabilizer concentration of 50 mg/L, and the results are shown in Figure 4 and Table 5. With the increase in cross-linker concentration, gelation time shortened and gel strength was enhanced. When the mass ratio of AN125SH and FQ-1 ranged from 3:5−3:4, the gel had benign properties with a gelation time range of 66−72 h and gel strength of 5.3−9.6 Pa.

2.1.5. Optimization of Stabilizer Concentration. Thiourea as a stabilizer could react with oxygen in a system and weaken thermo-oxidative degradation of polymer before the gel was formed; therefore, long-time stability was improved. The optimal stabilizer concentration was determined under the conditions of AN125SH concentration of 6000 mg/L and FQ-1 concentration of 10,000 mg/L, and the results are shown in Figure 5 and Table 6. The addition of stabilizer had no obvious effect on gel strength and gelation time, while it evidently enhanced the gel’s long-time stability at high-temperature and high-salinity conditions. However, when the stabilizer concentration exceeded 200 mg/L, gel strength and long-time stability slightly weakened. Hence, the optimal stabilizer concentration was 50−100 mg/L.

The gel formula was obtained through the above experiments, which included (4000−8000 mg/L) AN125SH + (8000−10,000 mg/L) FQ-1 + (50−100 mg/L) stabilizer. In the following experiments, the gel formula that include 6000 mg/L AN125SH + 8000 mg/L FQ-1 + 50 mg/L stabilizer was applied.

2.2. Properties of Gel.

2.2.1. Effect of Salinity on Gel Performance. Effects of salt type and concentration on gel properties were investigated, and the results are shown in Figure 6. With the increase in metal cation concentration, gel strength weakened and gelation time shortened. Polymer molecules were relatively stretched in low-salinity water, and more cross-linking points could react with the cross-linker, resulting in relatively high strength of the gel. With the increase in metal cation concentration, the double layer of polymer molecules was compressed, and polymer molecules curled, leading to the decrease in cross-linking point that involved in the reaction, increase in gelation time, and decrease in gel strength. Also, the effect of Ca²⁺ on gel performance was more obvious, which was ascribed to the fact that the compress effect of Ca²⁺ on the double layer was stronger than that of Na⁺.

The effect of simulated formation water salinity on gel strength is tabulated in Table 7. When salinity exceeded 11.3 × 10⁵ mg/L, gel was dehydrated after aging for 30 days, and gel was stable after aging for 60 days when salinity was lower than 5.6 × 10⁵ mg/L. The lower the salinity, the more stable the gel.

2.2.2. Effect of Temperature on Gel Performance. The effect of temperature on gel performance was studied and the
results are shown in Figure 7. With the increase in temperature, gelation time evidently shortened, while gel strength was first enhanced and then weakened. As temperature increases, the thermal movement of molecular chains was intensified and the probability of intermolecular collisions was enhanced, leading to the decrease in gelation time.\textsuperscript{24,25} However, the 3D network of the gel would be destroyed at high temperatures, and molecular chains were oxidized and broken, resulting in the drop in gel strength.

**2.2.3. Effect of pH on Gel Performance.** The effect of pH on gel performance was investigated, and the results are shown in Table 8. With the increase in pH, gelation time decreased, while gel strength increased first and then decreased. Also, when the pH value was above 9, gel was not formed. The stability of gel that formed under strong acid conditions was poor for the formation of thermoplastic resin, which reacted with the acylamino group and formed a linear cross-linking structure with the characteristics of high strength and crispness. Under alkaline conditions, polymers underwent severe hydrolysis.\textsuperscript{15,26,27} With the increase in hydrolysis degree, amide groups that were involved in the reactions decreased, leading to the decrease in gel strength and even nongelling.

**2.2.4. Long-Time Stability.** The changes in gel strength in high-temperature and high-salinity conditions are illustrated in Figure 8. With the extension of aging time, gel strength decreased to 2.0 Pa after aging for 80 days. As shown in Figure 9, after aging for 80 days, the strength was maintained at F.

![Figure 6. Effect of salinity on gel properties.](image1)

![Figure 7. Effect of temperature on gel properties.](image2)

![Figure 8. Long-time stability of the gel.](image3)

**Table 7. Effect of Salinity on Gel Strength**

| simulated formation water (× 10⁴ mg/L) | aging time (day) |
|---------------------------------------|------------------|
|                                       | 1    | 2    | 3    | 5    | 10   | 30   | 60   |
| 0                                    | A    | C^-  | D    | H    | H    | G    |      |
| 0.56                                 | A    | B    | C^-  | H    | H    | G    | F    |
| 1.13                                 | A    | B    | C    | H    | H    | G    | F    |
| 2.50                                 | A    | B    | C    | H    | H    | G    | E    |
| 5.60                                 | A    | B    | B^-  | G    | G    | E^-  |      |
| 11.3                                 | A    | A    | B    | F    | E    |      |      |
| 22.5                                 | A    | A    | B^-  | B    | D    |      |      |

**Table 8. Effect of pH on Gel Properties**

| pH value | gelation time (h) | gel strength (Pa) | gel strength after aging 30 days (Pa) |
|----------|-------------------|-------------------|--------------------------------------|
| 4        | 90                | 4.0               | 0.8                                  |
| 5        | 85                | 4.6               | 3.0                                  |
| 6        | 73                | 5.8               | 4.2                                  |
| 7        | 68                | 5.0               | 3.1                                  |
| 8        | 60                | 4.6               | 2.8                                  |
| 9        |                   |                   |                                      |
2.3. Microstructure. The microstructure of the gel, which was aged for 5 days, is shown in Figure 10. It could be observed that the evident network structure was formed. As shown in Figure 10a, the network was compact with thick backbone. After the microstructure was further magnified, it was found that salt particles adsorbed on the skeleton of networks. Moreover, a "spider web" network was covered on the skeleton, which evidently increased the network structure density. The dual network structure endowed the gel with favorable stability in high-temperature and high-salinity conditions (Figure 10b).

2.4. Profile Control Combined with Chemical Flooding Experiments. 2.4.1. Profile Control Performance of the Gel. The profile control performance of the gel is shown in Figure 11. In water flooding development, 66.21% of crude oil was recovered, which was produced from the high-permeability zone in the second layer and third layer. During gel injection, the gel preferentially entered into the high-permeability zone of the second layer and part of gel entered into the high-permeability zone of the third layer. In subsequent water flooding, injection water entered the third layer and activated the low-permeability zone first and then entered into high-permeability zone of the second and third layers with an enhanced oil recovery of 13.09%.

2.4.2. Combination of Gel Treatment and Chemical Flooding. For foam flooding, 3000 mg/L AOS was used as a foaming agent and 1000 mg/L KY-5SH was employed as a foam stabilizer with a gas–liquid ratio of 2:1. The initial foam volume was 620 mL and the foam half-life time was 14 min; the interfacial tension (IFT) between crude oil and AOS/KY-SSH solution was 0.29 mN/m. For surfactant flooding, the IFT between crude oil and KPS solution was 0.036 mN/m. The changes in water cut and oil recovery during the displacement process are depicted in Figures 12 and 13. During water flooding, 62.4–64.4% of crude oil was recovered. After the profile control was implemented, 4.5–4.8% of oil recovery was enhanced, which was ascribed to the plugging of high-permeability zone in the second layer and the activation of crude oil in the high-permeability zone in the third layer. For surfactant flooding, when the surfactant solution bypassed the plugging, it entered into the high-permeability layer again due to the viscosity of surfactant solution was similar to that of formation water, and the seepage resistance of the high-permeability layer was the lowest. Nonetheless, 8.5% of oil recovery was produced, which was ascribed to the enhancement of displacement efficiency due to the low IFT. For foam flooding, after foam was injected, it entered into high-

2.4. Profile Control Combined with Chemical Flooding Experiments. 2.4.1. Profile Control Performance of the Gel. The profile control performance of the gel is shown in Figure 11. In water flooding development, 66.21% of crude oil was recovered, which was produced from the high-permeability zone in the second layer and third layer. During gel injection, the gel preferentially entered into the high-permeability zone of the second layer and part of gel entered into the high-permeability zone of the third layer. In subsequent water flooding, injection water entered the third layer and activated the low-permeability zone first and then entered into high-permeability zone of the second and third layers with an enhanced oil recovery of 13.09%.

2.4.2. Combination of Gel Treatment and Chemical Flooding. For foam flooding, 3000 mg/L AOS was used as a foaming agent and 1000 mg/L KY-5SH was employed as a foam stabilizer with a gas–liquid ratio of 2:1. The initial foam volume was 620 mL and the foam half-life time was 14 min; the interfacial tension (IFT) between crude oil and AOS/KY-SSH solution was 0.29 mN/m. For surfactant flooding, the IFT between crude oil and KPS solution was 0.036 mN/m. The changes in water cut and oil recovery during the displacement process are depicted in Figures 12 and 13. During water flooding, 62.4–64.4% of crude oil was recovered. After the profile control was implemented, 4.5–4.8% of oil recovery was enhanced, which was ascribed to the plugging of high-permeability zone in the second layer and the activation of crude oil in the high-permeability zone in the third layer. For surfactant flooding, when the surfactant solution bypassed the plugging, it entered into the high-permeability layer again due to the viscosity of surfactant solution was similar to that of formation water, and the seepage resistance of the high-permeability layer was the lowest. Nonetheless, 8.5% of oil recovery was produced, which was ascribed to the enhancement of displacement efficiency due to the low IFT. For foam flooding, after foam was injected, it entered into high-

Figure 9. Images of gel.

Figure 10. Microstructure of the gel: (a) network with thick backbone; (b) dual network.

Figure 11. Profile control performance of the gel.

Figure 12. Oil recovery of gel treatment combined with surfactant flooding.
permeability zone in the third layer first and then part of foam entered into the high-permeability zone in the second layer; during the subsequent water flooding, the foam migrated into in-depth of the model and control profile, the first layer were activated, and ultimately, 12.4% of oil recovery was boosted.

3. CONCLUSIONS

A novel polymer gel was formed, and a combination of profile control and chemical flooding was systemically studied in this study. The novel polymer gel could maintain relatively high strength at high-temperature and high-salinity reservoir conditions, and the combination technology could sufficiently improve heterogeneity. The profile control ability of gel in the high-permeability layer and foam in the high-/middle-permeability layer synergistically adjusted the profile, resulting in the expansion of sweep volume. Moreover, the reduction in IFT synergistically enhanced displacement efficiency. Based on the experimental results, the following conclusions were drawn.

(1) Gel formula was optimized and the formula contained: (4000−8000 mg/L) AN125SH + (8000−10,000 mg/L) FQ-1 + (50−100 mg/L) stabilizer.

(2) Single profile control and subsequent water flooding could result in an enhance oil recovery of 13.09%; the combination of profile control and surfactant flooding and the combination of profile control and foam flooding could result in enhanced oil recovery values of 17.9 and 23.0%, respectively. For the reservoir where intralayer and interlayer heterogeneity were contemporarily existing, the synergistic effect of profile control and in-depth profile modification and flooding had better displacement efficiency for the improvement of sweeping efficiency and displacement efficiency.

4. EXPERIMENTAL SECTION

4.1. Chemicals and Fluids. Petroleum sulfonate (KPS) and five types of industrial polymers were supplied by Northwest Bureau of Sinopec (Urumchi, China), and the detailed parameters are tabulated in Table 9. Formaldehyde, polyethyleneimine (PEI), thiourea, sodium α-olefin sulfonate (AOS), sodium hydroxide, and phenol were purchased from Chengdu Kelong Chemical Reagents Corporation (Chengdu, China).

Crude oil with a viscosity of 22.5 mPa·s at reservoir temperature and formation water were obtained from Tahe channel sand reservoir (Xinjiang, China). The properties of formation water are tabulated in Table 10.

4.2. Preparation of Cross-Linker. 4.2.1. Preparation of Cross-Linkers 1 and 2 (FQ-1 and FQ-2). FQ-1 (FQ-2) was prepared by mixing 1.158 g of phenol with 10.0 (6.67) g of formaldehyde solution (mass concentration, 37%) at ambient

Table 9. Detailed Parameters of Industrial Polymers

| polymer sample | molecular weight \((\times 10^9 \text{ g/mol})\) | hydrolysis degree (%) | features | manufacture |
|----------------|---------------------------------|-----------------------|----------|-------------|
| KY-5SH         | 19                              | 30                    | comb-shaped | Beijing Hengju Group Co., Ltd. |
| AN391          | 12                              | 20                    | sulfonate group | SNF Group |
| AN12SSH        | 0.8                             | 25                    | sulfonate group | SNF Group |
| AN191          | 0.5                             | 25                    | sulfonate group | SNF Group |
| SAV522         | 0.4                             | 25                    | sulfonate group | SNF Group |
temperature under stirring. After 1 h, FQ-1 and FQ-2 were obtained.

4.3. Optimization of Gel Formula. 4.3.1. Preparation of Polymer Stock Solution. Polymer stock solution was prepared by adding 1.0 g of polymer powder particles into 200 mL of deionized water or formation water under stirring condition. After 2 h, homogeneous polymer stock solution was obtained. 

4.3.2. Optimization of Gel Formula. First, cross-linker and stabilizer were added into deionized water or formation water at ambient temperature. Then, polymer stock solution was added into the system under stirring condition until the solution was uniform. Subsequently, the solution was heated to 110 °C in a high-temperature oven. The gel formula was optimized according to gel strength, rheological and bottle methods were employed to measure gel strength. Gel strength in the rheological method was denoted as the elastic modulus that was measured by an Anton Paar MCR302 rheometer. Gel strength in the bottle method was expressed as an alphabetic code of A through I, which is shown in Table 11.28,29

| alphabetic code | description |
|-----------------|-------------|
| A               | The viscosity of gel is similar to that of polymer solution, and nondetectable gel is formed |
| B               | The viscosity of gel is slightly higher than that of polymer solution |
| C               | Most of the gel flows to the other end of the bottle when the bottle is turned over |
| D               | A small portion (5−10%) of the gel cannot flow to the bottle end by gravity upon inversion (tonguing shaped) |
| E               | A significant portion of gel cannot flow by gravity upon inversion |
| F               | The gel does not flow to the bottle end by gravity upon inversion |
| G               | The gel can flow to the middle of bottle by gravity upon inversion |
| H               | Only the surface of gel slightly deforms by gravity upon inversion |
| I               | No deformation occurs by gravity upon inversion |

4.4. Microstructure of Gel. The microstructure of gel was observed using a Quanta 200 FEI environmental scanning electron microscope (ESEM).

4.5. Three-Dimensional Model Displacement Experiments. A three-dimensional plate model was designed and assembled with a length of 14.4 cm, width of 14.4 cm, and height of 10.5 cm, as shown in Figure 14. The experimental procedures were as follows. (1) In the middle of the model, three different permeability layers (80 mD, 800 mD, and 300 mD) were prepared by filling quartz sand with sizes of 140–200, 20–40, and 80–100 mesh, respectively. The low-permeability areas on both sides of the model were filled with quartz sand with a size of 140200 mesh. The thickness of each layer was 3.5 cm. (2) The model was saturated with formation water by injecting formation water from wells #1, #2, and #5 and outputting from well #3. (3) Crude oil was injected into the model from wells #1, #2, and #5 and produced from well #3 to establish original oil saturation. (4) Water flooding (WF) was conducted by injecting water from well #1 and producing from #4 until the water cut reached to 98%. (5) A 0.3 PV gel system was injected (the injection volume was referred to the literature30), and it was placed for 24 h.30 (6) If chemical flooding would not be conducted, subsequent water flooding would be conducted, and if chemical flooding would be conducted, chemical flooding would be conducted followed by subsequent water flooding, such as foam flooding and surfactant flooding. All the displacement experiments were carried out with an injection rate of 0.5 mL/min and temperature of 110 °C.

**AUTHOR INFORMATION**

**Corresponding Author**

Fa-yang Jin — State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu, Sichuan 610500, People’s Republic of China; Email: jfy975@swpu.edu.cn

**Authors**

Qi-hang Li — State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu, Sichuan 610500, People’s Republic of China; https://orcid.org/0000-0002-3835-0693

Yi He — Data Centre of Xinjiang Oilfield Company, PetroChina, Xinjiang Oilfield Company, Karamay, Xinjiang 834000, People’s Republic of China

Qiang Luo — Research Institute of Experiment and Detection, PetroChina, Xinjiang Oilfield Company, Karamay, Xinjiang 834000, People’s Republic of China

Wen-fen Pu — State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu, Sichuan 610500, People’s Republic of China

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.9b03306

**Notes**

The authors declare no competing financial interest.
ACKNOWLEDGMENTS

This study was supported by Sichuan Science and Technology Program (2019YFG0148).

REFERENCES

(1) Bai, B.; Zhou, J.; Yin, M. A comprehensive review of polyacrylamide polymer gel for conformance control. Pet. Explor. Dev. 2015, 42, 525–532.
(2) Liu, R.; Du, D.-j.; Pu, W.-f.; Zhang, J.; Fan, X.-b. Enhanced oil recovery potential of alkyl alcohol polyoxyethylene ether sulfonate surfactants in high-temperature and high-salinity reservoirs. Energy Fuels 2018, 32, 12108–12140.
(3) Rishinézhad, M.; Romero-Zerón, L.; McManus, N.; Penlidis, A. Evaluating the performance of tailor-made water-soluble copolymers for enhanced oil recovery polymer flooding applications. Fuel 2017, 203, 269–278.
(4) Liu, Y.; Zhou, C.; Hou, H.; Li, H.; Gao, M.; Zhao, G.; Dai, C. Novel chemical flooding system based on dispersed particle gel coupling in-depth profile control and high efficient oil displacement. Energy Fuels 2019, 33, 3123–3132.
(5) Stoll, W. M.; AL Shureeqi, H.; Finol, J.; Al-Harthy, S. A. A.; Oyemakinde, S.; De Kruifj, A.; Van Wunnik, J.; Arkestjeijn, F.; Bouwmeester, R.; Faber, M. J. Alkaline/surfactant/polymer flood: from the laboratory to the field. SPE Reserv. Eval. Eng. 2011, 14, 702–712.
(6) Zou, C.; Zhao, P.; Hu, X.; Yan, X.; Zhang, Y.; Wang, X.; Song, R.; Luo, P. β-Cyclodextrin-functionalized hydrophobically associating acrylamide copolymer for enhanced oil recovery. Energy Fuels 2013, 27, 2827–2834.
(7) Bataweel, M. A.; Nasr-El-Din, H. A. Minimizing scale precipitation in carbonate cores caused by alkalis in ASP flooding in high salinity/high temperature applications. In SPE International Symposium on Oilfield Chemistry; Society of Petroleum Engineers: The Woodlands, Texas, USA, 2011; p 15.
(8) Du, D.-j.; Pu, W.-f.; Tan, X.; Liu, R. Experimental study of secondary crosslinking core-shell branched associative polymer gel and its profile control performance in low-temperature fractured conglomerate reservoir. J. Pet. Sci. Eng. 2019, 179, 912–920.
(9) You, Q.; Wen, Q.; Fang, J.; Guo, M.; Zhang, Q.; Dai, C. Experimental study on lateral flooding for enhanced oil recovery in bottom-water reservoir with high water cut. J. Pet. Sci. Eng. 2019, 174, 747–756.
(10) Bai, Y.; Wei, F.; Xiong, C.; Li, J.; Jiang, B.; Xu, H.; Shu, Y. Effects of fracture and matrix on propagation behavior and water shut-off performance of a polymer gel. Energy Fuels 2015, 29, 5534–5543.
(11) Goudarzi, A.; Zhang, H.; Varavei, A.; Taksadoum, P.; Hu, Y.; Delshad, M.; Bai, B.; Sepehrnoori, K. A laboratory and simulation study of preformed particle gel for water conformance control. Fuel 2015, 140, 502–513.
(12) Zhao, J.-z.; Jia, H.; Pu, W.-f.; Liao, R. Influences of fracture aperture on the water-shutoff performance of polyethyleneimine cross-linking partially hydrolyzed polyacrylamide gels in hydraulic fractured reservoirs. Energy Fuels 2011, 25, 2616–2624.
(13) Zhang, Y.; Gao, M.; You, Q.; Fan, H.; Li, W.; Liu, Y.; Fang, J.; Zhao, G.; Jin, Z.; Dai, C. Smart mobility control agent for enhanced oil recovery during CO2 flooding in ultra-low permeability reservoirs. Fuel 2019, 241, 442–450.
(14) Liu, Y.; Dai, C.; Wang, K.; Zhao, M.; Gao, M.; Yang, Z.; Fang, J.; Wu, Y. Investigation on preparation and profile control mechanisms of the dispersed particle gels (DPG) formed from phenol-formaldehyde cross-linked polymer gel. Ind. Eng. Chem. Res. 2016, 55, 6284–6292.
(15) Liu, Y.; Dai, C.; Wang, K.; Zou, C.; Gao, M.; Fang, Y.; Zhao, M.; Wu, Y.; You, Q. Study on a novel cross-linked polymer gel strengthened with silica nanoparticles. Energy Fuels 2017, 31, 9152–9161.
(16) Needham, R. B.; Threlkeld, C. B.; Gall, J. W. Control of water mobility using polymers and multivalent cations. In SPE Improved Oil Recovery Symposium; Society of Petroleum Engineers: Tulsa, Oklahoma; 1974; p 10.
(17) Gou, S.; Luo, S.; Liu, T.; Zhao, P.; He, Y.; Pan, Q.; Guo, Q. A novel water-soluble hydrophobically associating polyacrylamide based on oleic imidazoline and sulfonate for enhanced oil recovery. New J. Chem. 2015, 39, 7805–7814.
(18) Zhao, T.; Xing, J.; Dong, Z.; Tang, Y.; Pu, W. Synthesis of polyacrylamide with superb salt-thickening performance. Ind. Eng. Chem. Res. 2015, 54, 10568–10574.
(19) Pu, W.; Jiang, F.; He, Y.; Wei, B.; Tang, Y. Synthesis of a novel comb micro-block hydrophobically associating copolymer for Ca2+/Mg2+ resistance. RSC Adv. 2016, 6, 43634–43637.
(20) Jiang, F.; Pu, W.; Li, Y.; Du, D. A double-tailed acrylamide hydrophobically associating polymer: Synthesis, characterization, and solution properties. J. Appl. Polym. Sci. 2015, 132, 45269.
(21) Kamal, M. S.; Sultan, A. S.; Al-Mubaiyedh, U. A.; Hussein, I. A. Review on polymer flooding: rheology, adsorption, stability, and field applications of various polymer systems. Polym. Res. 2015, 55, 491–530.
(22) Dai, C.; Zhao, G.; You, Q.; Zhao, M. A study on environment-friendly polymer gel for water shut-off treatments in low-temperature reservoirs. J. Appl. Polym. Sci. 2014, 131, 40154.
(23) Zhao, G.; Dai, C.; Chen, A.; Yan, Z.; Zhao, M. Experimental study and application of gels formed by nonionic polyacrylamide and phenolic resin for in-depth profile control. J. Pet. Sci. Eng. 2015, 135, 552–560.
(24) He, H.; Wang, Y.; Qi, Z.; Sun, X. Gelation performance and feasibility study of an environmental friendly improved inorganic aluminum gel for conformance control under harsh reservoir conditions. J. Energy Resour. Technol. 2017, 139, No. 012911.
(25) Zhu, D.; Bai, B.; Hou, J. Polymer gel systems for water management in high-temperature petroleum reservoirs: a chemical review. Energy Fuels 2017, 31, 13063–13087.
(26) Sengupta, B.; Sharma, V. P.; Udayabhanu, G. Gelation studies of an organically cross-linked polyacrylamide water shut-off gel system at different temperatures and pH. J. Pet. Sci. Eng. 2012, 81, 145–150.
(27) Sengupta, B.; Sharma, V. P.; Udayabhanu, G. A. Study of the Effect of the Concentration of Constituents on the Characteristics of a Cross-Linked Polyacrylamide Gel. Pet. Sci. Technol. 2012, 30, 1865–1881.
(28) Reddy, B. R.; Eoff, L.; Dalrymple, E. D.; Black, K.; Brown, D.; Rietjens, M. A natural polymer-based cross-linker system for conformance gel systems. SPE J. 2003, 8, 99–106.
(29) Vasquez, J.; Dalrymple, E. D.; Eoff, L.; Reddy, B. R.; Civian, F. Development and evaluation of high-temperature conformance polymer systems. In SPE International Symposium on Oilfield Chemistry: Society of Petroleum Engineers: The Woodlands, Texas, 2005; p 16.
(30) Chen, L.; Wang, J.; Yu, L.; Zhang, Q.; Fu, M.; Zhao, Z.; Zuo, J. Experimental investigation on the nanosilica-reinforcing polyacrylamide/polyethyleneimine hydrogel for water shutoff treatment. Energy Fuels 2018, 32, 6650–6656.