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Research Article

Adaptability Study of Hot Water Chemical Flooding in Offshore Heavy Oilfields

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As a new heavy oil development technology, hot water chemistry flooding has great potential in offshore heavy oil fields development. In this paper, the adaptability of hot water chemical flooding was studied based on the typical model of offshore heavy oil fields. The main controlling factors affecting the hot water chemical flooding were analyzed and evaluated by single factor analysis. The technical boundary was established for offshore heavy oil fields. In addition, the hot water chemical flooding scheme was designed by a case study of a well group oilfield D. The results indicate that crude oil viscosity and well spacing have great influences on hot water chemical flooding performance. Hot water chemical flooding is favorable when the crude oil viscosity is between 300 and 1000 mPa·s and well spacing is around 200~400 m. The hot water chemical flooding scheme of the target well group results in 40.2×10^4 tons of incremental oil, and 6.3% of recovery factor being enhanced, which shows strong evidence that hot water chemical flooding enables great oilfield development performance.

1. Introduction

Heavy oil is one of the most important oil resources in the world and is widely distributed across the world. The reserves of heavy oil resources in China are also considerable [1]. The heavy oil resources with underground crude oil viscosity of 150~1000 mPa·s in the Bohai oilfield are of great percentage [2, 3]. At present, the heavy oil reservoirs in Bohai oilfield are mainly developed by conventional water flooding, which generally has poor development effect and low reserve recovery. They still have great potential to be extracted and produced [4–7].

The heavy oil reservoirs in Bohai oilfield have complex geological conditions, broken structures, and multiple oil-water systems with complex relationships [8–10]. It is characterized by large well spacing, irregular well pattern, high heterogeneity, deep burial, and consolidated reservoir cementation [11–13]. At the same time, offshore oil production is also affected by many factors such as platform space, service life, logistics resources, and the offshore environment [14–16]. The requirements for marine environmental protection and platform safety are also very strict. All these factors restrict the application of thermal recovery methods in offshore oilfields, which have been commonly adopted in onshore oilfields [17].

As a displacement method to enhance the recovery of heavy oil, hot water chemical flooding plays a role in the combination of physical and chemical effects [18–20]. The physical effect is mainly generated by heat, which is manifested in two aspects: (1) reducing the viscosity of the heavy oil by heating the reservoir and improving the mobility of heavy oil. The development performance gets improved with the adjusted mobility ratio and increased sweep efficiency; (2) heat can improve the microscopic displacement efficiency of heavy oil and enhance oil recovery. Chemical action is also mainly manifested in two aspects. (1) By

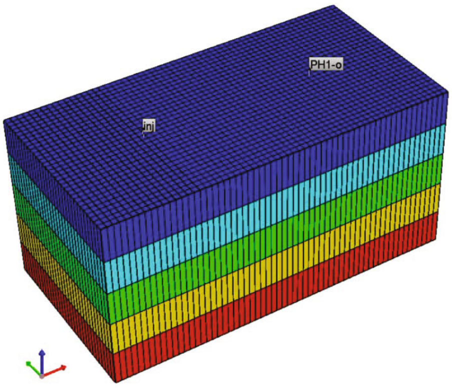

Figure 1: Meshing of the typical simulation model.

Table 1: Numerical simulation characterization of EOR mechanism for hot water chemical flooding.

EOR mechanism	Numerical simulation realization
Thermal viscosity reduction	Viscosity-temperature relation table at different temperatures
Displacement efficiency improvement by thermal method	High and low temperature relative permeability curve interpolation
Viscosity reduction by chemical agent	(1) the viscosity reduction rate of agent at different temperatures (2) by defining chemical reaction to generate oil with lower viscosity
Changing water phase viscosity to control mobility ratio	Nonlinear viscosity relation

Table 2: Results of water cut and recovery factor of 10 years production under different viscosity conditions.

Parameter			Value		
Oil viscosity/mPa·s	200	400	600	800	1000
Water cut/%	94.32	95.08	95.38	95.48	95.50
Recovery factor/%	14.66	11.73	10.15	9.06	8.21

adding chemical agents to the injected hot water, the viscosity of heavy oil gets reduced, thus improving the water-oil mobility ratio in the part of the reservoir that is not mainly affected by hot water. (2) The mobility ratio can be effectively controlled by adding the chemical agent with viscosifying effect, preventing the fingering and channeling effects. The synergistic effect manifests as the superposition of the mechanisms by injecting hot water and chemical agent to improve the water-oil mobility ratio, and finally increase the volumetric sweep efficiency and displacement efficiency [21, 22].

2. Study on the Influencing Factors of Hot Water Chemical Flooding for Offshore Heavy Oil Development

The offshore heavy oil development performance is mainly influenced by formation property, fluid property, and development factors. The numerical model is established based on the formation and fluid properties of oilfield D. Single factor analysis method is implemented to study the influence of crude oil properties, reservoir thermal physical properties, well spacing, and reservoir thickness on heavy oil development performance. Based on the sensitivity analysis, the technical boundary of hot water chemical flooding in offshore oilfield is determined.

2.1. Typical Simulation Model Build up for Offshore Heavy Oil Fields. CMG STARS module was used to establish a typical model for heavy oilfield to study the adaptability of hot water chemical flooding. The parameters of reservoir properties, fluid properties, thermophysical properties, relative permeability curve, and crude oil viscosity, as well as the viscosity-temperature curve, are established based on the general properties of Bohai heavy oilfields and laboratory experimental results. The total number of model grids is $61 \times 31 \times 5 = 9455$, and the grid size is $10\,\text{m} \times 10\,\text{m} \times 2\,\text{m}$. The model is a positive rhythm reservoir. The permeability of each layer is $3000 \times 10^{-3}\,\mu\text{m}^2$, $3500 \times 10^{-3}\,\mu\text{m}^2$, $4000 \times 10^{-3}\,\mu\text{m}^2$, $4500 \times 10^{-3}\,\mu\text{m}^2$, and $5000 \times 10^{-3}\,\mu\text{m}^2$. The model consists of one production well and one injection well, and it is shown in Figure 1. The characterization of the hot water chemical flooding mechanism in the numerical simulation model is shown in Table 1 [23–25].

Based on the water-flooding scheme, the numerical simulation study is carried out until the water cut reach 95%. In the simulation process, under different oil viscosity, the sensitivity analysis is limited to 10 years of production for the convenience of comparison. Water cut and recovery factor

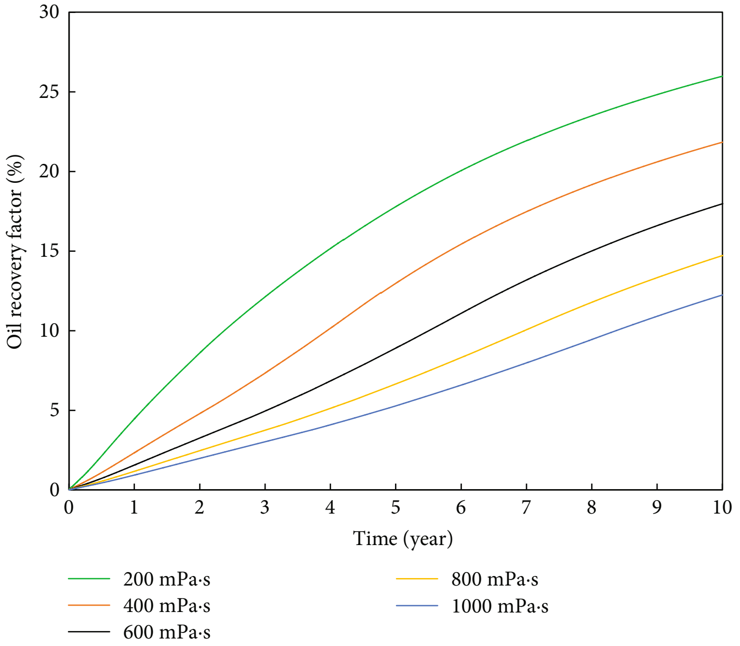

Figure 2: Recovery factors of hot water chemical flooding simulation with different oil viscosity.

Table 3: Influence of viscosity on the effect of different development methods.

Parameters	Recovery factor at different viscosity (%) 200 mPa·s	400 mPa·s	600 mPa·s	800 mPa·s	1000 mPa·s	Maximum difference between recovery factor (%)
10-year water flooding	14.66	11.73	10.15	9.06	8.21	6.45
10-year hot water chemical flooding	25.97	21.83	17.91	14.65	12.17	13.80

Table 4: Analysis table showing the influence of crude oil thermophysical properties on hot water chemical flooding performance.

The parameter types	Parameter	Range	Maximum difference between recovery factor (%)	Influence on hot water chemical flooding performance
Properties of crude oil	Compressibility/(1/kPa)	1×10^{-7} $\sim 1 \times 10^{-6}$	0.03	Tiny
	Coefficient of thermal expansion/(1/°C)	1×10^{-4} $\sim 1 \times 10^{-3}$	0.14	Tiny
	Coefficient of thermal conductivity/(J/m·day·°C)	1×10^{3} $\sim 1 \times 10^{5}$	0.01	Tiny

of water-flooding scheme simulation with 10 years production are shown in Table 2.

2.2. Study on the Influencing Factors of Offshore Heavy Oil Reservoir Development. The permeability of offshore heavy oil reservoirs is generally greater than 2000 μm^2. The injectivity parameters can be continuously optimized and adjusted in the development process. Therefore, in this study, the influence of permeability and injectivity parameters on the effect of hot water chemical flooding is no longer considered. In this paper, the influences of formation property and fluid property on the performance of hot water chemical flooding are evaluated in terms of recovery factor.

2.2.1. Adaptability Study of Hot Water Chemical Flooding to Formation Crude Oil Properties. Firstly, the influence of crude oil viscosity on the development performance of hot water chemical flooding was analyzed. Crude oil viscosity was set to be 200, 400, 600, 800, and 1000 mPa·s. The simulation results are shown in Figure 2. It indicates that crude oil viscosity has a great influence on the recovery factor of 10 years of production by hot water chemical flooding. There is a maximum of 13.8% difference in recovery factor, and it can be seen in Table 3.

Secondly, the influence of the thermophysical properties of crude oil on the performance of hot water chemical flooding is studied. The numerical simulation results are shown in

Table 5: Analysis of the influence of rock thermal physical properties on hot water chemical flooding performance.

Parameter type	Parameter	Range	Maximum difference between recovery factor (%)	Influence on hot water chemical flooding performance
Rock property	Thermal capacity/(J/m^3·°C)	1×10^6 ~ 5×10^6	0	Tiny
	Compressibility/(1/kPa)	1×10^6 ~ 10×10^6	0.23	Tiny
	Coefficient of thermal expansion/(1/kPa)	1×10^{-7} ~ 50×10^{-7}	0	Tiny
	Coefficient of thermal conductivity/(J/m·day·°C)	0.5×10^5 ~ 5×10^5	0.26	Tiny

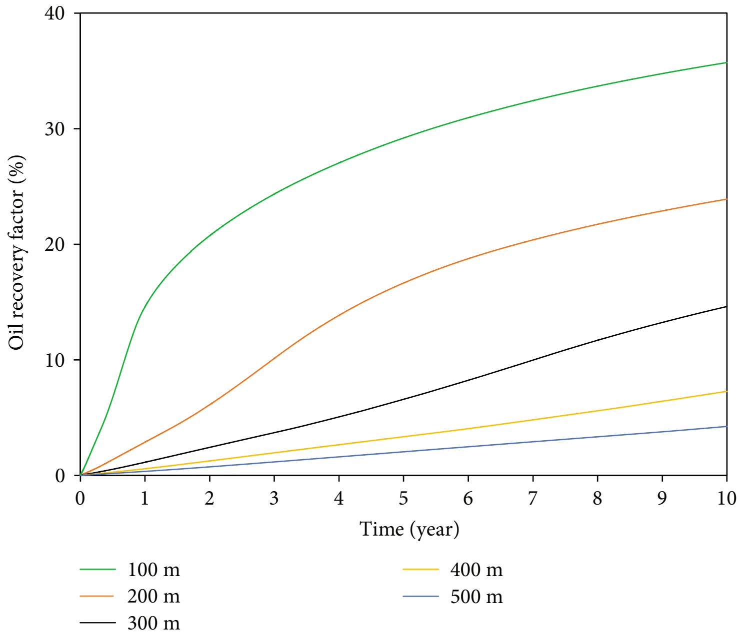

Figure 3: The influence of well spacing on the recovery factor of hot water chemical flooding.

Table 4. It can be seen that the compressibility coefficient, thermal expansion coefficient, and thermal conductivity coefficient of crude oil affect the recovery factor of hot water chemical flooding by 0.2% in the case of 10 years of hot water chemical flooding. Therefore, the influence of thermal physical parameters of crude oil on hot water chemical flooding can be ignored.

2.2.2. Adaptability Study of Hot Water Chemical Flooding to Thermal Physical Properties of Reservoir Rocks. In order to study the influence of thermophysical properties on the hot water chemical flooding performance, sensitivity studies are conducted. The rock thermal capacities were set to be 1.00×10^6, 2.58×10^6, and 5.00×10^6 J/m$^3\cdot\circ$C. The rock compressively coefficients were set to be 1×10^{-6}, 5×10^{-6}, and 10×10^{-6} 1/kPa. The rock thermal expansion coefficients were set to be 1×10^{-7}, 10×10^{-7}, and 50×10^{-7} 1/kPa. The thermal conductivity coefficients of rock were set to be 0.50×10^5, 1.63×10^5, and 5.00×10^5 J/m·day·°C. The results are shown in Table 5. It is indicated that the thermal capacity and thermal expansion coefficient of rock have little influence on the development performance, and the influence of rock compression coefficient and thermal conductivity coefficient on the recovery factor is less than 0.3%. The comprehensive analysis shows that the influence of rock thermal physical properties on the development performance can be ignored.

2.2.3. Adaptability Study of Hot Water Chemical Flooding to Well Spacing. Well spacing is an important factor that influences the recovery factor of offshore oilfield. Generally, offshore oilfield is usually developed with large spacing. The directional well spacing is typically 300 to 500 m, and 300 m after infill drilling. With this situation, it is necessary to evaluate the adaptability of hot water chemical flooding to well spacing [26, 27].

In the typical model, the well spacing is set to be 100 m, 200 m, 300 m, 400 m, and 500 m to study the influence of well spacing on the recovery factor of hot water chemical flooding development. According to the simulation results that shown in Figure 3, well spacing is an important factor affecting the final recovery factor. Under the hot water

Table 6: Influence of well spacing on the performance of different development methods.

Parameter	Recovery factor under difference well spacing					Maximum difference between recovery factor (%)
	100 m	200 m	300 m	400 m	500 m	
10-year water flooding	20.94	12.88	9.06	6.46	4.31	16.63
10-year hot water chemical flooding	35.74	23.95	14.65	7.30	4.26	31.48

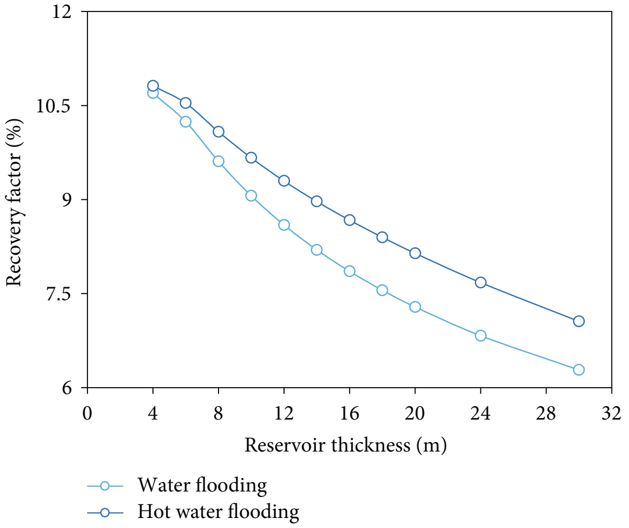

Figure 4: The influence of reservoir thickness on recovery factor of water flooding and hot water flooding.

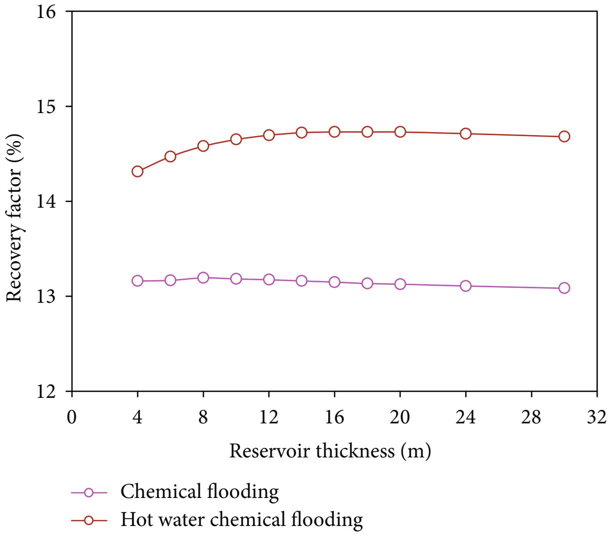

Figure 5: The influence of reservoir thickness on recovery factor of chemical flooding and hot water chemical flooding.

chemical flooding mode, the recovery factor of 100 m well spacing is 31.5% higher than that of 500 m well spacing. Details can be found in Table 6.

2.2.4. Adaptability Study of Hot Water Chemical Flooding to Reservoir Thickness. Reservoir thickness has different degrees of influence on different development methods. In the typical model, the reservoir thickness ranges from 4 m to 30 m. The influence of reservoir thickness on the development performance of hot water chemical flooding is studied. According to the simulation results shown in Figures 4 and 5, reservoir thickness has a great influence on the recovery factor under the water flooding and hot water flooding development modes, and the recovery factor decreases with the increase of reservoir thickness. The maximum difference of recovery degree under water flooding development mode is 4.4%, and the maximum difference of recovery factor under hot water flooding development mode is 3.8%. As for hot water chemical flooding, reservoir thickness has a certain influence on the recovery factor with the maximum recovery difference of 0.4%. While under the chemical flooding development method, the reservoir thickness has little influence. The maximum difference of recovery factor is only 0.1%. With the increase of thickness of heavy oil reservoir, chemical flooding or hot water chemical flooding can greatly improve the development effect compared with water flooding.

3. Study on the Adaptation Limit of Hot Water Chemical Flooding

Since reservoir thickness affects the hot water chemical flooding performance, it is believed that hot water chemical flooding also has certain adaptability to reservoir thickness in this paper. Therefore, based on the study, the influences of crude oil viscosity, spacing, and thickness on the hot water chemical flooding performance are further analyzed and evaluated using the single factor analysis method. Moreover, the contribution of thermal effect, chemical effect, and synergistic effect on the improvement of the final recovery factor of hot water chemical flooding under different parameters are quantitatively evaluated. Based on the synergistic effect index, the adaptation conditions of offshore heavy oil hot water chemical flooding are established. Three parameter settings in the typical model are shown in Table 7.

3.1. Study on Viscosity Limit of Formation Crude Oil. According to the simulation results, the contribution degree of the three oil incremental mechanisms to the recovery factor under different viscosity was plotted, and it is shown in Figure 6. The results indicate that the synergistic effect of hot water and chemical agents begins to appear when the viscosity of crude oil is greater than 200 mPa·s. When the viscosity of crude oil reaches 600 mPa·s, the contribution value reaches its maximum of 1.6%, and then decreases with the increase of viscosity. When the viscosity of crude oil is greater than 1000 mPa·s, the contribution value drops to

Table 7: Parameter settings in simulation model for hot water chemical flooding.

Factor	Level											
Viscosity/mPa·s	100	150	200	300	400	500	600	700	800	900	1000	1200
Thickness/m	2	4	6	8	10	12	14	16	18	20	24	30
Well spacing/m	100	150	200	250	300	350	400	450	500			

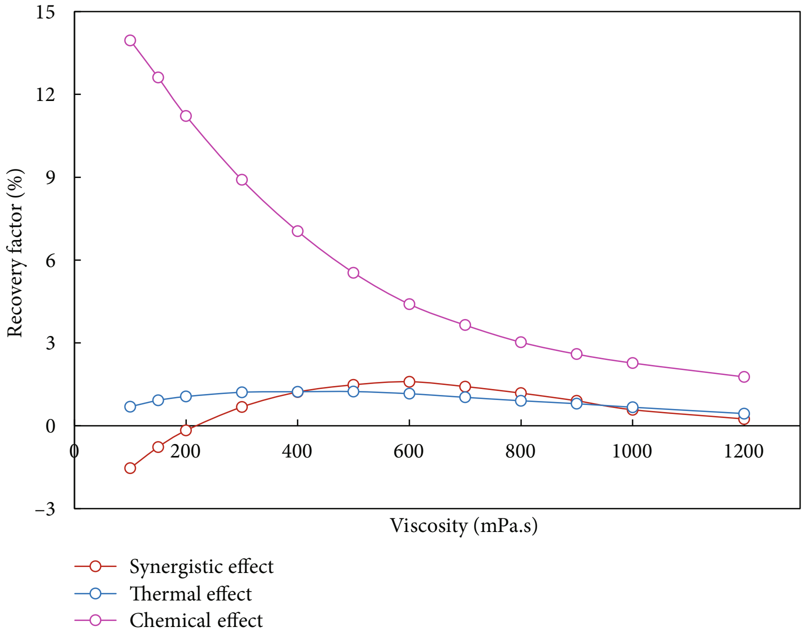

Figure 6: Contribution of oil incremental mechanism to the recovery factor of hot water chemical flooding under different viscosity.

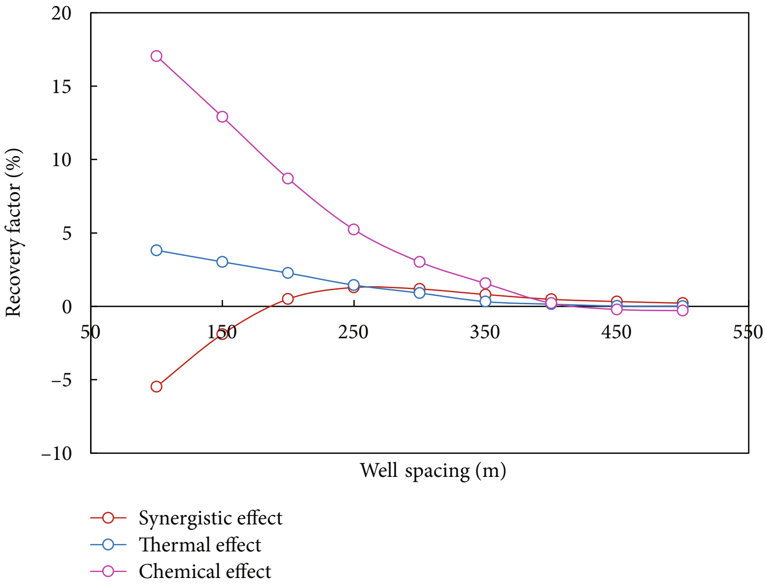

Figure 7: The contribution of three oil incremental mechanisms to the recovery factor of hot water chemical flooding under different well spacing.

0.5%. Taking the contribution value of 0.5% with synergistic effect as the technical boundary, the hot water chemical flooding is favorable when the crude oil viscosity is 300~1000 mPa·s. The recovery factors are improved by 3.5% ~ 10.8% compared with the water-flooding scheme, and the recovery is improved by 0.5% ~ 1.6% by synergistic

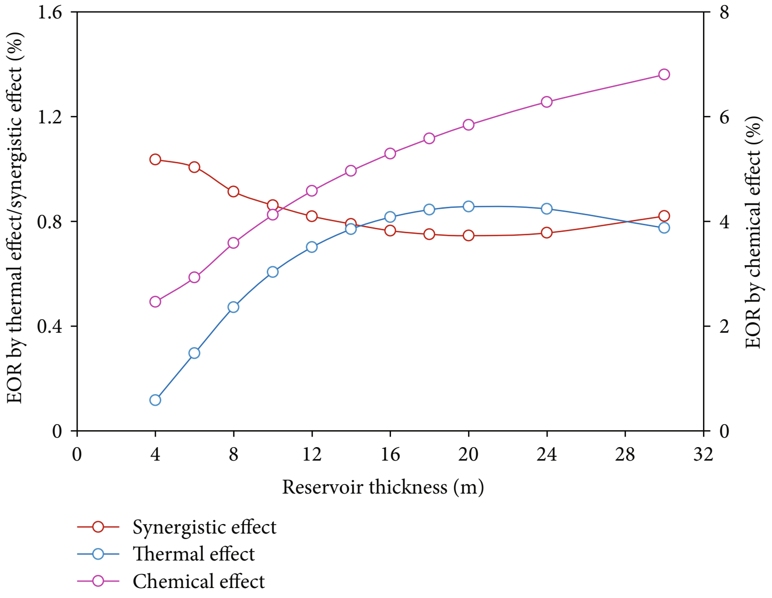

Figure 8: Contribution of three oil incremental mechanisms to the recovery factor of hot water chemical flooding under different reservoir thicknesses.

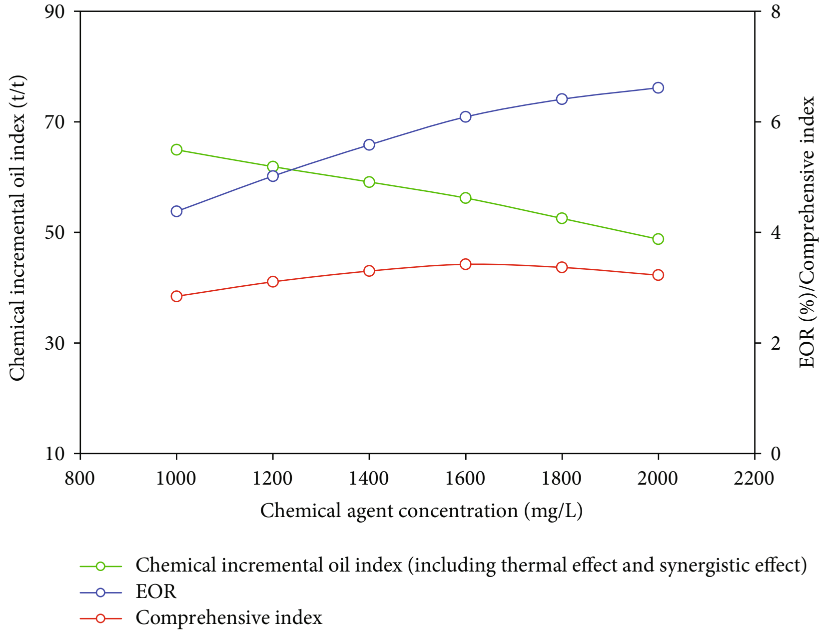

Figure 9: Optimization results of chemical agent concentration for hot water chemical flooding.

effect. The synergistic effect of hot water chemical flooding is the best when the viscosity of formation crude oil is 600 mPa·s.

3.2. Study on Well Spacing Limit. According to the simulation results, the contribution degree of the three oil incremental mechanisms to the recovery factor under different well spacing is plotted, and it is shown in Figure 7. The results show that when the well spacing is larger than 180 m, the synergistic effect begins to appear. When the well spacing is 300 m, the contribution of synergistic effect to the recovery degree reaches its peak of 1.2%, and then decreases to less than 0.5% when the well spacing is larger than 400 m. Similarly, taking the contribution value of 0.5% with synergistic effect as the technical boundary, the hot water chemical flooding is favorable when the well spacing is 200~400 m. The recovery factor of hot water chemical flooding is 0.9% ~ 11.5% higher than that of the water-flooding scheme. The synergistic effect improves the recovery by 0.5% ~ 1.3%. The synergistic effect of hot water chemical flooding is the best when the well spacing is 300 m.

3.3. Study on Reservoir Thickness Limit. According to the simulation results, the contribution degree of the three oil

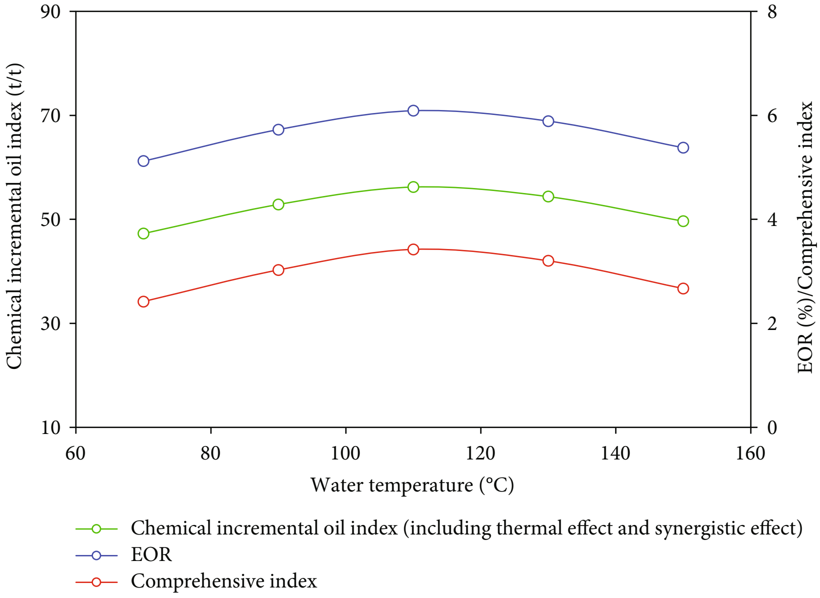

Figure 10: Optimization results of hot water injection temperature for hot water chemical flooding.

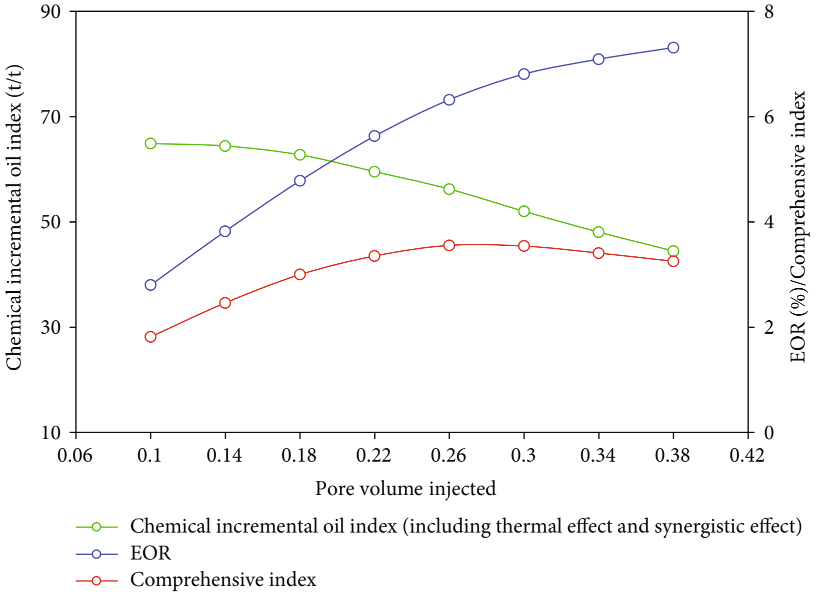

Figure 11: Optimization results of chemical agent injection volume for hot water chemical flooding.

incremental mechanisms to the recovery degree under different reservoir thicknesses is plotted in Figure 8. The research results show that with the increase of reservoir thickness, the synergistic effect of hot water chemical flooding decreases first and then increases. The main reason is that when the reservoir thickness is between 12 m and 24 m, the thermal effect and chemical effect have better effects on the development of heavy oil reservoirs, and the synergistic effect get reduced. As a whole, the synergistic effect can improve the recovery by 0.7% ~ 1%. Similarly, taking the contribution value of 0.5% with synergistic effect as the technical boundary, reservoir thickness has little limitation on the development of heavy oil with hot water chemical flooding. When the thickness of heavy oil reservoir reaches the technical boundary of the conventional development method, it is also suitable to carry out hot water chemical flooding.

4. Pilot Test Scheme Design of Hot Water Chemical Flooding in Bohai Oilfield D

Oilfield D is a layered structural reservoir, characterized by medium-shallow depth burial, large layer thickness, ultra-high porosity, and ultra-high permeability. The crude oil viscosity is 210~ 460 mPa·s, the average reservoir temperature is 57°C. The current comprehensive water cut is 88%, and

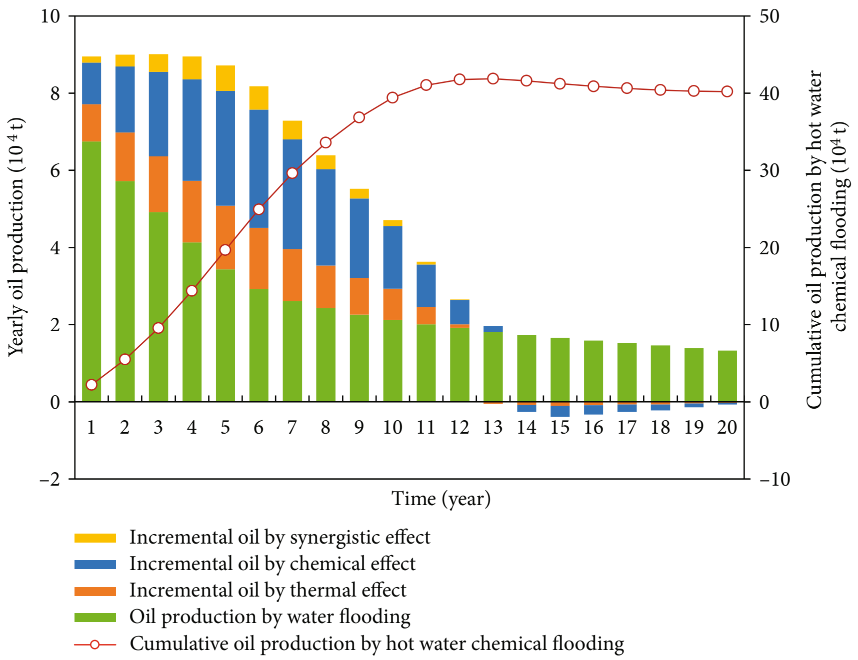

Figure 12: Recommended scheme indexes for hot water chemical flooding in pilot test area.

the recovery is 11%. Based on the adaptability analysis of hot water chemical flooding in offshore oil fields, it is favorable to carry out hot water chemical flooding. Through screening, the pilot test area of hot water chemical flooding is determined to be the 3 injection and 8 production well group, with the reserve of 6.36 million tons. At present, this well group adopts conventional water flooding development; therefore, the water-flooding scheme is taken as the basic scheme to study the oil incremental effect. On this basis, the parameters such as hot water temperature, chemical agent concentration, and chemical injection volume of hot water chemical flooding were optimized by taking EOR value, chemical incremental oil index, which is defined as incremented oil per ton of chemical agent injected and comprehensive index, which is defined as the EOR value times the chemical incremental oil index as the objective function, and the optimal scheme was finally offered.

4.1. Optimal Design of Injection Parameters. The numerical simulation of hot water chemical flooding is carried out to generate design samples for chemical agent concentration optimization. The results are shown in Figure 9. It can be seen from the figure that with the increase of chemical concentration, the EOR amplitude of hot water chemical flooding increases simultaneously, but the growth rate gradually decreases when the concentration exceeded 1600 mg/L. The comprehensive index reached its peak at 1600 mg/L, therefore the chemical agent concentration is recommended to be 1600 mg/L.

Similar process is conducted for temperature optimization. The optimization result of hot water injection temperature is shown in Figure 10. With the increase of hot water injection temperature, the EOR value of hot water chemical flooding increases first and then decreases. However, all indexes reach the peaks at 110°C, so 110°C is recommended as the injection temperature of hot water chemical flooding.

Finally, chemical agent injection volume optimization is carried out. As shown in Figure 11, with the increase of chemical agent injection volume, the EOR value of hot water chemical flooding increases, but the growth rate gradually decreases. The peak value of the comprehensive index occurs when the injection volume is 0.26 PV; consequently, the injection volume of chemical agent is recommended to be 0.26 PV.

4.2. Recommend Scheme. Based on the optimization results of injection parameters, the recommended scheme of the pilot test for hot water chemical flooding under optimal parameters was calculated. The concentration of chemical injection is 1600 mg/L, the temperature of hot water injection is 110°C, and the chemical agent injection volume is 0.26 PV (10 years). The chasing water flooding is implemented right after the end of hot water chemical flooding. As shown in Figure 12, compared with the conventional water flooding development, the recommended scheme yields 402,000 tons of cumulative incremental oil, among which the thermal effect contributes 31.6%, the chemical effect contributes 58.1% and the synergistic effect contributes 10.3%. The recovery factor increases by 6.3 percent. Therefore, from the perspective of oil incremental effect, under certain adaptation conditions, hot water chemical flooding can be used as a new technology for heavy oil development.

5. Conclusion

(1) As a new technology for heavy oil development, hot water chemical flooding can reduce the crude oil

viscosity through thermal and chemical effects, resulting in the improvements of oil-water mobility ratio and sweep efficiency. Under certain reservoir conditions, the synergistic effect of thermal effect and chemical effect can further improve the development performance of hot water chemical flooding

(2) It is found that crude oil viscosity and well spacing are important factors affecting the development performance of hot water chemical flooding. The hot water chemical flooding is favorable when the crude oil viscosity is 300~1000 mPa·s. Compared with the water-flooding scheme, the recovery factors are enhanced by 3.5% ~ 10.8%, from which the synergistic effect contributes 0.5% ~ 1.6%. The hot water chemical flooding is favorable when the well spacing is 200~400 m. Compared with the water-flooding scheme, the recovery factor is enhanced by 0.9% ~ 11.5%, where the synergistic effect contributes 0.5% ~ 1.3%. The synergistic effect of hot water chemical flooding achieve the best performance when the well spacing is 300 m

(3) The hot water chemical flooding scheme of the target well group results in 40.2×10^4 tons of incremental oil, and 6.3% of recovery factor being enhanced, which shows strong evidence that hot water chemical flooding enables great oilfield development performance

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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