Optimization Study of Polymer-Surfactant Binary Flooding Parameters in Maling Jurassic Low Permeability Reservoir

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Abstract

The low-permeability Jurassic reservoir in Changqing Maling has been in the middle and high water cut stage after the long-term development of water injection. In order to improve development efficiency and further explore a new way to enhance oil recovery of the reservoir, a significant development test, and a polymer-surfactant flooding study were carried out in the Maling Beisan area in 2011.

Compared with other polymer-surfactant flooding reservoirs of PetroChina, the Jurassic reservoir in the Beisan area had relatively low permeability and high salinity of formation water and injected water, which puts forward higher requirements on the injectivity and salt resistance of the binary system. At the same time, the viscosity of the formation crude oil was low, and the viscosity of the polymer required to achieve the optimum fluidity ratio was relatively low, which is an important advantage of implementing binary flooding in the reservoir.

In this paper, hydrophobic associating polymers and betaine surfactants were selected through laboratory experiments. According to the experimental data, numerical simulation technology was used to analyze and optimize the influence factors, including injection speed, injection-production ratio, slug size, slug polymer, and surfactant concentration. Finally, the development index of binary flooding was predicted.

The results show that the optimized polymer-surface system had good injectivity and high formation compatibility. Through on-site differential control measurement of injection and production, the recovery was enhanced significantly. This study had guiding significance for the production of polymer-surface flooding in similar reservoirs.

Introduction

The development of Changqing Oilfield started from the Jurassic reservoir. Currently, most Jurassic reservoirs have been in the stage of high water cut development (comprehensive water cut of 69.0%, recovery degree of reserves of 76.5%); the overall decline of the reservoir was large (13.6%/11.8%); the water cut was accelerated; the oil recovery speed was low; the distribution of remaining oil was scattered and complex, and it was difficult to stabilize production. Thus, it was urgent to carry out technical research to improve oil recovery.

Polymer-surfactant flooding technology can effectively reduce water-oil mobility ratio, expand swept volume of water drive, and improve the efficiency of oil displacement. It was an important means to effectively reduce water cut and improve the final recovery of reservoirs during the middle and high water-cut stage. Compared to other oil fields of PetroChina, there were some difficulties in the development of polymer-

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surfactant flooding in the low-permeability Jurassic reservoir in Changqing due to its low-permeability, strong heterogeneity, high salinity of formation water and injected water, etc. The successful experience of the medium and high-permeability reservoir was difficult to be employed, so it was necessary to study a binary system with good injectivity and high-efficiency salt resistance. Combined with the corresponding adjustment technology to further improve the recovery of this reservoir.

Test Overview

The main oil reservoir in the study area is the Jurassic system yan10 and the secondary yan9. The depth of the yan10 reservoir was 1,500-1,750m; the average thickness was 5.9m; the average effective porosity was 15.0%; the average effective permeability was $110 \times 10^{-3} \mu m^2$; the oil saturation was 65% and the formation water salinity was 23.2g/L. Before the on-site test, the comprehensive water cut was 88.54%, and the recovery was 23.53%. To further improve oil recovery, 14 new wells were drilled in the test area, the well pattern was adjusted from irregular anti-seven-point well pattern to five-point well pattern, and the well spacing between injector and producer was adjusted from 250-350 m to 150m, resulting in a pattern with 9 injectors and 16 producers (**Figure 1**). The injection mode of "polymer pre-slug + main slug + sub-slug + polymer protection slug" was selected as the injection scheme of polymer-surfactant flooding. The total injection volume was 0.65PV and the injection speed was 0.15PV/a.

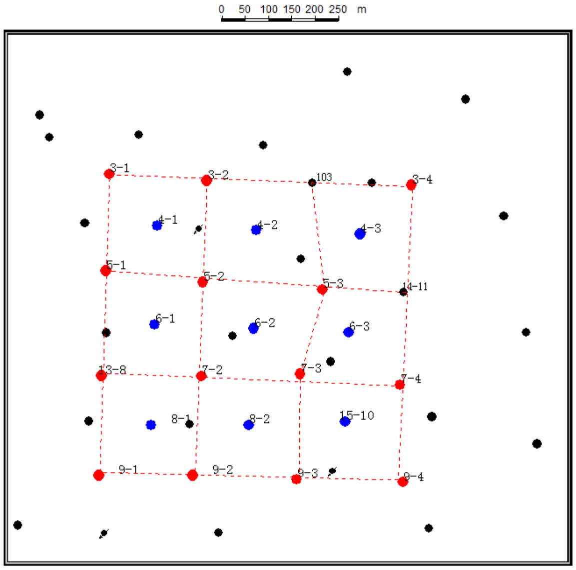

Figure 1—Well location in test area. The red dots represents producer, and the blue dots are injector.

Optimization of a Binary System

According to the characteristics of the low-permeability Jurassic reservoir in Changqing, the formulation of the system was studied. The selected polymer molecular weight should be suitable for low permeability reservoir. For high calcium/magnesium ion and high salinity formation, the selected polymer should have good salt resistance and viscosity enhancement ability. The core of technology research is that the system has good viscosity enhancement, good injection performance, strong ability of controlling fluidity, and it can improve swept volume, reduce oil-water interfacial tension to ultra-low, improve oil displacement efficiency. The system also should stable (salt resistance, shear resistance, small adsorption, etc.).

Polymer Optimization. 29 samples of low molecular weight polymers were collected in the laboratory. They were hydrophobic associating polymers, star polymers, composite polymers, functional polymers, zwitterion polymers, etc. All of them had the ability to resist salt and shear, and their molecular weight ranged from 6 to 20 million.

By evaluating the performance of hydrophobic associating polymer, the polymer had better viscosity increasing ability, and the solution with the same concentration had higher viscosity than the solution used in the Beisan area (**Figure 2**). The performance of this polymer was relatively stable and the viscosity remained basically the same as the injection water temperature increased (**Figure 3**). The viscosity retention rate was high after rock sand adsorption and the viscosity remained the same after shear at a medium speed of 2000RPM/min. However, the viscosity will decrease at high shear speed only. The resistance coefficient of the core displacement experiment was 12.82 and the residual resistance coefficient was 1.79 (**Figure 4**).

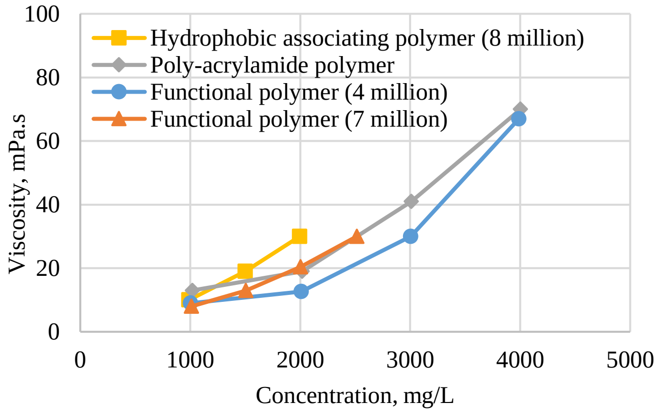

Figure 2—Comparison of viscosity enhancement between hydrophobic associating polymer and other polymers.

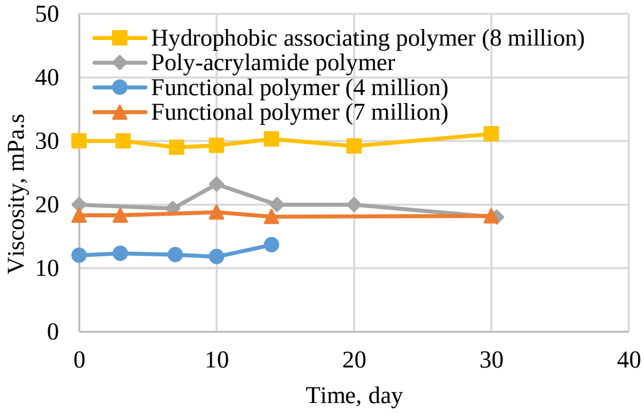

Figure 3—Comparison of stability between hydrophobic associating polymer and other polymers.

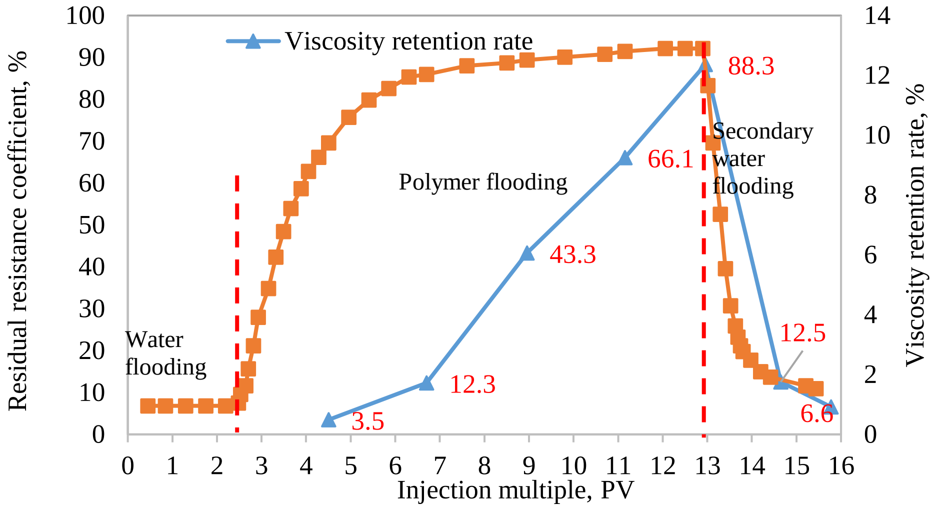

Figure 4—Injection experiment of hydrophobic associating polymer.

Compared to the polyacrylamide polymer and functional polymer, the hydrophobic associating polymer had better properties of increasing viscosity, salt resistance, shear resistance, and adsorption resistance. Therefore, hydrophobic associating polymer (8 million) was selected as the experimental polymer.

Surfactant Optimization. The zwitterions produced by the ionization of amphoteric surfactant in aqueous solution have a certain chelating effect on the divalent metal ions, such as calcium and magnesium, giving them strong salt resistance.

Based on the characteristics of oil and water in the Jurassic reservoir, the betaine formulation system was optimized. Hydroxypropyl-sulfo betaine surfactant was synthesized by introducing hydroxysulfonic group into straight chain alkane, which gave the system excellent salt resistance and emulsification performance (**Table**

1). The core experiment shows that when the concentration was greater than 0.25%, the oil displacement efficiency increased and the oil washing efficiency slowed down. The oil washing efficiency experiment shows when the concentration was greater than 0.25%, the interfacial tension increased and the oil washing efficiency decreased. Therefore, the optimal concentration of betaine was determined to be 0.2-0.25% (**Table 2**).

Table 1—Selection and comparison of surfactant for oil displacement in test area.

Surfactant	Emulsification index	Oil-water interfacial tension (mN/m)
Betaine	82	2.3×10^{-3}
AES	78.6	6.9×10^{-1}
Nonionic surfactant 1#	35	5.6×10^{-3}
LH-1	23.6	8.2×10^{-4}
Petroleum sulfonate 1#	36.9	4.7×10^{-2}
Gemini surfactant	52.3	3.8×10^{-3}

Table 2—Results of the oil displacement test of betaine surfactant with different concentrations.

	Porosity (%)	Oil saturation (%)	Permeability (mD)	Surfactant concentration (wt%)	Oil recovery			Slug and viscosity
					Water flooding	Chemical flooding	Ultimate	
1	18.4	62.2	57.9	0.1	39.94	12.06	52	0.3PV main slug +0.2PV protection slug, Polymer1500ppm, viscosity 30cp
2	19.68	65.3	104.3	0.15	36.3	16.26	52.56	
3	18.39	66.4	76.3	0.2	36.4	20.33	56.73	
4	17.3	65.07	59.2	0.25	37.3	22.19	59.49	
5	18.96	64	70.7	0.3	37.38	23.74	61.12	

Adaptability Evaluation Of Binary System. Through a previous study, the binary system (hydrophobic associating polymer + betaine surfactant) suitable for the Jurassic oil reservoir was developed. The binary system had a synergistic viscosity increase effect (**Figure 5**), good shear resistance, and good thermal stability. Compared with water flooding and polymer flooding, binary flooding increased oil displacement efficiency by 20.5% and 14.9%, respectively (**Figure 6)**.

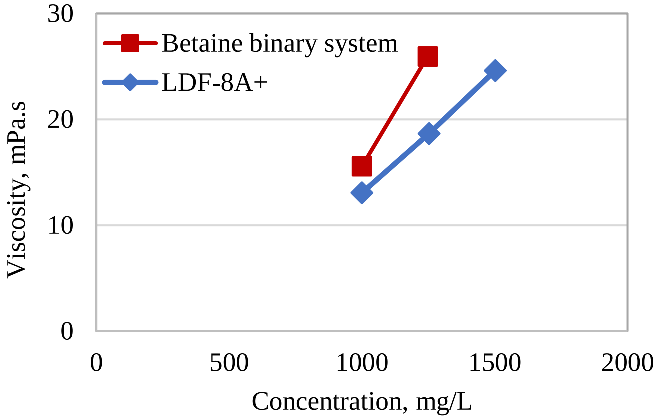

Figure 5—Viscosity and concentration curve of the binary system.

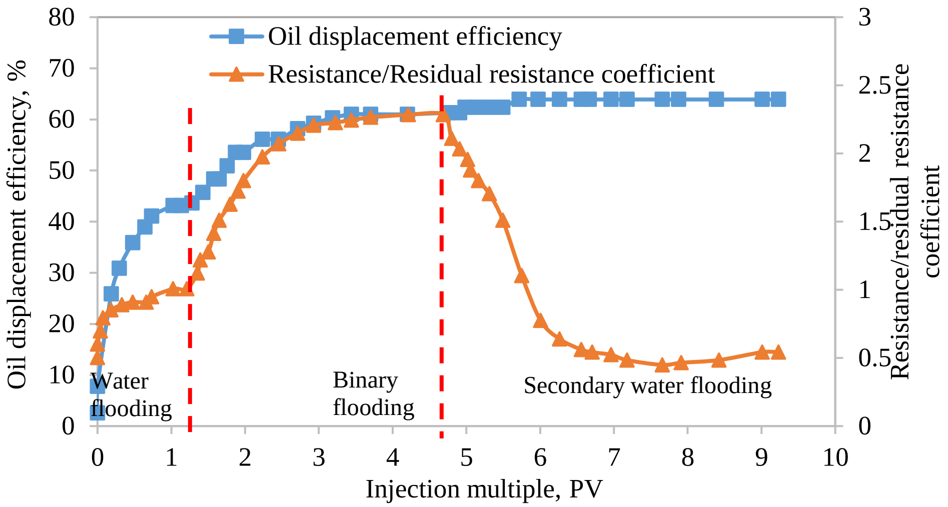

Figure 6—Core displacement experiment of binary system.

Effect of Injection-Production Parameters

Based on the evaluation experiment of the parameters of the binary system and the model of the binary flood of the Jurassic reservoir in the Beisan area, after injected into the binary system, the simulation stopped when the water cut reached 98% under water flooding. The single-variable method was used to study the effect of different parameters on polymer flooding. The water cut and the recovery curve under different injection and production parameters was used to evaluate the increase in recovery and the decrease in water cut.

Effect of Injection Speed. The faster the injection speed was, the higher the recovery rate was. But the faster the water cut rising speed was, the shorter the corresponding production time was. When the injection speed was greater than 0.15pv/a, the recovery rate increased slowly (**Figure 7**). The optimal injection rate was estimated to be about 0.15pv/a.

Effect of Injection-Production Ratio. The cumulative oil production under different injection-production ratio was predicted using numerical simulation. With the increase in injection production ratio, the decrease range of water cuts increased. However, the water content increased quickly. When the injection-production ratio was less than or equal to 0.8, the larger the injection-production ratio was, the greater the recovery increased; when the injection production ratio was greater than 0.8, the recovery rate decreased (**Figure 8**). Thus, the suitable injection-production ratio was about 0.8.

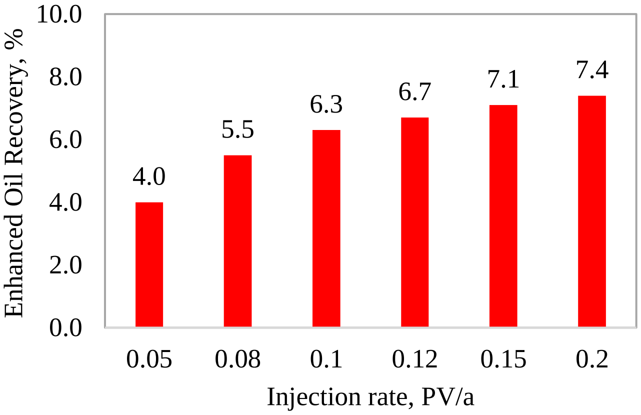

Figure 7—Numerical simulation of the effect of the injection rate on oil recovery.

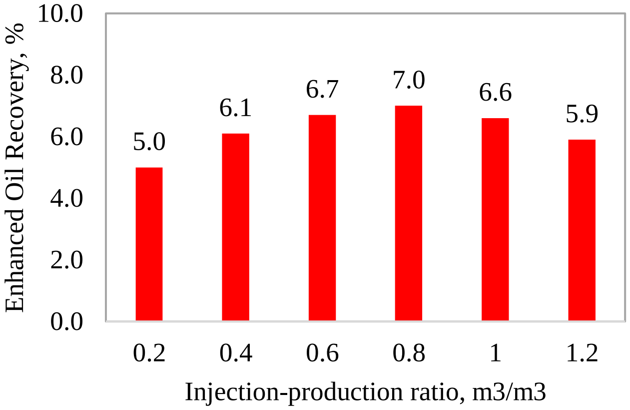

Figure 8—Numerical simulation of the effect of the injection-production ratio on oil recovery.

Effect of the Size of the Main Slug. With increasing slug size, the recovery rate increased and the increasing rate of water cut slowed. When the main slug size was greater than 0.3pv, the recovery rate increased slowly (**Figure 9**). The size of the main slug was determined to be about 0.3pv.

Effect of the Polymer Concentration of the Main Slug. The effect of binary flooding was studied by varying the polymer concentration of the main slug. With the increase of polymer concentration, oil recovery increased. When the concentration was greater than 2000mg/L, the oil recovery rate gradually increased (**Figure 10**). Thus, the optimal concentration was determined to be 2000mg/L.

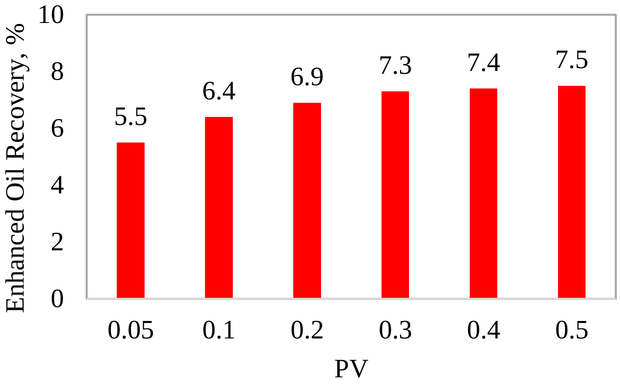

Figure 9—Numerical simulation of the effect of the size of the main slug on oil recovery.

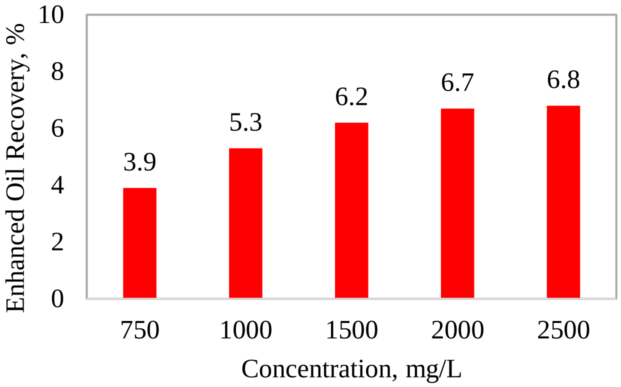

Figure 10—Numerical simulation of the effect of polymer concentration on oil recovery.

Effect of the Surfactant Concentration of the Main Slug. The effect of binary flooding was simulated by changing the surfactant concentration of the main slug. With an increase in surfactant concentration, the recovery rate increased. When the concentration was greater than 0.15%, the oil recovery rate increased slowly (**Figure 11**). The optimum concentration was approximately 0.2%.

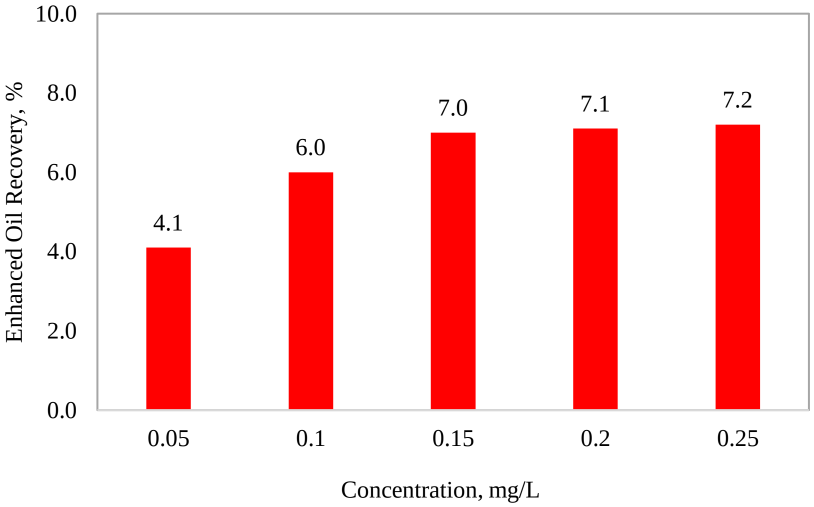

Figure 11—Numerical simulation of the effect of surfactant concentration on oil recovery.

Table 3—Rank of influencing factors in numerical simulation.

Numerical simulation parameters	Sensitivity coefficient on EOR	Sensitive coefficient on water cut
Injection-production ratio	0.407	0.411
Polymer concentration	0.224	0.255
Surfactant concentration	0.194	0.132
Injection speed	0.192	0.087
Total amount of binary slug injection	0.133	0.000

Sensitivity Analysis. Based on the concept of variation coefficient in statistics, sensitivity coefficient was introduced as the evaluation metrics of polymer flooding parameters (**Table 3**). Taking the decrease of water content as an example, the expression for calculating the sensitivity coefficient is as follows:

$$S = \frac{1}{\overline{\Delta EOR}} \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} \left(\Delta EOR_i - \overline{\Delta EOR} \right)^2} \;, \ldots\ldots\ldots\ldots (1)$$

Where, $\overline{\Delta EOR}$ means the average recovery increment, %; n is the number of numerical simulations, it was set to be 5 in this study; ΔEOR_i is the increasing recovery range under the value of group i, %;

Through the calculation and statistics of the sensitivity coefficient, the sensitivity from strong to weak is as follows (Table 3): injection-production ratio, polymer concentration, surfactant concentration, injection speed, total amount of binary slug injection.

Parameter Optimization Results. Based on the above studies and field test performance, it was determined that the injection rate was maintained at 0.15pv / a, the injection production ratio was 0.75, the polymer concentration was kept at 2000mg / L, the surfactant concentration was adjusted from 0.12% to 0.2%, the main slug size was adjusted from 0.2pv to 0.3pv and the overall injection volume was 0.75pv. After adjustment, the recovery rate increased by 1.8% compared to the current development scheme (**Figure 12**).

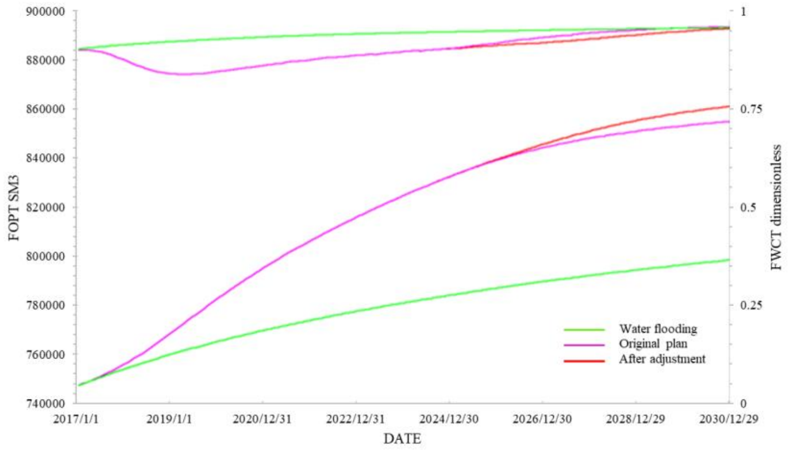

Figure 12—Comparison of recovery efficiency before and after optimization using numerical simulation.

Field Test Results

In August 2016, the pre-slug was injected into the test area. In June 2017, the binary system was injected. Currently, a binary system of 0.28pv (designed volume of 0.65pv) has been injected in total, accounting for 43.5% of the designed volume. Daily oil production increased from 10.9t to 20.5t, comprehensive water cut decreased from 95.2% to 91.7% (**Figure 13**), the cumulative oil production increased by 9400t. The benefit of binary flooding was obvious.

From 2017 to 2018, five wells were chosen to remove the formation plugging. After the measurements, daily liquid production increased significantly, daily oil production increased by 2.8t, and cumulative oil production increased by 628t. The parameters of four oil wells were optimized, with the daily oil production increase of 1.52t and the cumulative oil production increase of 971t. In 2019, the parameters optimization was carried out in two oil wells. At present the daily oil production increased by 1.23t and the cumulative oil production increase by 482t.

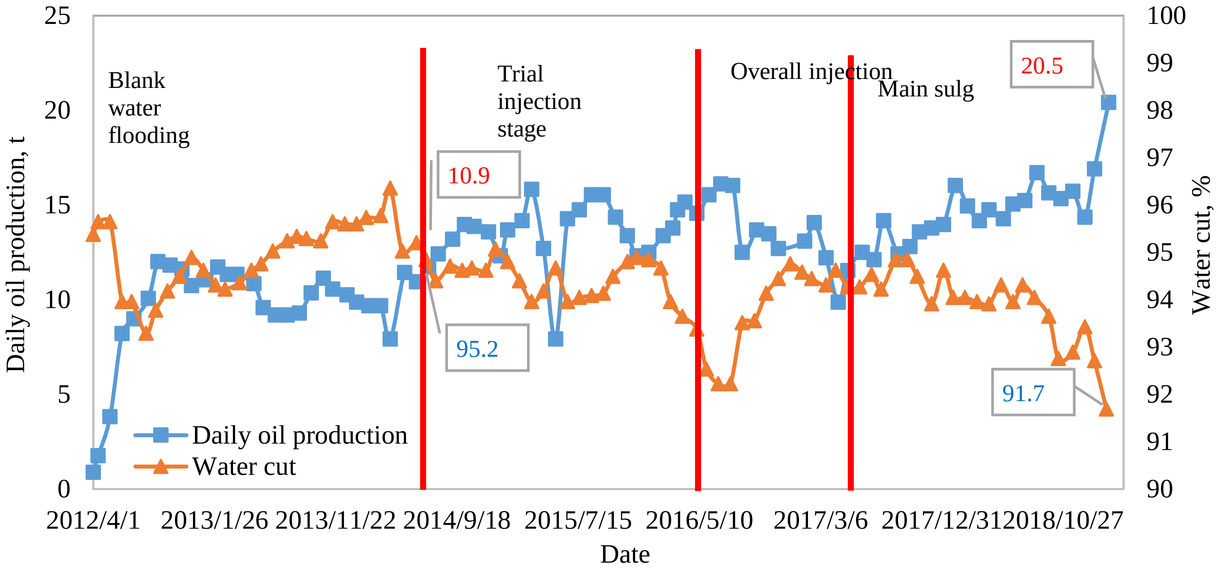

Figure 13—Daily oil production and water cut curve of the test area.

Conclusions

1. For Changqing low permeability and high salinity reservoir, low molecular weight and salt resistant polymer was the preferred choice. The hydrophobic associating polymer (8 million) currently selected in the laboratory is the polymer with good stability, shear resistance, small adsorption, high resistance coefficient, high viscosity retention rate of the Berea core displacement fluid and high efficiency of oil displacement.
2. For a Changqing's low permeability and high salinity reservoir, the performance of the surfactant for oil displacement should be based on the ability of anti-adsorption, salt resistance, and strong oil washing to maintain the continuous injection of chemicals. At present, the optimized betaine surfactant had good adaptability.
3. In the research of chemical flooding in the Jurassic reservoir of Changqing, the sensitivity of injection and production parameters from strong to weak was as follows: injection production ratio, polymer concentration, surfactant concentration, injection speed, total injection amount of binary slug.
4. The development of chemical flooding technology was limited to improving oil recovery in low-permeability reservoirs, relying only on the improvement of the chemical system performance to enhance the ultimate oil recovery, which must be combined with fine injection and production control.
5. For chemical flooding in low-permeability reservoirs, it was necessary to adjust injection-production parameters, improve the injection profile, and reduce the plugging rate near the well. The small and low molecular weight polymer should be studied and developed in the laboratory, and a reasonable injection concentration should be estimated and determined. At the same time, special measurements were taken to remove the plug around the oil wells. As a result, a series of EOR supporting technologies that were suitable for Changqing's low-permeability reservoir was proposed and developed.

Conflicts of Interest

The author(s) declare that they have no conflicting interests.

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