

Research Article

Experimental Investigation on a Novel Particle Polymer for Enhanced Oil Recovery in High Temperature and High Salinity Reservoirs

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Conventional polymer flooding include polymer flooding, surfactant-polymer flooding (SP), alkaline-surfactant-polymer flooding (ASP), and crosslinked polymer gel flooding. However, these technologies in oilfield, especially in high temperature and high salinity, are limited due to the poor ability of temperature and salinity resistance of polymer. In this work, a novel polymer particle (soft microgel, SMG) is used as the research object under the reservoir condition of high salinity (20×10^4 mg/L) to evaluate the physical and chemical properties of submillimeter-scale SMG and the effect of profile control and oil displacement. The investigation of the physical and chemical properties of submillimeter-scale SMG shows that it has the characteristics of low viscosity, easy injection, good plugging property, swelling property, rheological property, and excellent thermal stability. After 6 months of high temperature and high salinity aging, there is no hydration and hydrolysis of submillimeter-scale SMG as the traditional polymers under high temperature and high salinity. The parallel two-core flooding experiments indicate that the submillimeter-scale SMG has a better effect of profile control and oil displacement, which increases the fraction flow rate (f_w) of low-permeability core from 5.12% before SMG-flooding to 85.29% and the total increase of recovery as high as 14.07%. The comprehensive analysis demonstrates that the submillimeter-scale SMG has the potential to solve the problem that the polymer flooding cannot be applied to the high temperature and high salinity reservoir, and it is also expected to improve the uneven waterflooding in the reservoir.

1. Introduction

Conventional and mature EOR technologies based primarily on polymer (HPAM) include polymer flooding, surfactant-polymer flooding (SP), alkaline-surfactant-polymer flooding (ASP), and crosslinked polymer gel flooding. These technologies have achieved significant success worldwide [1–9]. However, the temperature and salinity resistance of the polymer is limited, and as a continuous phase high viscosity fluid, its mechanism of oil displacement is also contradictory [10–17]. Over the years, many researchers have carried out a lot of studies aiming at these problems, such as the

development of thermo-resistant and salt-resistant monomer copolymer, comb polyacrylamide polymer, and hydrophobic association polymer. The temperature resistance and salinity resistance of these polymers have been improved to some extent, but these problems have not been solved fundamentally. Therefore, the application of polymer flooding is limited in high temperature and high salinity oilfield.

Given the problems for traditional polymer, Wu et al. proposed the theory of targeting oil displacement by water dispersion system, established the waterflooding sweep control technology, and developed the corresponding novel

particle polymer dispersion system (soft microgel, SMG) [10–12, 16, 17]. SMG can be prepared from acrylamide, 2-acrylamide-2-methylpropylsulfonic acid, and self-made polymerizable temperature-resistant monomer by reversed-phase microemulsion polymerization, reversed-phase emulsion polymerization, and reversed-phase suspension polymerization. It can be divided into nanoscale SMG, microscale SMG, and submillimeter-scale SMG. In particular, SMG has the characteristic of swelling only in aqueous solution. Furthermore, it has the strong ability to resist temperature resistance and salinity. Up to now, water-flooding sweep control technology based on SMG has not only achieved good results in many sandstone and conglomerate oilfields in China but also achieved remarkable success in a carbonate oilfield in the Middle East [17–24].

Conventional polymer flooding in oilfield is limited for poor resistance ability of polymer under high temperature and high salinity reservoir conditions. In order to address this application challenge, in this work, a novel particle polymer (soft microgel, SMG) was used as the research object to evaluate the physical and chemical properties of submillimeter-scale SMG and the effect of profile control and oil displacement under high temperature and high salinity. Through these investigations, we strive to provide more meaningful guidance for submillimeter-scale SMG performance optimization and improve the application of polymer flooding in oilfield with high temperature and high salinity.

2. Materials and Methods

2.1. Experimental Materials. The novel particle polymer solution, the concentration of 99.95%, is provided by RIPED (Research Institute of Petroleum Exploration and Development, CNPC, Beijing, China). According to the oilfield water quality table, the simulated formation brine with salinity of 20×10^4 mg/L can be prepared, in which the concentration of Ca^{2+} and Mg^{2+} is close to 2×10^4 mg/L. Artificial sandstones: 38 mm in diameter and 7 cm in length.

2.2. Preparation of SMG Dry Powder. The SMG solution is added into a beaker of alcohol with the concentration of 99.7% while stirring with a glass rod to make the SMG into full contact with the alcohol. And then, the separable solid of SMG is extracted by repeatedly filtering and washing. Then, the extracted separable solid of SMG is placed in an oven at 60°C for 5 hours to obtain SMG dry powder.

2.3. Preparation of SMG Aqueous Solution. The SMG aqueous solution with a concentration of 3000 mg/L can be prepared by adding simulated formation brine with a salinity of 20×10^4 mg/L to SMG solution. And then, ultrasonic dispersion of the SMG aqueous solution is carried out to make it full swelling.

2.4. Swelling Property Measurement of SMG. SEM (scanning electron microscope) is used to observe the morphology of

dry SMG powder, and the average particle size of SMG in the original state is statistically obtained, which was taken as the initial median particle size (D_0) of unhydrated swelling SMG. The particle size of SMG aqueous solution with 3000 mg/L concentration is measured regularly using the laser particle size analyzer. The measurement intervals are 1 day, 3 days, 5 days, 7 days, 10 days, and 15 days, respectively.

2.5. Rheological Property Measurement of SMG. HAAKE RS600 was used to determine the viscosity of SMG aqueous solution with a concentration of 3000 mg/L at different temperatures and shear rates. The determination temperatures are 25°C , 40°C , 60°C , and 80°C , respectively.

2.6. Thermal Stability Property Measurement of SMG. High-concentration (5×10^4 mg/L) SMG aqueous solution is prepared with simulated formation brine and then loaded into high temperature and high pressure aging tanks and placed in a 130°C constant temperature oven. After 1 month, 3 months, and 6 months, they are taken out to observe the change and evaluate the thermal stability property. The reason why high-concentration SMG aqueous solution is chosen here is to conduct better observation and study.

2.7. Plugging Property Measurement of SMG. The artificial sandstone core (2000 mD) is successively dried, vacuumed, saturated simulated the formation of brine, and permeability was measured. Subsequently, the plugging property of SMG aqueous solution with a concentration of 3000 mg/L is tested. The SMG aqueous solution is prepared with simulated formation brine with a salinity of 20×10^4 mg/L. The specific operation steps are as follows: (1) *primary waterflooding*: brine is injected into the artificial sandstone rock core until the pressure is stable; (2) *SMG-flooding*: 3 times the pore volume of the SMG aqueous solution is injected into the core; (3) *subsequent waterflooding*: 6 times the pore volume (PV) of the brine is injected into the core. In particular, the experimental displacement rate is 1 ml/min. The pressures at end of primary waterflooding, SMG-flooding, and subsequent waterflooding are P_1 , P_2 , and P_3 , respectively. The resistance factor (F_R) and residual resistance factor (F_{RR}) can be calculated by

$$F_R = \frac{P_2}{P_1}, \quad (1)$$

$$F_{RR} = \frac{P_3}{P_1}. \quad (2)$$

2.8. Parallel Two-Core Flooding Experiment. The artificial sandstone cores (1000 mD and 3000 mD) are successively dried, vacuumed, saturated, simulated the formation of brine, and permeability was measured. Subsequently, these cores are saturated with crude oil from Bohai oilfield and aged for 48h. When the water-cut of the produced liquid of high-permeability (PH) core reaches 98% or above, the SMG

aqueous solution treated as shown Section 2.3 of this paper is injected into the cores. The pore volume multiple injected of SMG aqueous solution is 1. And then, subsequent waterflooding was carried out. The standard at the end of the experiment is that the water-cut of the total produced liquid in the subsequent waterflooding stage reached 98% or above for 5 consecutive points. The experimental displacement rate is 1 ml/min. The experimental results are shown in Tables 1 and 2 and Figures 1 and 2.

3. Results and Discussion

3.1. Swelling Property. As shown in Figure 3, SMG dry powder is a regular spherical shape under SEM (scanning electron microscope), with an initial median particle size (D_0) of $11.39\ \mu\text{m}$. As shown in Figure 4, SMG can swell in aqueous solution by absorbing water, and the particle size of SMG gradually increased with the hydration time. After 10 days of hydration expansion, the particle size tends to be constant, ranging from 15.233 to $70.315\ \mu\text{m}$, and the median particle size is $35.192\ \mu\text{m}$. The test results show that SMG has excellent salinity resistance and hydration expansion performance even high salinity, and the expansion multiple is about 6.

3.2. Rheological Property. As shown in Figure 5, submillimeter-scale SMG is characterized by low viscosity and shear resistance, with a viscosity of only $0.8\sim 2.6\ \text{mPa}\cdot\text{s}$. The apparent viscosity fluctuates slightly when the shear rate is $1\sim 100\ \text{s}^{-1}$; when shear rate is $100\sim 600\ \text{s}^{-1}$, the apparent viscosity keeps stable, showing Newtonian fluid feature to some extent. In addition, at high temperature and high shear rate, SMG viscosity tends to be stable and close to water, with lower flow resistance than traditional polymers and easier to flow in the reservoir.

3.3. Thermal Stability Property. The aqueous solution of SMG before aging is a milky white liquid in Figure 6. After aging, the total liquid amount of aging tank is basically the same as before aging, without loss of liquid amount. The upper part is floating with a large cylindrical solid formed by the consolidation of SMG effective components and mineral salts in water under high temperature and salinity, and the lower part is aqueous solution, as shown in the Figure 7. Furthermore, these large cylindrical solids are soft in texture and can be lightly crushed with glass rods. This study shows that SMG has excellent temperature and salinity resistance and can exist stably at high temperature and salinity, without the hydrolysis and hydration reaction of traditional polymer at high temperature and salinity.

3.4. Plugging Property. The experiment results of SMG plugging performance are shown in Figure 8. During SMG-flooding, SMG particles gradually block the pore throat in the core with the injection of SMG aqueous solution, which can be explained by changes in injection pressure. In

addition, the pressure increases sharply as the SMG aqueous solution continues to be injected after injection of approximately 1PV. What is noticeable is that when the injection volume is close to 3PV, the injection pressure drops significantly, which is due to the partial expulsion of SMG trapped in the core in the early stage.

The pressure of subsequent waterflooding is characterized by a slight rise in stability. And, the repeated fluctuation of the pressure reflects the characteristics of repeated temporary plugging and broken migration of SMG in the cores. F_R and F_{RR} are 147 and 126, respectively, and the value of these parameters is positively correlated with the amount of SMG aqueous solution injected.

3.5. Effect of Profile Control and Oil Displacement. The results of parallel two-core flooding experiment are shown in Tables 1 and 2 and Figures 1 and 2.

3.5.1. Primary Waterflooding. With the injection of simulated formation brine, the injection pressure increases gradually and the recovery rate increases gradually. Subsequently, the water-cut increases rapidly, while the injected pressure gradually decreases and tends to be stable due to the breakthrough of waterflooding. When the injection volume reaches about 0.85PV, the water-cut of the high-permeability core reaches 98%. And then, SMG aqueous solution is injected when the water-cut of high-permeability core is maintained at 98% or above for 5 consecutive points.

3.5.2. SMG-Flooding. SMG continuously transports and accumulates in the core with the injection of SMG aqueous solution. When the injection pore volume is greater than 0.3PV, the injection pressure gradually increases, while the water-cut decreases significantly, from 94.87% in the primary waterflooding stage to 64.28%, with the maximum reduction of water-cut reaching 30.59%. Furthermore, it can also be seen from Figure 2 that fraction flow rate of low-permeability (LP) core had also been significantly improved, from 5.12% in the primary waterflooding stage to 85.29%, an increase of 80.17%.

3.5.3. Subsequent Waterflooding. The injected pressure fluctuates slightly with the injection of brine due to the continuous temporary plugging and breakthrough of SMG in the cores. At the same time, the low-permeability core still has a high fraction flow rate of $70\%\sim 88\%$, and the recovery rate of parallel two-core still keeps a small increase.

The experimental results demonstrate that submillimeter-scale SMG has a better effect of profile control and oil displacement. It can reduce water-cut, improve the fraction flow rate of low-permeability core which will be benefit to expand the swept volume of waterflooding, and thereby increase the recovery factor. The increment of recovery (SMG-flooding + subsequent waterflooding) is as high as 14.07%.

TABLE 1: Oil displacement effect of submillimeter-scale SMG aqueous solution.

Core number	Porosity (%)	K (mD)		SMG injected concentration (mg/L)	Soi (%)	Primary waterflooding recovery (%)	PV _{SMG}	SMG recovery increment (%)	Subsequent waterflooding recovery incremental (%)	Recovery (%)	Recovery increment (%)
		Ka	Kw								
6-9 (LP)	28.76	985	526	3000	71.79	19.93	1	30.05	9.50	58.58	14.07
7-15 (HP)	30.66	2958	1348		75.51	50.27		0.65	0.28	51.20	

TABLE 2: Profile control (fraction flow rate, f_w) effect of submillimeter-scale SMG aqueous solution.

Core number	Primary waterflooding (%)	SMG-flooding (%)	Subsequent waterflooding (%)
6-9 (LP)	5.13	84.85	82.35
7-15 (HP)	94.87	15.15	17.65

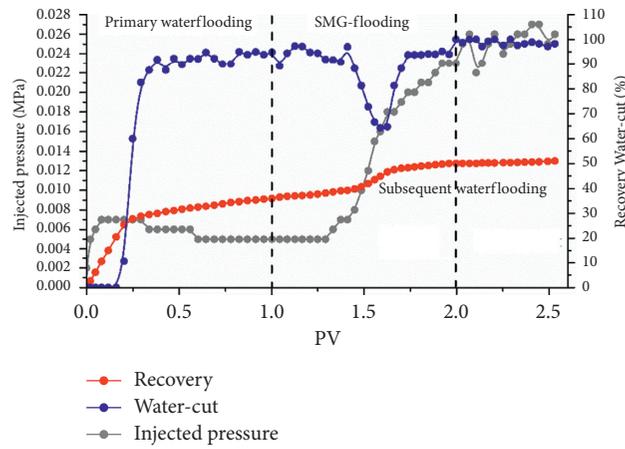


FIGURE 1: The relation curve of recovery, water-cut, and injected pressure with the increase of injection pore volume.

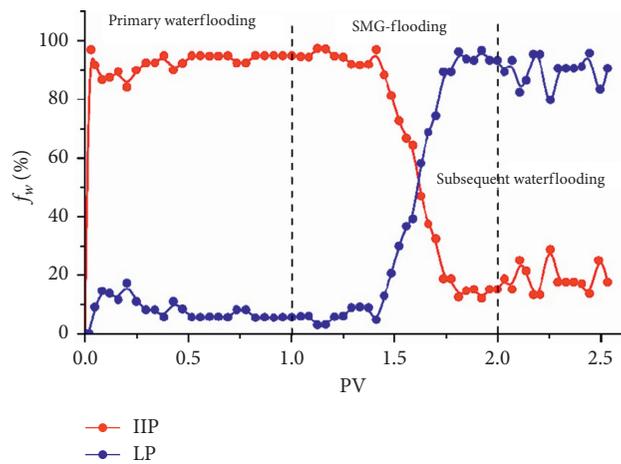


FIGURE 2: The curve of profile control (fraction flow rate, f_w).

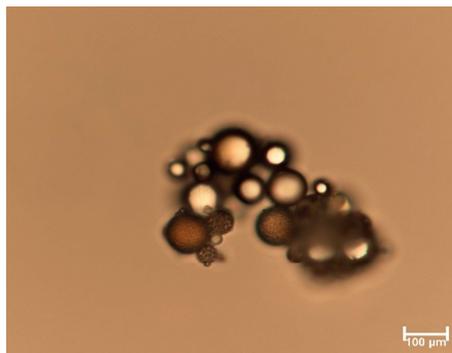


FIGURE 3: Microscope image of submillimeter-scale SMG morphology. The shape of SMG is regular sphericity, and the initial median particle size is $11.39\ \mu\text{m}$.

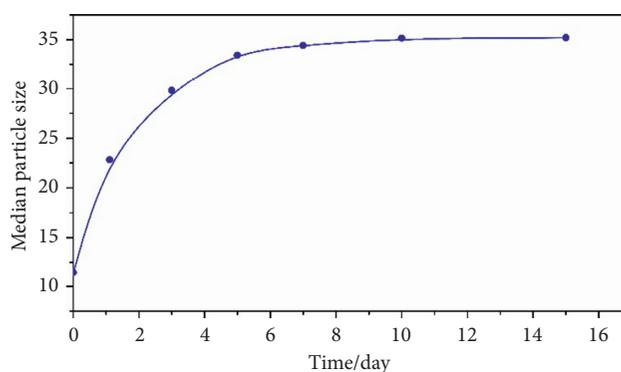


FIGURE 4: Curve of median particle size of submillimeter-scale SMG over time. The particle size of SMG gradually increased with the hydration time. After 10 days, the median particle size reaches a relative constant value.

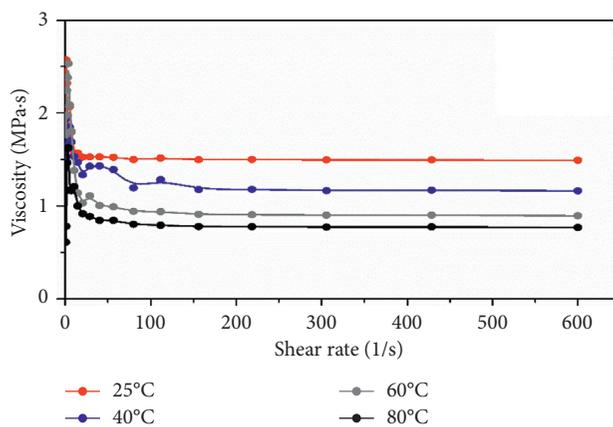


FIGURE 5: The rheological curve of submillimeter-scale SMG. It is characterized by low viscosity and shear resistance, with a viscosity of only $0.8 \sim 2.6\ \text{mPa}\cdot\text{s}$.



FIGURE 6: Submillimeter-scale SMG aqueous solution before aging.



FIGURE 7: Submillimeter-scale SMG aqueous solution after aging. The upper part is floating with a large cylindrical solid formed by the consolidation of SMG effective components and mineral salts; the lower part is aqueous solution. (a) 1 month, (b) 3 months, (c) 6 months.

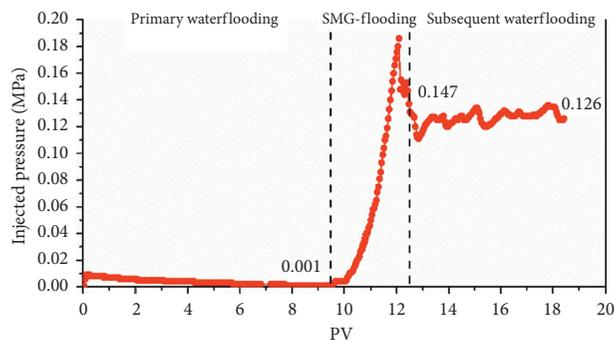


FIGURE 8: Pressure curve of submillimeter-scale SMG plugging property test. The resistance factor (F_R) and residual resistance factor (F_{RR}) are 147 and 126. The value of these parameters is positively correlated with injection volume of SMG aqueous solution.

4. Conclusions

- (1) The submillimeter-scale SMG shows excellent swelling property, rheological property, and thermal stability property. Interestingly enough, it can still exist stably after 6 months of high temperature and high salinity aging, and there is no hydration and hydrolysis of SMG as the traditional polymers.
- (2) The submillimeter-scale SMG has a better effect of profile control and oil displacement. After the injection of 1PV SMG aqueous solution, the fractional flow rate of low-permeability core is significantly improved, from 5.12% to 85.29%, and the recovery is significantly increased up to 14.07%.
- (3) This work indicates that the submillimeter-scale SMG has the potential to solve the problem that the polymer flooding cannot be used in the high temperature and high salinity reservoir, and it is also expected to improve the uneven waterflooding in the reservoir.
- (4) Oilfield tests of submillimeter-scale SMG should be carried out actively to further verify the feasibility of the novel particle polymer in high temperature and high salinity reservoirs.

Data Availability

The Excel data used to support the findings of this study were supplied by Yang Liu under license and so cannot be made freely available. Requests for access to these data should be made to Yang Liu, liu2021@petrochina.com.cn or 695724431@qq.com.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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