Exploring Influential Factors for Composite Flooding with Polymer Viscosity Reducers in Heavy Oils

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Abstract

Extracting heavy oil presents significant challenges due to its high viscosity, poor fluidity, elevated asphalt content, and the complexities involved in its development. Traditional extraction methods often fall short of meeting the developmental needs for such oil. Currently, the use of polymer viscosity reducer composite flooding technology has shown promising results both domestically and internationally in heavy oil extraction. While the prospects for this technology are encouraging, there is limited research on the primary factors of the polymer viscosity reducer affecting oil recovery, underscoring the need for further investigation.

A numerical model was formulated using the STARS module of CMG to assess the development of heavy oil extraction via viscosity reducer flooding, polymer flooding, and polymer with viscosity reducer composite flooding. The study contrasted the impacts of these varied injection methodologies on heavy oil recovery. Results indicated that the composite flooding for the polymer and viscosity reducer enhanced the recovery rate by 48.22%, outperforming water flooding or single chemical flooding. Both single-factor analysis and orthogonal design were employed to assess variables such as injection slug, polymer mass concentration, the mass concentration of viscosity reducer, injection timing, and the rate of chemical composite flooding. In terms of enhancing oil recovery, the injection plug volume had the most pronounced impact on recovery, while the timing of injection had minimal impact on efficiency.

This research furnishes crucial technical backing for the enhancement of heavy oil reservoirs through chemical composite flooding. It significantly advances the deployment and application of polymer viscosity reducer chemical composite flooding in similar reservoirs. Moreover, the findings are poised to offer pivotal references and direction for employing chemical composite flooding techniques in heavy oils.

Introduction

Heavy oil, refers to crude oil with a viscosity greater than 50 mPa· s under reservoir conditions or greater than 100 mPa· s for degassed crude oil. Heavy oil is characterized by high viscosity, low mobility, high content of asphalt and heavy hydrocarbons, high cost, low recovery rates, and complex geological conditions, making its development challenging. Most heavy oil reservoirs are difficult to develop using natural energy or water flooding methods. Currently, the main development methods for heavy oil include thermal recovery techniques and cold recovery techniques. Thermal recovery techniques mainly involve steam flooding and steam-assisted gravity drainage, steam-assisted gravity drainage, in-situ combustion, and electric heating techniques (Yuan and

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Wang 2018). These techniques primarily lower the viscosity of heavy oil to enhance recovery rates. They involve injecting high-temperature and high-pressure steam, and hot water, or using electric heating cables to deliver heat to the reservoir, thereby increasing the reservoir temperature and reducing the viscosity of heavy oil. Cold recovery of heavy oil refers to methods of developing heavy oil reservoirs without relying on high-temperature and high-pressure heat media generated by boilers. This approach uses reservoir treatment techniques, wellbore viscosity reduction techniques, and lifting techniques to lower the viscosity of crude oil and improve its flow performance, thereby increasing recovery rates (Xue et al. 2022). Cold recovery techniques for heavy oil mainly include dilution technology, microbial oil displacement technology, chemical oil displacement technology, etc (Chugh et al. 2000).

Chemical oil recovery techniques for heavy oil mainly use chemical agents composed of polymers, alkalis, and surfactants for oil displacement. Among these, polymer flooding is the most widely applied technology to enhance recovery rates (Liu et al. 2020). The mechanism behind its enhanced recovery lies primarily in increasing the sweep efficiency and reducing the water-oil mobility ratio (Amirian et al. 2018).

Asghari and Nakutnyy (2008) conducted polymer flooding experiments on heavy oils with various viscosities, investigating the impact of permeability, displacement speed, and polymer concentration on the effectiveness of polymer flooding. The results showed that after water flooding, to further enhance recovery rates through polymer flooding, the injected polymer concentration needed to exceed a certain value; otherwise, the effect was minimal, and the degree of recovery enhancement by polymers was inversely proportional to the injection rate. Wang and Dong (2009) investigated the influence of polymer viscosity on heavy oil recovery rates. In the case where the viscosity of the heavy oil was 430 mPa·s, and a polymer slug of 0.5 PV was injected, the effective viscosity of the polymer was 3.6 mPa·s, and the recovery rate increased from 41.9%, as seen in water flooding, to 44.1%. Wassmuth et al. (2007) conducted polymer flooding experiments on heavy oils with different viscosities and found that, under reasonable experimental conditions, the recovery rate from polymer flooding was twice that of water flooding. Shi et al. (2010) conducted a study using numerical simulations to investigate the influence of residual resistance factors on incremental oil recovery in polymer flooding. When the RRF increased from 1.5 to 3, the average incremental oil production in polymer flooding increased by 4%. When the RRF reached 6, the incremental recovery rate was 18%. Sedaghat et al. (2013) conducted polymer flooding experiments and numerical studies on a five-spot system with fractured heavy oil reservoirs. Through their research, it was discovered that due to the distribution of the polymer solution within the matrix, in the case of a 45° fracture pattern, the recovery rate of longer fractures would increase, while in a 0° fracture pattern, there would be no change in the recovery rate. Saboorian-Jooybari et al.(2016) established the polymer flooding criteria for heavy oil reservoirs through experiments: reservoir depth less than 5250 ft, porosity greater than 21%, oil viscosity less than 5400 mPa.s, and crude oil gravity greater than 11°API. Lu et al. (2021) discussed the mechanism of enhanced oil recovery by polymer flooding for Changqing, Daqing and other oilfields, and found that there was no positive correlation between polymer viscosity and polymer effect.

Viscosity reduction flooding is primarily achieved by reducing interfacial tension and improving the properties of the oil-water interface, causing the deformation of heavy oil emulsions into water-in-oil emulsions. This process decreases the viscosity and flow resistance of heavy oil, thereby increasing the recovery rate. Guo et al. (2010) aimed to reduce the viscosity of high-viscosity oil in the Tarim Basin's Tahe Oilfield in Xinjiang. They employed an orthogonal method to synthesize a heavy oil-soluble co-polymer viscosity-reducing agent. At 50°C, the addition of this viscosity-reducing agent lowered the crude oil viscosity from 12881mPa.s to 585mPa.s, achieving a viscosity reduction rate of 95.5%. Ghloum et al. (2015) found through experiments viscosity of oil samples decreases with a reduction in temperature. However, when the effect of different viscosity reducers on representative oil sample was studied, at 5000 psi and at reservoir temperature of 190 °F, it was noticed that reduction in viscosity of oil sample from 16,230 centipoises to less than 850 centipoises could be achieved. Wu et al. (2018)studied the viscosity-reducing effect on Henan Oilfield using anionic-nonionic surfactants as viscosity reducers. At a temperature of 30°C, the viscosity of Henan Oilfield was 5888 mPa·s. With an oil-to-water ratio of 3:7 and a viscosity reducer concentration of 0.5%, the viscosity decreased to 29 5mPa·s, achieving a viscosity reduction rate of approximately 95%. Liu et al. (2020) synthesized a water-soluble viscosity-reducing agent using anionic surfactant XJ and nonionic emulsifying agent OP-10. They conducted core-flooding experiments and micro-visual experiments on heavy oil and compared the experimental results with numerical simulation results. At 50°C, the viscosity of the test oil decreased from 1330 mPa·s to 8.49 mPa·s, achieving a viscosity reduction rate of 99%. When applying this viscosity-reducing agent to the J8 block, the daily oil production increased from 7.2 t/d to 15.4 t/d. Liu et al. (2023) investigated the impact of temperature on the viscosity-reducing agent MoO3-ZrO2/HZSM-5. The viscosity of heavy oil increased as the temperature rose. At a temperature of 220°C, the viscosity reduction effect became stable. At 280 degrees Celsius, with a viscosity-reducing agent dosage of 1wt%, the viscosity reduction rate of the heavy oil was 82.26% .

Zhao et al. (2015) conducted an optimization study on suitable polymer and viscosity reducer systems for the Ertan Reservoir in the Shengli Oilfield. The recovery of water flooding was only 41.1%. However, using a polymer system with a mass fraction of 0.3% combined with a nonionic viscosity reducer system of 0.2% could increase the recovery rate by 18.67% compared to water flooding. Sun et al. (2019) conducted research on the characteristics of high viscosity and poor mobility in Block 25 of Shengli Oilfield. They employed chemical agents such as viscosity-reducing agents and polymers to study the dosage of these agents. Experimental results indicated that the combined drive of polymer and viscosity-reducing agents effectively enhanced the ultimate recovery rate. The optimal injection volume for viscosity-reducing agents was 0.1 PV, while for polymers, it was 0.2 PV. The timing of the combined drive injection should follow 1 PV of water flooding. Qi et al. (2023) proposed a composite drive approach involving an Interfacial Active Polymer (IAP) and Emulsifying Viscosity Reducer (EVR) to address the issue of lateral flow in high permeability channels encountered with traditional OVR. Experimental results showed that the polymer-viscosity reducer composite drive could reduce the viscosity of heavy oil from 1000 mPa·s to 325.7 mPa·s. In the high permeability zone, the composite drive achieved an oil recovery rate of 89.85%.

Through the literature review above, it has been verified that composite flooding significantly improves recovery rates compared to single polymer/viscosity-reducing agent flooding. The mechanisms for increasing recovery rates using polymers and viscosity-reducing agents have been clarified. However, there has been no systematic analysis of the impact of factors such as polymer or viscosity-reducing agent mass concentration, plug size, injection rate, and viscosity on recovery. Therefore, the main purpose of this study is to, based on understanding the oil recovery mechanisms of polymers and viscosity-reducing agents, perform sensitivity analysis and orthogonal design on the injection plug volume, polymer mass concentration, viscosity-reducing agent mass concentration, timing of polymer-viscosity-reducing agent composite flooding, and injection speed of the composite flooding, to clarify their respective effects on recovery rates.

The structure of this paper is as follows: The introduction is presented first, followed by the second section introducing reservoir model, fluid model, and chemical agent parameters, along with a detailed description of the simulation scheme. The third section begins by comparing different injection methods for polymer-viscosity-reducing agent composite flooding. It then performs a single-factor analysis on factors, including injection concentration, injection timing, and injection speed, followed by a comparison of the sensitivity of different parameters using an orthogonal design. The final section summarizes the main points and conclusions of this paper.

Methodology and Numerical Model

Reservoir Model. Using CMG software's STARS module, a three-dimensional heterogeneous model was established with a grid size of 21×21×7. The grid dimensions were set as 21×10 m in the I direction, 21×10 m in the J direction, and 7×2.5 m in the Z direction. Due to the fact that the reservoir in this block exhibits a log-normal distribution with a coefficient of variation of 0.65 and an average permeability of 2000 mD, the horizontal permeability are uniform. However, the vertical permeabilities vary. From top to bottom layer, the permeability is set to be 100 mD, 520 mD, 1510 mD, 2040 mD, 2730 mD, 3300 mD, 3800 mD. The well pattern is arranged in a five-spot configuration, and no influence from bottom water or edge water was observed in the reservoir.

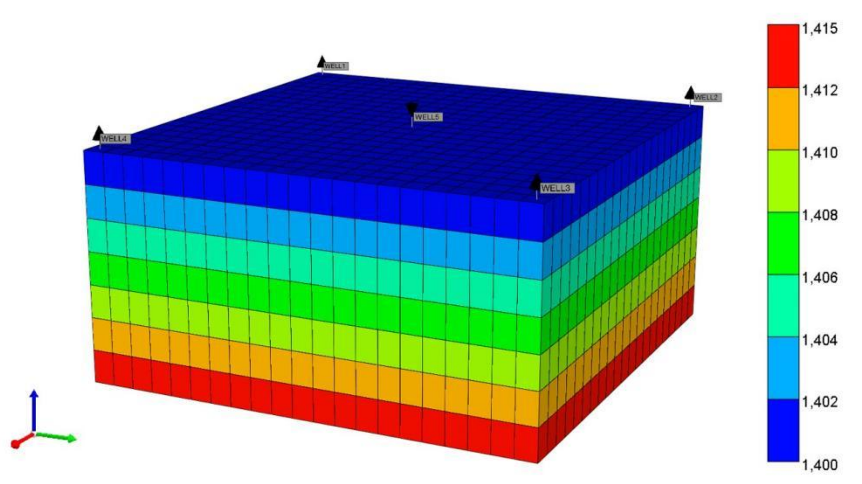


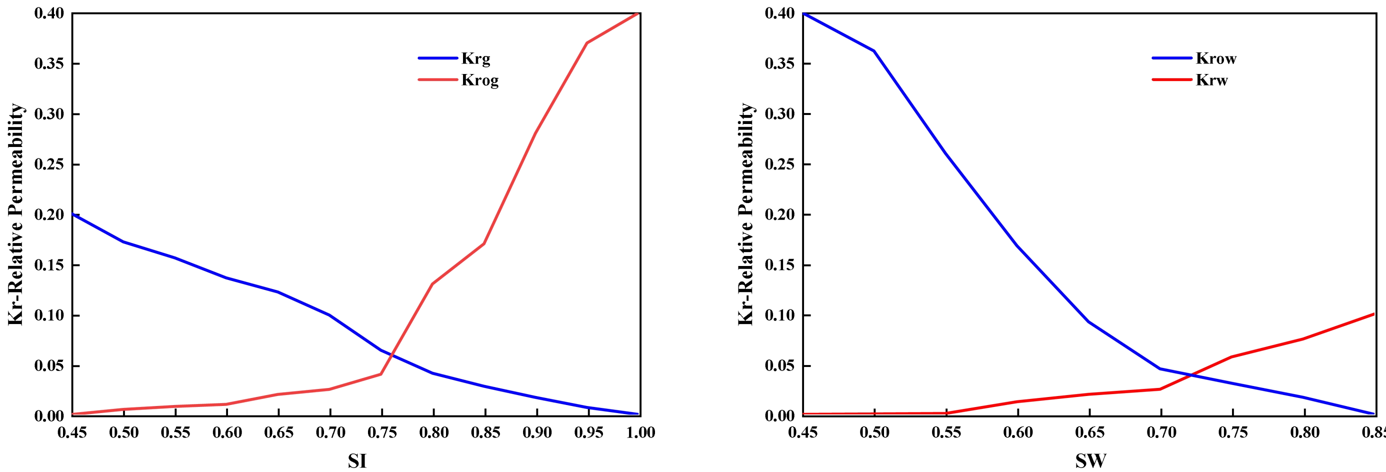
Figure 1—Display of Three-Dimensional Numerical Reservoir Model.

To simulate the actual reservoir conditions as closely as possible, the reservoir model and fluid model are based on the geological description and field conditions from the Ying 8 Block in Shengli Oilfield. The specific parameters are shown in **Table 1**.

Table 1—Reservoir and Fluid Parameter Settings.

Attribute name	Value	Unit
Grid size in the X direction	210	m
Grid size in the Y direction	210	m
Grid size in the Z direction	17.5	m
Underground heavy oil Viscosity	136	mPa·s
Surface crude oil density	0.961	g/cm^3
Average porosity	0.31	%
Average permeability	2000	mD
Oil saturation	55	%
Net-to-Gross ratio	0.69	/
Reservoir reference depth	1400	m
Reservoir reference pressure	13	MPa
Reservoir temperature	57.6	℃

Relative Permeability Curves. Relative permeability curves can effectively describe the fluid flow characteristics of reservoirs within rock formations. **Figure 2** shows the relative permeability curves for oil-water and gas-liquid phases. According to the oil-water phase permeability curve, the water saturation values at the irreducible water saturation points are greater than 0.5, indicating a pronounced hydrophilic property of the reservoir.



(a)Oil-Water phase permeability curve (b)Gas-Liquid phase permeability curve

Figure 2—Block relative permeability curves.

Polymer Viscosity Concentration. The polymer viscosity concentration curve depicts the viscosity variation of polymer solutions at different concentrations. In polymer flooding simulation, using viscosity concentration curve enables a more accurate depiction of the rheological properties of polymer solutions and viscosity changes with concentration. By inputting the polymer viscosity concentration curve data into the STARS software, the viscosity of polymer solutions can be calculated for different concentrations. The viscosity-concentration relationship curve is shown in **Figure 3**.

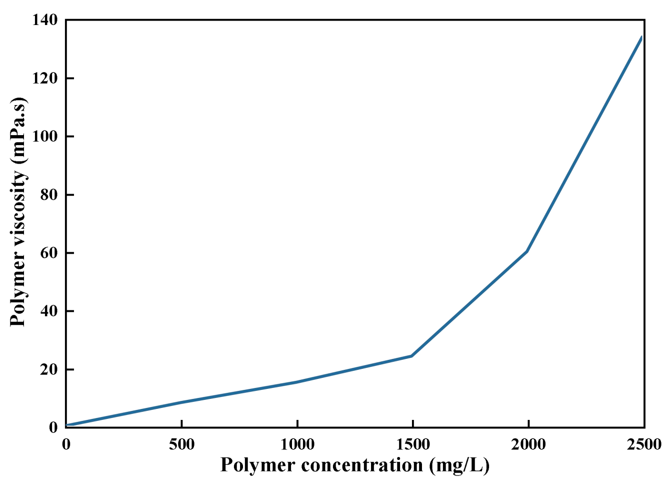


Figure 3—Polymer viscosity-concentration curve.

Polymer Adsorption. The adsorption phenomenon refers to the retention of polymer molecules from polymer aqueous solutions as they flow over rock surfaces. A small amount of adsorption has a minor impact on the entire oil recovery process, but excessive polymer retention can affect the control of the water-oil mobility ratio.

The polymer mass concentration and static adsorption used in the established numerical model are shown in **Figure 4**.

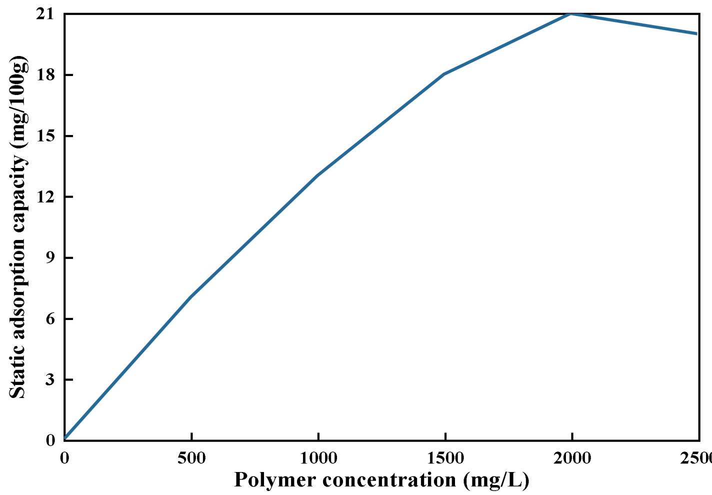


Figure 4—Relationship between polymer mass concentration and adsorption capacity.

Inaccessible Pore Volume. The inaccessible pore volume is the proportion of the total rock volume occupied by the portion of pore volume where polymer molecules cannot enter the pore throats. In this simulation, the value of the inaccessible pore volume is set to about 10% to the total pore volume of the rock.

Residual Resistance Factor for the Adsorbing Component. Residual resistance factor the adsorbing component is an indicator used to describe the residual resistance factor of polymers in the oil displacement process. In this simulation, the RRFT value is set to 2.

Chemical Reaction between Viscosity Reducer and Heavy Oil. After adding the viscosity reducer to the formation, the reducer reacts with heavy oil (Oil) to form light oil (LITT_OIL) and water (Water), the reaction formula is as follows.

a Reducer +b Heavy Oil→ c Light_OIL+d Water,..(1)

where a, b, c, and d represent the number of moles of viscosity reducer, heavy oil, light oil, and water, respectively. After the completion of the reaction, the viscosity of heavy oil is 300 mPa·s, the viscosity of light oil is 30 mPa·s, and the viscosity reduction rate of the viscosity reducer is 90%.

Simulation Workflow. In the process of enhancing oil recovery (EOR), water flooding is first carried out to obtain the recovery rate of water flooding. Subsequently, the chemical injection methods were compared to verify the feasibility of chemical composite flooding of polymer viscosity reducer by measuring enhanced oil recovery. Then, the single-factor analysis method was used to design the experiment, and the sensitivity analysis and orthogonal design of the five parameters of the polymer viscosity reducer composite flood, including injection slug, polymer/viscosity reducer mass concentration, injection timing, and injection rate of composite flooding.

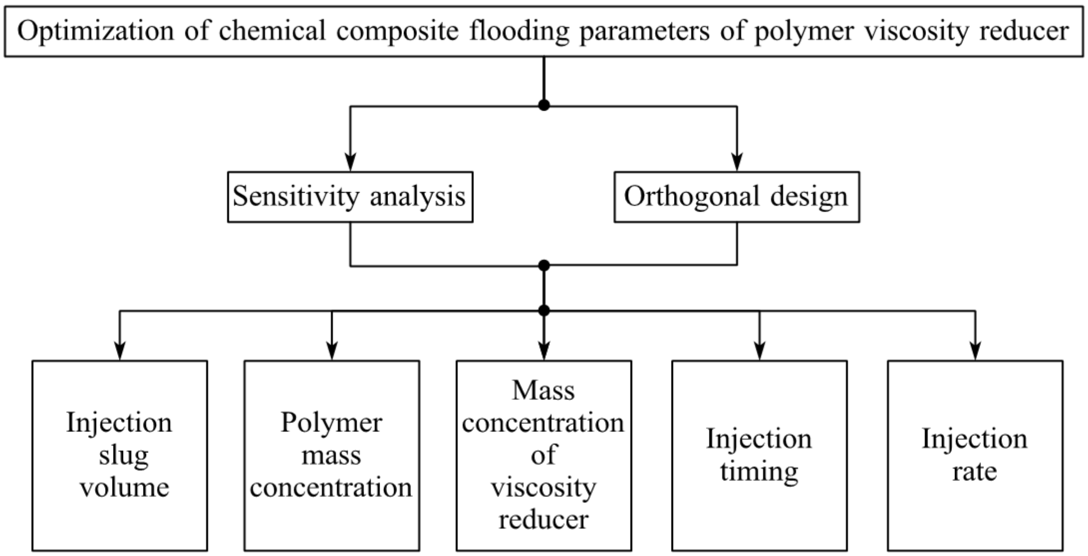


Figure 5—Simulation workflow.

Results and Discussion

Comparison of Chemical Injection Methods. In this study, six different oil displacement methods were adopted for comparative experiments. The specific experimental steps are as follows.

1.The first injection method involves water flooding

2.The second method is to inject 0.6 PV of viscosity reducer with a 60% water cut.

3.The third injection method involves injecting 0.6 PV of polymer at a 60% water cut.

4.The fourth method is to first inject 0.3 PV of viscosity reducer, followed by injecting 0.3 PV of polymer.

5.The fifth method is to first inject 0.3 PV of polymer, followed by injecting 0.3 PV of viscosity reducer.

6.The sixth method involves injecting a composite system of 0.6 PV of polymer and viscosity reducer.

In the experimental protocol, the mass concentration of the polymer was 1000 mg/L, the mass concentration of the viscosity reducer was 2000 mg/L, and the viscosity reduction rate was 90%.

From **Table 2**, it can be concluded that using polymer, viscosity reducer, injecting viscosity reducer first followed by polymer, or injecting polymer first followed by viscosity reducer, all contribute to an increased recovery rate for heavy oil. The recovery rate for oil displacement using a viscosity reducer is only 0.03% higher than that using polymer. The recovery rate for injecting polymer first followed by viscosity reducer is 0.45% higher than that of injecting viscosity reducer first followed by polymer. The recovery rate for polymer viscosity reducer composite flooding is 56.05%, which is 36.17% higher than water flooding, and more than 15% higher than all four other chemical injection methods.

Table 2—Effects of different injection methods of chemical agents on enhanced oil recovery.

Injection scheme	Water flooding	Viscosity reducer	Polymer	Viscosity reducer+ polymer	Polymer+ viscosity reducer	Chemical composite flooding
Recovery (%)	19.88	36.83	36.80	40.14	40.59	56.05
EOR (%)	/	16.95	16.92	20.26	20.71	36.17

As shown in **Figure 6**, water flooding results in the least cumulative oil production, while the cumulative oil production variation among the four injection methods--using polymer, viscosity reducer, injecting polymer first followed by viscosity reducer, and injecting viscosity reducer first followed by polymer--is minimal. The chemical composite flooding exhibits the highest cumulative oil production with the most significant increase.

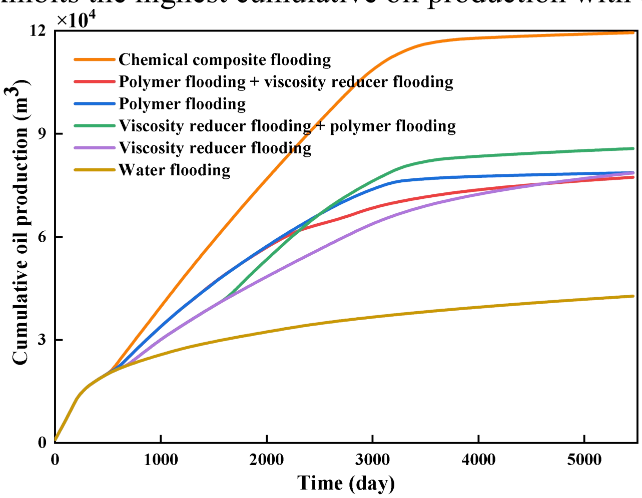


Figure 6—Effect of different injection methods of chemical agents on cumulative oil production.

Figure 7 displays the viscosity oil production curves for the six injection methods. Water flooding shows a gradual decrease in daily oil production. Injecting polymer viscosity reducer composite flooding into heavy oil results in a rapid increase in daily oil production. During the period from 1000 to 1500 days, the daily oil production remains relatively stable without significant changes. However, after 1500 days, the daily oil production started to decline significantly.

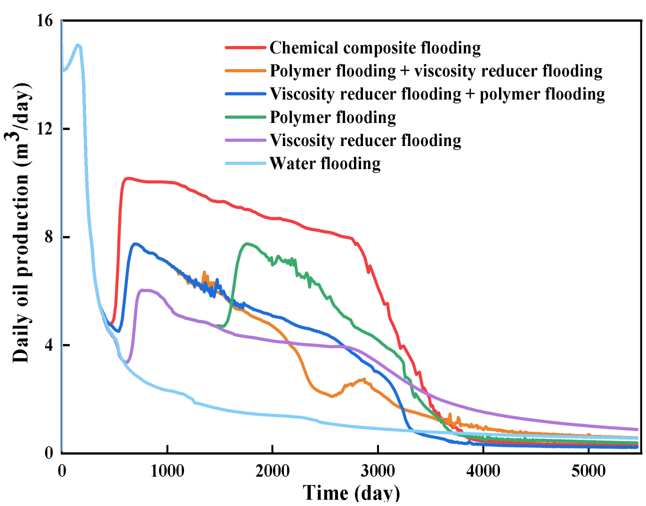


Figure 7—Daily oil curve of different injection methods of chemical agents.

As shown in **Figure 8**, in order to better compare the oil saturation of different chemical injection methods and composite flooding, we analyzed the first, fourth, and seventh layers of the model. In the chemical composite flooding, the oil saturation of the first layer is only low around the injection well, the oil saturation of the fourth layer has decreased significantly, and the oil saturation of the seventh layer is the lowest. By comparing the oil saturation distribution maps of injecting polymer first followed by viscosity reducer, injecting viscosity reducer first followed by polymer, and chemical composite flooding in the first layer, we find that the displacement range of chemical composite flooding is broader and it exhibits a more effective displacement of crude oil. This is primarily because polymer viscosity reducer composite flooding fully utilizes the synergistic effect of polymer and viscosity reducer. The polymer creates a dense front that enhances the displacement effect, while the viscosity reducer reduces the viscosity of the displacing agent, improving its fluidity. The combination of these two factors further enhances the effectiveness of the composite flooding and reduces the oil saturation.

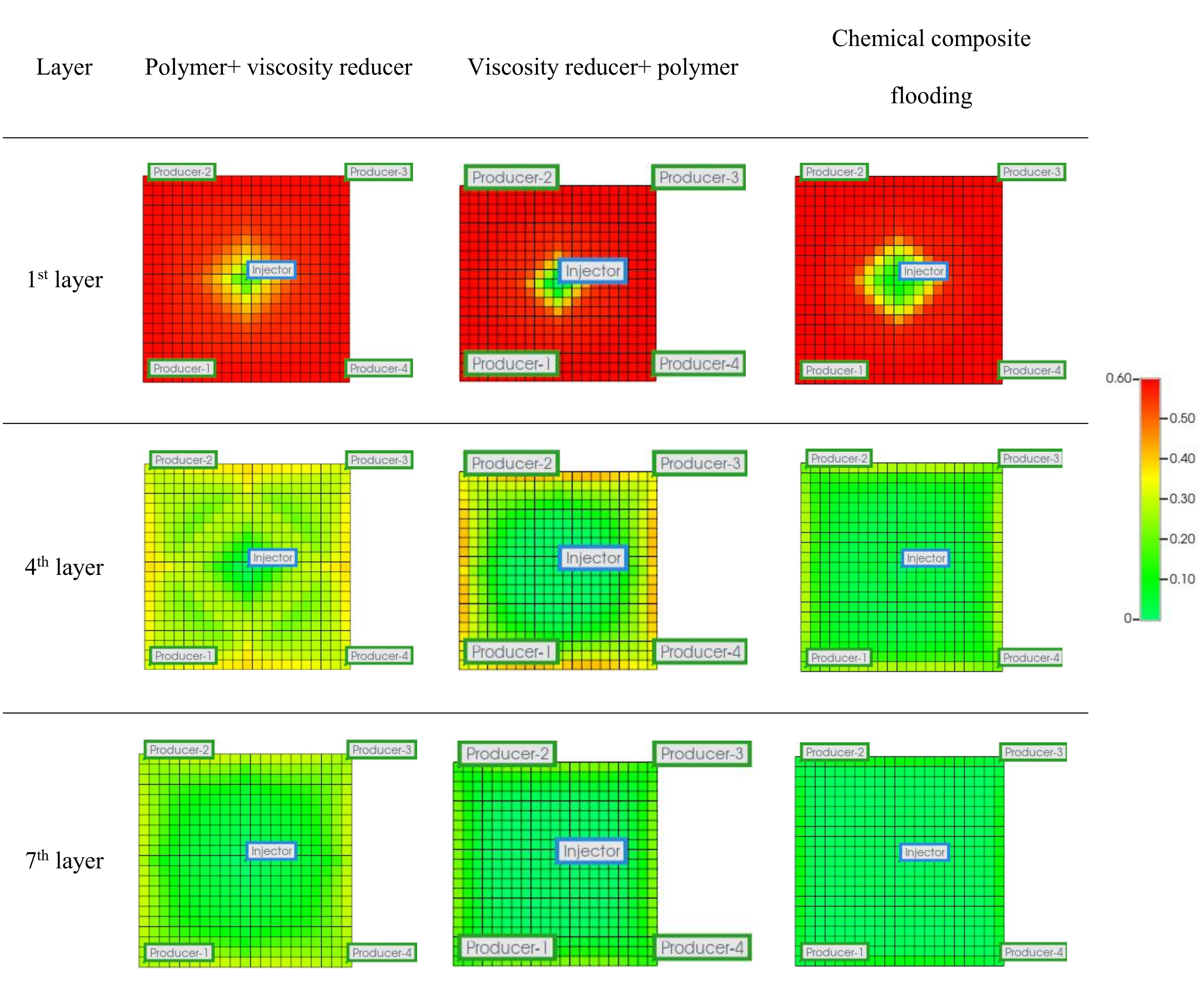


Figure 8—Oil saturation distribution for different injection methods.

Figure 9 is a viscosity comparison chart for different injection methods on January 1, 2035. In the chemical composite flooding, within the first layer of the model, the viscosity reducer only affects the area around the injection well. The closer to the injection well, the greater the degree of viscosity reduction. In the fourth layer, the viscosity reducer has a broader range of influence and a stronger ability to reduce viscosity, except for a slightly less effective reduction in viscosity around the perimeter. In the seventh layer, the viscosity of the heavy oil around the perimeter is also reduced, resulting in the best viscosity reduction effect. Compared to the first layer, the approach of injecting polymer first followed by viscosity reducer only affects the area around the injection well, and its viscosity reduction effect is weaker. Injecting viscosity reducer first followed by polymer has a broader influence, surpassing the effectiveness of injecting polymer first followed by polymer. This indicates that under the same formation conditions, the injection sequence may lead to different effects on the viscosity reduction in composite flooding.

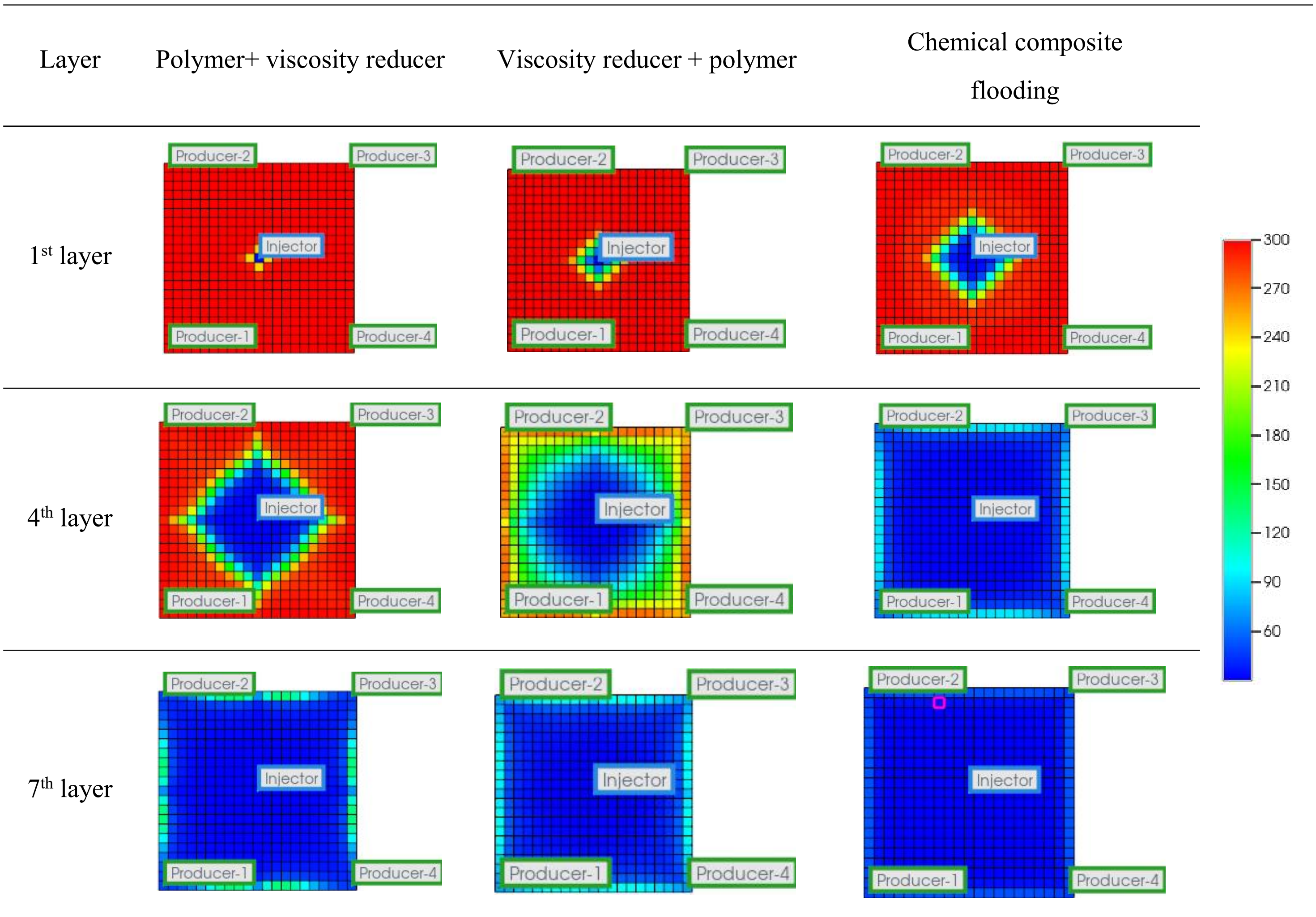


Figure 9—Viscosity distribution of different injection methods and composite displacement of chemical agents.

Optimization of composite drive parameters of polymer viscosity reducer. In oil field development, polymer viscosity reducer are chemical additives used for reservoir improvement, primarily employed to regulate the viscosity of the two-phase fluid of oil and water to enhance crude oil recovery. Optimizing the polymer viscosity reducer drive parameters can more effectively implement reservoir development practices, leading to increased recovery rates, reduced production costs, slowed reservoir depletion, and achieving a more sustainable oil field development. This article focuses on the optimization of the injection slug volume, polymer mass concentration, viscosity reducer mass concentration, injection time, and injection rate in the injection section of the composite drive.

Chemical Composite Flooding Injection Slug Volume. Properly planning the plunger volume for composite flooding can achieve efficient oilfield development and also balance the investment cost of chemical flooding. To better verify the impact of injected plunger volume on recovery rates, four sets of experiments were conducted for comparison. Under a water cut of 60%, injecting polymer at a mass concentration of 2000 mg/L and viscosity reducer at a mass concentration of 2000 mg/L, with an injection rate of 0.1 PV/a, the study investigated the variation in recovery rates and cumulative oil production for injected plunger volumes of 0.2 PV, 0.4 PV, 0.6 PV, 0.8 PV.

As shown in **Table 3**, the recovery rate of water flooding is 19.88%, the recovery rate is 35.60% when the volume of the injection composite flooding plug is 0.2 PV, which is 15.72% higher than that of water flooding, and the recovery rate is 64.25% when the volume of the composite flooding plug of the polymer viscosity reducer is 0.8 PV, which is 44.37% higher than that of water flooding, and the injection section slug is in the range of 0.2 PV-0.8 PV, the larger the volume of the injection section plug, the higher the degree of recovery.

Table 3—Plug volumes of different composite sections enhance oil recovery.

Plan	Water flooding	0.2PV	0.4PV	0.6PV	0.8PV
Recovery (%)	19.88	35.60	46.47	56.03	64.25
EOR (%)	/	15.72	26.59	36.15	44.37

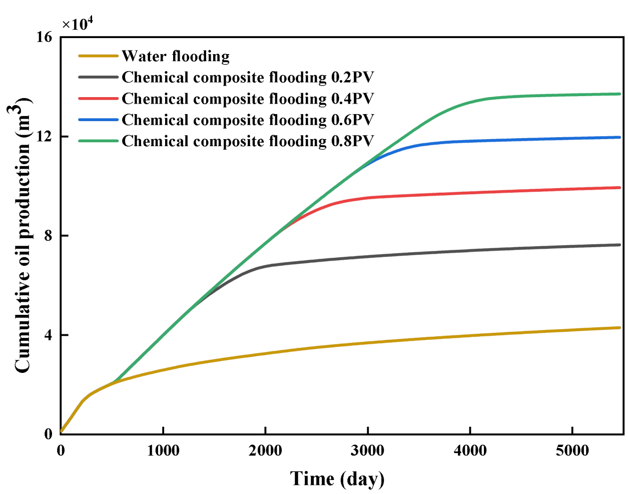


Figure 10—Effect of plugs of different volume sections of composite flooding on cumulative oil production.

Figure 10 illustrates the correspondence between the cumulative oil production and the size of the slug for water flooding and four different injection slug size schemes. The results reveal that cumulative oil production demonstrates an increasing trend with the augmentation of the injection slug volume, indicating that higher production levels lead to greater cumulative oil yields. From the graph, it can be observed that when the injection slug size ranges from 0.2 PV to 0.6 PV, there is a rapid increase in cumulative oil production. However, as the injection slug size ranges from 0.6 PV to 0.8 PV, the rate of increase in cumulative oil production becomes smaller. Moreover, augmenting the slug volume will also escalate economic costs.

Mass Concentration of Viscosity Reducer in Chemical Composite Flooding. To evaluate the effect of different viscosity reducer concentrations on the viscosity of heavy oil and its effect on oil production, we set the following experimental conditions: the composite flooding of polymer and viscosity reducer was injected at an injection rate of 0.1PV/a, with a total injection amount of 0.6PV and a polymer mass concentration of 2000mg/L. By studying the effects of various viscosity reducer effects on enhancing oil recovery, the aim is to highlight the different viscosity-reducing effects of these agents in composite flooding.

As shown in **Table 4**, within the range of viscosity reducer mass concentrations between 1000-3000 mg/L, the higher the mass concentration of the viscosity reducer, the higher the recovery rate. The recovery rate of the viscosity reducer mass concentration of 2000 mg/L increased by 8.67% compared to that of 1500 mg/L, while the recovery rate of the viscosity reducer concentration of 3000 mg/L only increased by 5.49% compared to the mass concentration of 2000 mg/L. This indicates that in the process of using polymer viscosity reducer composite flooding for oil recovery, a higher mass concentration of polymer is not necessarily better.

Table 4—Effects of different viscosity reducer mass concentrations on enhanced oil recovery.

Oil recovery plan	Water flooding	1000mg/L	1500mg/L	2000mg/L	3000mg/L
		80%	85%	90%	95%
Recovery(%)	19.88	47.42	60.37	69.04	74.53
EOR (%)	/	32.04	34.40	49.16	54.65

Figure 10 displays the cumulative oil production at different viscosity reducer mass concentrations. Compared to water flooding, higher viscosity reducer mass concentrations result in greater cumulative oil production. **Figure 11** illustrates the daily oil production at different viscosity reducer mass concentrations. When no viscosity reducer is added, the daily oil production follows a linear downward trend. When the water cut reaches 60%, varying concentrations of viscosity reducer are added. Among them, at a viscosity reducer mass concentration of 3000 mg/L, the daily oil production increases the fastest, reaching a peak of 56 m^3/day. During the 1000-2800-day period after adding the viscosity reducer, daily oil production remains relatively stable without significant fluctuations. Beyond this time frame, daily oil production experiences a significant decline. When the viscosity reducer mass concentrations are 2000 mg/L, 1500 mg/L, and 1000 mg/L, the daily oil production initially rises and then falls, with the most pronounced decrease observed at a viscosity reducer mass concentration of 1000 mg/L. After six years of viscosity reducer injection, the daily oil production notably decreases.

Figure 12 illustrates the viscosity comparison of the seventh layer in the model with and without the addition of a viscosity reducer when the viscosity reducer mass concentration is 3000 mg/L. On the left side is the viscosity plot for January 2020, where no viscosity reducer is injected, and both the injection and production wells contain heavy oil with a viscosity of 300 mPa·s. On the right side is the viscosity plot for January 2035, where the viscosity of the heavy oil has reduced from 300 mPa·s to 30 mPa·s, indicating a significant reduction in viscosity and an ideal viscosity reduction effect.

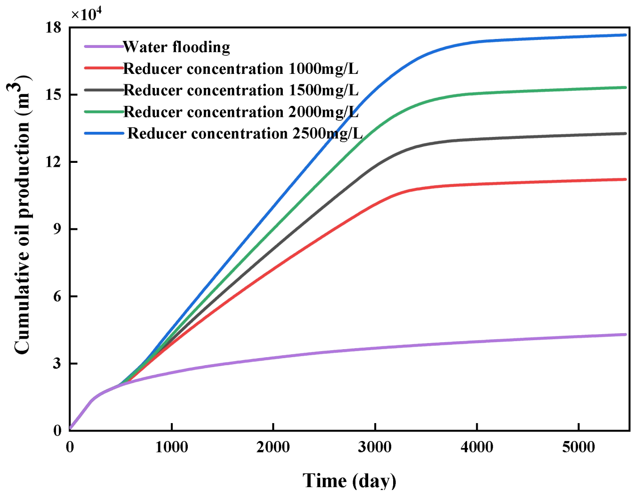


Figure 10—Effect of different viscosity reduction rates on cumulative oil yield in composite flooding.

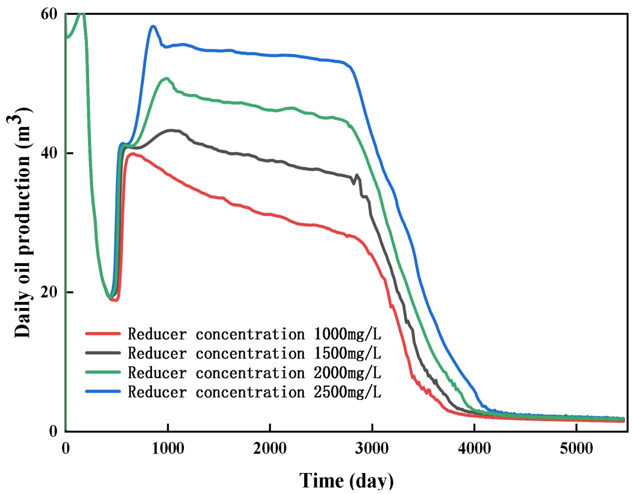


Figure 11—Effect of different viscosity reducing rates on daily oil production of composite flooding.

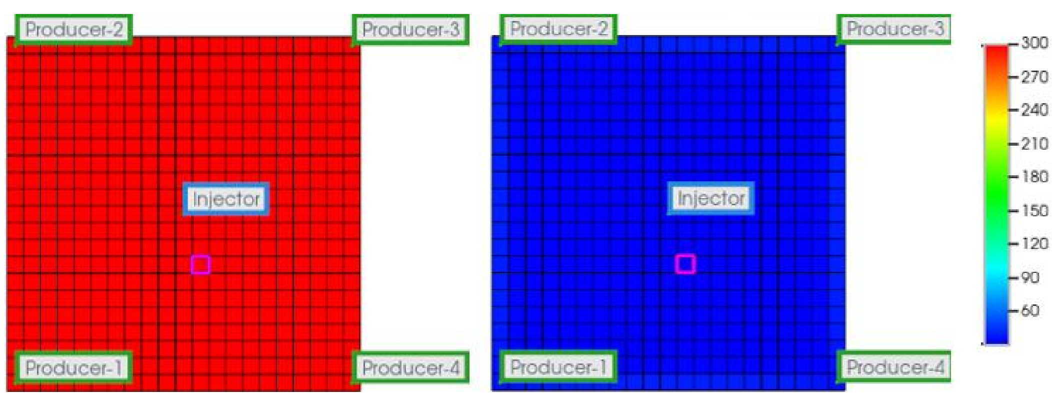


Figure 12—Viscosity distribution. The left figure is the viscosity graph before injection of polymer viscosity reducer composite flooding, and the right figure is the viscosity graph after 15 years of polymer viscosity reducer composite flooding injection.

Mass Concentration of Polymer in Chemical Composite Flooding. In the chemical composite flooding involving polymer and viscosity reducer, injecting different polymer mass concentrations leads to varying oil displacement effects of the composite flooding. Optimal selection of the polymer mass concentration contributes to the superior oil displacement performance of the polymer viscosity reducer composite flooding. To investigate the influence of polymer mass concentration on recovery rates, the following experiments were conducted: Injecting the polymer viscosity reducer composite flooding at a rate of 0.1PV/a for a total volume of 0.6 PV, with a viscosity reduction rate of 90% for the viscosity reducer, under conditions with a water cut of 60%, while varying the polymer mass concentration.

As shown in **Table 5,** there is a positive correlation between the mass concentration of the polymer and the recovery rate. As the mass concentration of the polymer increases, the recovery rate also increases. The recovery rate of water flooding is 19.88%, while the recovery rate of polymer flooding with a mass concentration of 500mg/L is 61.86%, which is 41.98% higher than that of water flooding. Polymers can modify the interactions between oil and water, forming barriers. The addition of polymers increases the viscosity of the flooding fluid and reduces the permeability of water in the pores, enhancing the oil permeability. Therefore, compared to water flooding, polymer flooding can significantly improve the recovery rate.

Figure 13 displays the cumulative oil production for water flooding, using only viscosity reducer, and chemical composite flooding with different concentrations of polymer. Compared to water flooding, whether using only a viscosity reducer or employing chemical composite flooding with various polymer concentrations, all show a significant increase in cumulative oil production. The higher the concentration of polymer, the greater the cumulative oil production.

Table 5—Effects of different polymer mass concentrations on enhanced oil recovery.

Oil recovery plan	Water flooding	500mg/L	1000mg/L	1500mg/L	2000mg/L
Recovery (%)	19.88	61.86	64.82	68.52	71.87
EOR (%)	/	41.98	44.94	48.64	51.99

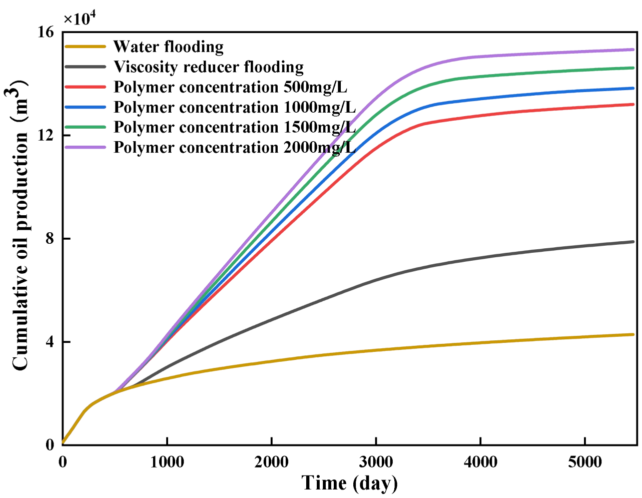


Figure 13—Cumulative oil production at different polymer mass concentrations.

Injection Timing of Chemical Composite Flooding. The volume of the injection section slug is 0.6 PV, the mass concentration of the viscosity reducer is 2000 mg/L (the viscosity reduction rate is 90%), the mass concentration of the polymer is 1000 mg/L, and the polymer viscosity reducer composite flooding is designed to be injected when water cut is 60%, 70%, 80% and 90% respectively, and the recovery and cumulative oil obtained by the four schemes are shown in **Table 6** and **Figure14**.

Table 6—Compound flooding at different injection times.

Oil recovery plan	Water flooding	60%	70%	80%	90%
Days of water injection (days)		330	480	730	1050
Recovery (%)	19.88	55.14	55.08	55.07	55.06
EOR (%)	/	35.26	35.20	35.19	35.18

The earlier the injection polymer viscosity reducer, the higher the degree of recovery, the composite flooding recovery rate of the polymer viscosity reducer injected at 60% is 55.14%, which is 35.26% higher than that of the water flooding recovery rate of 19.88%, and the composite flooding recovery rate of polymer viscosity reducer injection at 90% moisture content is 55.06%, which is only 0.08% lower than that of 60% water content. The effect of injection timing on recovery is very small compared to the effect of polymer viscosity reducer injected plugs on oil recovery. Therefore, when carrying out composite drives infused with polymer viscosity reducers, it is not necessary to pay too much attention to the specific timing of injection. As shown in Figure 14, although the strategy of early injection of polymer viscosity reducer over a 10-year period can increase cumulative oil production, the final cumulative oil production is not affected by the timing of injection.

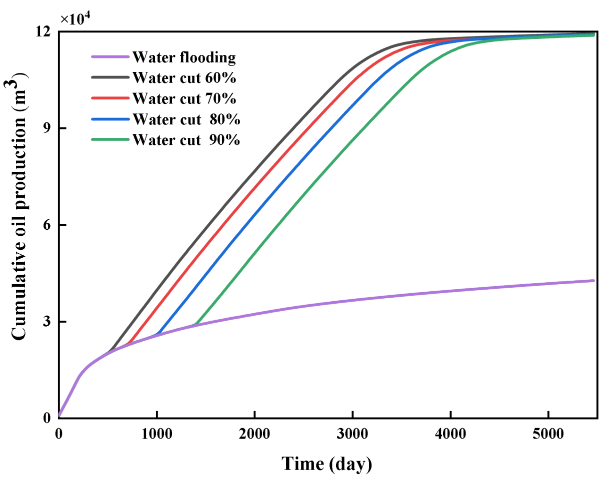


Figure 14—Effect of different injection timing of compound flooding on cumulative oil production.

Injection Rate of Chemical Composite Flooding. The injection speed of chemical compound flooding will impact the production efficiency of the oilfield, and selecting the appropriate injection rate can assist in achieving better oil displacement efficiency. In this study, when the water cut reaches 60%, a composite flooding of polymer viscosity reducer is injected. The volume of the injected compound slug is 0.6 PV, the mass concentration of the viscosity reducer is 2000 mg/L, with a viscosity reduction rate of 90%, and the polymer's mass concentration is 1000 mg/L. The effects of different injection speeds on the efficiency of chemical compound flooding are compared.

From **Table 7**, it can be observed that as the injection rate increases, the recovery rate of water flooding shows an increasing trend. For the polymer viscosity reducer composite flooding, within the range of injection rates from 0.05PV/a to 1.00PV/a, the recovery rate increases. However, when the injection rate exceeds 0.10PV/a, the recovery rate starts to decrease. Within the injection rate range of 0.05PV/a to 0.15PV/a, the highest incremental recovery rate of the composite flooding compared to water flooding occurs at an injection rate of 0.075PV/a, with a value of 37.09%. Conversely, the lowest incremental recovery rate for the composite flooding is observed at an injection rate of 0.05PV/a, at 30.78%. Within the range of injection rates from 0.075PV/a to 0.150PV/a, the difference in recovery rates for composite flooding is 1.08%, while the difference in recovery rates for water flooding is 3.13%. This indicates that changing the injection rate has minimal impact on the recovery rate of polymer viscosity reducer composite flooding.

Table 7—Composite flooding with different injection velocities enhances oil recovery.

Injection rate(PV/a)	0.05	0.075	0.1	0.125	0.15
Recovery (%)	47.64	56.15	57.23	56.82	56.37
Water flooding recovery(%)	16.86	19.06	21.24	21.38	22.19
EOR(%)	30.78	37.09	35.99	35.44	34.18

Figures 15 and **16** depict the impact of water flooding and chemical composite flooding at various injection rates on cumulative oil production. For water flooding, a higher injection rate leads to greater cumulative oil production. The difference in cumulative oil production between an injection rate of 0.100 PV/a and 0.125 PV/a for water flooding is not significant. In the case of composite flooding, when the injection rates are 0.050 PV/a, 0.075 PV/a, and 0.100 PV/a, higher injection rates result in higher cumulative oil production. At injection rates of 0.100 PV/a, 0.125 PV/a, and 0.150 PV/a, during the early stages of extraction, cumulative oil production increases with higher injection rates. However, in the middle to later stages of extraction, there is no significant variation in cumulative oil production for injection rates of 0.125 PV/a and 0.150 PV/a.

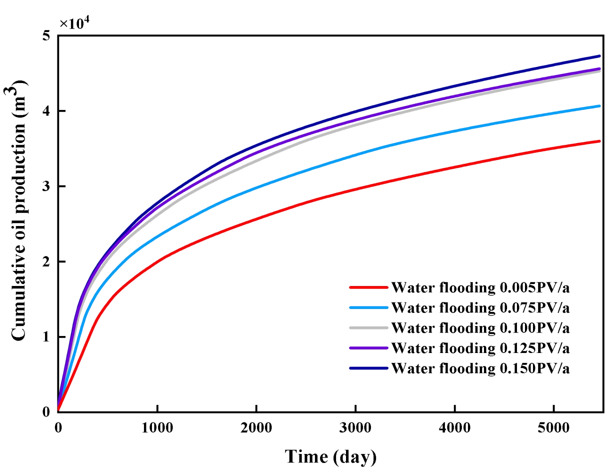


Figure 15—Effects of different injection speeds of water flooding on cumulative oil production.

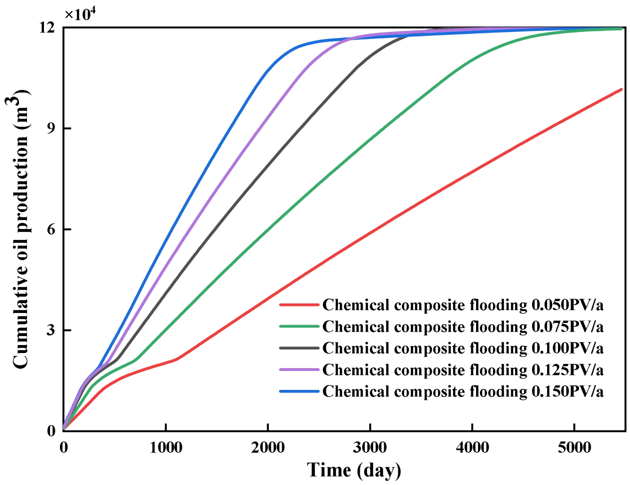


Figure 16—Effect of different injection speeds on cumulative oil yield of composite flooding.

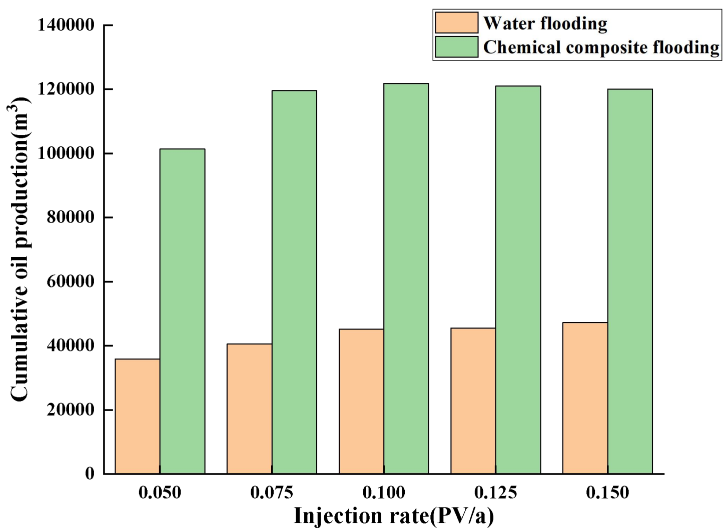


Figure 17—Comparison of cumulative oil production at different injection rates.

Orthogonal Design. An orthogonal design experiment is a design method to study multi-factor and multi-level, mainly using orthogonal table tools for overall design, comprehensive comparison, and statistical analysis. According to the orthogonality, some representative points are selected from the comprehensive experiment for experiments, these points have the characteristics of "uniform dispersion, neatness and comparable", and reasonable arrangement of experiments with orthogonal tables can greatly reduce the number of experiments and improve the efficiency of the experimental site (Gong et al. 2008).

Table 8—Orthogonal design experiment table.

Serial number / Line number	Injection plug（PV）	Viscosity reducer concentration (mg/L)	Polymer concentration (mg/L)	Injection timing（%）	Injection rate（PV/a）	EOR（%）
1	0.3	1000	500	50	0.075	13.06
2	0.3	1500	1000	60	0.100	21.70
3	0.3	2000	1500	70	0.125	28.22
4	0.3	3000	2000	80	0.150	35.07
5	0.4	1000	1000	70	0.150	20.18
6	0.4	1500	500	80	0.125	23.56
7	0.4	2000	2000	50	0.100	38.05
8	0.4	3000	1500	60	0.075	40.39
9	0.5	1000	1500	80	0.100	26.83
10	0.5	1500	500	70	0.075	26.52
11	0.5	2000	2000	60	0.150	43.94
12	0.5	3000	1000	50	0.125	47.96
13	0.6	1000	2000	60	0.125	33.23
14	0.6	1500	1500	50	0.150	38.25
15	0.6	2000	1000	80	0.075	43.18
16	0.6	3000	500	70	0.100	52.79

In this experiment, five factors and four levels were selected, including polymer mass concentration, mass concentration of viscosity reducer, volume of polymer viscosity reducer composite flood injection segment, timing of composite drive injection, and composite flood injection rate, and adopted orthogonal table design, a total of 16 sets of experiments were required, and the parameter design of each group of experiments was shown in **Table 8**.

To visualize the sensitivity of each factor to enhanced oil recovery, a range analysis was performed using statistical methods, and the results are shown in **Table 9**.

Table 9—Orthogonal design results.

Factor	Mean value1	Mean value2	Mean value3	Mean value4	Range	Relative difference	Importance ranking
Injection plug（PV）	24.51	30.54	36.32	41.87	17.36	8.68	1
Polymer concentration（mg/L）	28.98	33.26	33.42	37.58	8.60	2.15	3
Viscosity reducer concentration（mg/L）	23.33	27.51	38.41	44.06	20.74	6.91	2
Injection timing（%）	34.82	34.33	32.16	31.93	2.89	1.93	5
Injection rate（PV/a）	30.79	34.84	34.37	33.24	4.05	2.03	4

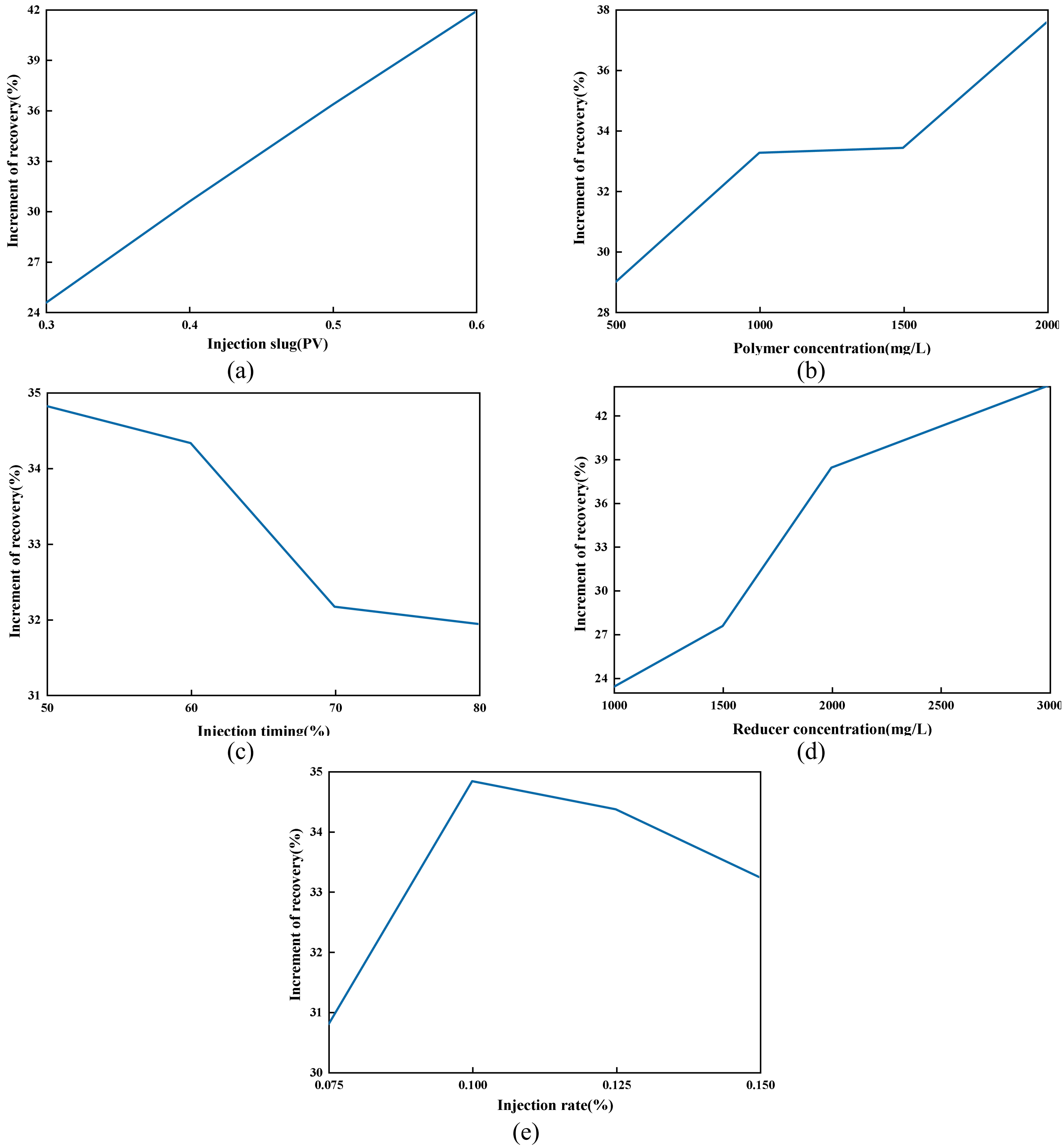


Figure 18—Oil recovery increment under different parameters: (a) injection slug; (b) Polymer concentration; (c) the mass concentration of viscosity reducer; (d)injection timing; (e) Injection rate.

Analysis of **Table 9** shows that the importance of each factor is as follows: chemical composite flooding injection slug volume, chemical composite displacement adhesive mass concentration, chemical composite flooding injection timing, chemical composite flooding polymer mass concentration, and chemical composite flooding injection rate. The mass concentration of chemical composite flooding polymer, chemical composite flooding injection timing, and chemical composite flooding did not have a great effect on oil recovery, and the volume of chemical composite flooding injection plug was the factor that had the greatest impact on the recovery effect.

To further analyze the trend of the impact of each factor on oil recovery, the change in oil recovery with each factor is plotted based on the results of Table 9, as shown in **Figure 18**. It can be concluded that the volume of the injection volume increases, and so does the recovery rate. Increasing the volume of the injection slug can expand the range of chemical agents, improve the chance of contact between chemical flooding agents and crude oil, increase the displacement efficiency of crude oil in reservoirs, and improve oil recovery.

It also can be observed that as the mass concentration of the polymer increases, the overall increase in recovery rate also shows an upward trend (Figure 18(b)). The slower increase in recovery rate when the polymer mass concentration increases from 1000 mg/L to 1500 mg/L may be due to having already achieved a certain level of enhanced production effect at lower concentrations. When the concentration is low, the polymer can form an effective displacement system with the crude oil, reducing the viscosity of the oil, improving the interaction between oil and water, and thereby increasing the recovery rate. However, as the concentration gradually increases, the additional amount of polymer may not significantly improve the displacement effect, as a high displacement efficiency has already been achieved, and further increasing the concentration has a relatively minor impact on enhancing the recovery rate.

In chemical composite flooding, there is a positive correlation between the mass concentration of the viscosity reducer and increased oil recovery. The higher the mass concentration of the viscosity reducer, the more effectively it can reduce the viscosity of crude oil, enhance its interaction with crude oil, and consequently improve the oil recovery rate.

The later the chemical composite flooding injection is initiated, the less effective the EOR will be. Later injection times can lead to uneven distribution of crude oil and chemical adsorption and repulsion, insufficient energy balance, and the release of crude oil may be limited, thus affecting the effect of enhanced oil recovery.
When the chemical composite flooding rate exceeds 1.0 PV/a, the rate of increased recovery begins to decline. If the chemical composite flooding rate is too high, it might lead to insufficient contact and mixing between the polymer or viscosity reducer and the crude oil, diminishing their mutual interaction, reducing displacement efficiency, and subsequently lowering the enhanced oil recovery effect.

Conclusions

In this paper, the effect of oil recovery on chemical composite flooding of heavy oil polymer viscosity reducer was studied, and the following conclusions were drawn:

1. Polymer-viscosity reducer composite flooding has a better oil recovery effect compared to the four other methods of single polymer injection, single viscosity reducer injection, polymer injection followed by viscosity reducer injection, and viscosity reducer injection followed by polymer injection. This is because the polymer expands the sweep volume, while the viscosity reducer reduces the viscosity of the oil in the swept area, resulting in a synergistic enhancement effect.
2. Factors influencing the recovery rate: The recovery rate is positively correlated with the volume of the injection slug, the concentration of polymer, and the concentration of viscosity reducer. The timing of injection has a minimal impact on the recovery rate.
3. The impact of harvesting efficiency follows the sequence in the following order: injection slug volume>viscosity reducer concentration>polymer concentration > injection rate> injection timing.

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Conflicting Interests

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

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