Residual oil start-up mechanism of polymer/surface dual flooding after polymer flooding in medium-high permeability reservoir

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Abstract. The remaining oil distribution and displacement mechanism of poly/surface dual flooding stage in medium and high permeability reservoir are not clear. In this paper, the reservoir conditions in Gangxi Area 3 of Dagang Oilfield were taken as the research object. Based on nuclear magnetic resonance and large model physical simulation experiment, the characterization of micro and macro residual oil start-up mechanism and enhanced oil recovery experiment were carried out respectively after polymer flooding poly/surface binary flooding. The experimental results suggest that polymer-surfactant flooding could increase the oil displacement efficiency by 12-29% after polymer flooding, and the contribution of porous to recovery degree is in the order of medium pore, large pore, and small pore. When the surfactant concentration is higher than 0.25%, the increase of oil displacement efficiency tends to be stable, and further enhancing oil recovery requires the expansion of sweep volume. Physical model experiments results show that medium permeability layer has the highest contribution to the recovery degree in the chemical flooding stage, and the displacement mechanism is mainly based on the synergistic effect of expanding sweep volume and improving displacement efficiency. The contribution of low permeability layer to recovery degree is next, and the displacement mechanism is mainly to expand sweep volume. The high permeability layer has the lowest contribution to the recovery degree, and the oil displacement mechanism is mainly to improve the oil displacement efficiency.

Keywords: Polymer-surfactant flooding, Nuclear magnetic resonance, Recovery factor, Starting mechanism.

1. Introduction

In order to solve the problem of low water flooding recovery in medium and high permeability reservoirs, polymer flooding technology has been applied to the old oil fields represented by Daqing, which has achieved a better effect of enhanced oil recovery [1-3]. As the development continues and the injection and production Wells form advantageous channels, the polymer application becomes less effective and new measures to enhance oil recovery are needed. Polysurface binary flooding is an innovative technology after polymer flooding, which can expand the sweep volume of polymer and improve the washing efficiency of surfactant [4-6]. The high permeability reservoir in Dagang oilfield is rich in reserves, but the phenomenon of inter injection and production Wells is obvious. it has reached the development stage of "double high" (water cut is higher than 60%, and the degree of recoverable reserves is higher than 60%). At present, the application of polymer flooding or polymer surface binary flooding technology has achieved obvious effect of oil increase and precipitation [7-9]. With the development of polymer flooding, it is difficult to determine whether continuous injection of chemical systems is effective or not, and the contribution degree of polymers and surfactants in various core pores. Therefore, it is necessary to carry out relevant research to support the design of oilfield post-polymer flooding development scheme.

At present, nuclear magnetic resonance technology is widely used in the industry to study the distribution of remaining oil in core pores at different displacement stages, and certain research results have been achieved. Fan Meng, aiming at the development of polymer flooding in high permeability heavy oil reservoirs, based on the nuclear magnetic resonance technology, analyzed that the oil signal of medium and large pores decreased after polymer flooding, and the polymer significantly improved the sweep degree of small pores and the basic law of displacement efficiency of medium and large pores

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[10]. Liu Zheyu made clear the difference between single-mode and complex mode pore structure cores through the in-situ NMR displacement experiment of natural cores, and the main reason for the utilization of residual oil in large and medium pores to enhance oil recovery in binary composite flooding [11]. Using nuclear magnetic resonance technology, Zhang Zhentao et al. compared the emulsification effect of chemical flooding on crude oil in each pore and the effect of reducing interfacial tension, and analyzed that the injection of surfactant after gas flooding has a higher degree of use on small pores [12]. Sun Chen used ultraviolet fluorescence and heavy water nuclear magnetic resonance technology to analyze all the displacement test cores for conglomerate reservoirs, to clarify the utilization of microscopic remaining oil in pore throat of different sizes, and to give the application limit template of chemical flooding in different types of conglomerate reservoirs [13]. It is found in literature research that there has been a clear explanation for the characterization of microscopic residual oil utilization in homogeneous core, but homogeneous core is difficult to represent the permeability change of the actual reservoir. It is necessary to associate the NMR micro-characterization with the macroscopic physical experiment to clarify the contribution of each system to the oil recovery in binary flooding, so as to provide reference for the actual oilfield development.

2. Conditions of experiment

2.1 Material of experiment

The polymer was partially hydrolyzed polyacrylamide BHHP-112 provided on site, with a relative molecular weight of 25 million, hydrolysis degree of about 25% and solid content of 88%. The surfactant is DWS-3 nonionic surfactant with an effective content of 40%. The experimental oil was the crude oil from the third section of Gangxi in Dagang Oilfield. The simulated oil was prepared with dehydrated crude oil and kerosene in a certain proportion. The viscosity was 17mPa·s at 53℃. In the process of experiment, the mother liquor of polymer and surfactant was prepared by using the sewage produced from the oil well and diluted to the concentration required by the experimental scheme. The salinity of the produced sewage was shown in Table 1.

Table 1. The ion composition of the sewage in the Gang Xi

Type of ions	K^++Na^+	Mg^{2+}	Ca^{2+}	Cl^-	SO_4^{2-}	HCO_3^-	CO_3^{2-}	Total salinity
Content(mg/L)	2043	36	39	1347	0	3126	135	6750

The NMR experimental core is an artificial homogenous columnar core with quartz sand epoxy resin cement, and the relevant parameters are shown in Table 2. The large-scale physical displacement experimental core is a longitudinal three-layer heterogeneous high-pore core with a size of 80 cm×80 cm×4.5cm. The gas permeability of the high, middle and low layers is $3000\times10^{-3}\mu m^2$, $900\times10^{-3}\mu m^2$ and $300\times10^{-3}\mu m^2$, respectively, and the porosity is 32%. Electrode layout: 36 pairs are distributed in each layer, 108 pairs in total, for oil saturation monitoring, one injection and one production well pattern. The model is shown in Figure 1.

Table 2. Physical property parameters of experimental cores

Plan	Length (cm)	Diameter (cm)	Porosity (%)	Permeability ($\times10^{-3}\mu m^2$)	Oil saturation (%)
1	8.45	2.52	30.00	636	72.83
2	8.29	2.52	29.59	770	72.85
3	8.45	2.52	28.77	675	72.52
4	8.12	2.52	29.98	748	73.69
5	8.03	2.52	30.01	705	73.92

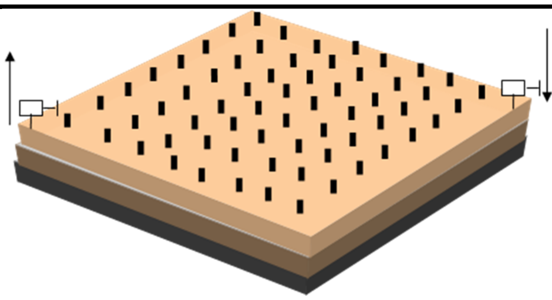


Figure 1. Physical experimental model of flat plate

2.2 Experimental instruments and procedures

2.2.1 Instruments and equipment

BROOKFIELD DV-II+Pro Brinell viscomter was used to test the viscosity of the system, and TX-500 rotary drop interfacial tensimeter was used to test the interfacial tension of the system. Related supporting instruments and equipment include HJ-6 multi-head magnetic agitator, electronic balance (JA2003A, Accuracy is 1mg), beaker, test tube and Brock nuclear magnetic resonance instrument (Fourier 80, Germany Brock Magnetic Resonance Division)

A displacement experimental device, including SG83-1 incubator, advection pump (LB-1), pressure sensor, core gripper, hand pump and intermediate vessel, was used to evaluate the oil displacement effect in core of polymer dual system.

2.2.2 Experimental procedures

(1) The permeability of the core is measured by gas;
(2) After the core is pumped out for 2 hours, the site sewage is saturated and the porosity is measured;
(3) The saturated sewage model was placed in a thermostatic box at 53℃ for more than 12 hours;
(4) When the model is saturated with oil, the oil floods until there is no water at the outlet of the model, the original oil saturation is determined, and the T2 spectrum is measured by core scanning.

(5) After water flooding to 100% water content at the outlet of the model, T2 spectrum was measured by core scanning.
(6) The surfactant and polymer mother liquor were prepared according to the experimental scheme, and stood at room temperature for 12 hours. Then the required binary composite system was prepared, and the binary composite system was placed in a constant temperature box for 2 hours;
(7) Chemical flooding was carried out according to the experimental scheme;
(8) After all the chemical slug was injected, water flooding was followed, and the water cut at the outlet reached 100%. The core was scanned and the T2 spectrum was determined;
The injection rate was 0.6mL/min during the above experiment, and the changes of oil saturation were monitored after saturated oil, water flooding, poly flooding and binary composite flooding.
All the experiments were carried out at 53℃ in Gangxi Reservoir.

3. Results and Discussion

3.1 Comparison of oil displacement effect

The oil displacement experiment schemes include: water flooding to 100% water cut at the outlet, polymer (1500mg/L) flooding 3PV, poly/surface binary flooding 3PV, and subsequent water flooding to 100% water cut. Among them, the binary system: the polymer concentration is 1500 mg/L, 2000mg/L, 2500mg/L, and the surfactant concentration is 0.15%, 0.25%, 0.30%. The results of oil displacement experiment are shown in Table 3.

Table 3. Experimental data of oil displacement in binary system with different concentrations

Plan	Concentration of polymer (mg/L)	Concentration of surfactant (%)	Viscosity (mPa·s)	Interfacial tension (mN/m)	Oil recovery factor (%)			
					Water	Polymer	Twoelement	EOR
1	1500	0.15	39.67	2.03×10^{-2}	30.05	10.30	12.06	52.41
2	2000	0.15	71.23	3.97×10^{-2}	29.98	9.90	16.95	56.83
3	2500	0.15	117.33	5.56×10^{-2}	30.05	10.13	19.35	59.53
4	2000	0.25	70.40	8.92×10^{-3}	30.17	9.72	27.14	67.03
5	2000	0.3	70.82	7.80×10^{-3}	30.20	9.89	28.07	68.16

The final oil displacement efficiency of columnar core flooding experiment is 52.41%~68.16%. After polymer flooding, the oil displacement efficiency was increased by 12.06~28.07%. It can be seen that only relying on polymer flooding to improve the oil displacement efficiency is only about 10%, and the improvement range is limited. With the implementation of binary flooding and the increase of concentration, the final oil displacement efficiency is gradually improved. When the surfactant concentration is constant, the final oil displacement efficiency increases with the increase of polymer concentration, which indicates that the high viscosity of polymer can effectively expand the sweep volume and improve the utilization degree of crude oil. When the polymer concentration is constant, the final oil displacement efficiency increases with the increase of surfactant concentration. The increase of surfactant concentration can effectively reduce the oil-water interfacial tension, increase the capillary number, reduce the adhesion of crude oil on the rock surface, and improve the oil displacement efficiency. Therefore, the improvement of oil displacement efficiency in the binary system is generally the result of the synergistic effect of the expanded sweep volume of polymer and the improvement of the washing efficiency of surfactant.
It is worth noting that when the surfactant concentration reaches a critical value, the increase of oil displacement efficiency becomes stable. For example, compared with scheme 4, the polymer concentration of scheme 2 is the same, the surfactant increases from 0.15% to 0.25%, the oil displacement efficiency increases by 10.19 percentage points, and the interfacial tension decreases from 10^{-2} to 10^{-3}, indicating that the DSS-3 surfactant can reduce the capillary force and improve the oil displacement efficiency. The comparison between scheme 4 and scheme 5 showed that although the surfactant increased by 0.05%, the oil displacement efficiency increased by less than 1 percentage point. It shows that 0.25% surfactant can basically exert the maximum effect of oil washing in the affected area.

3.2 Comparison of recovery degree

NMR instrument mainly reflects the fluid in large and small pores through the length of time component of T2 distribution spectrum [14-16]. The relaxation time of fluid in core pores mainly depends on the strength of fluid molecules under the applied force of pore solid surface [17-18]. When the force exerted by the pore solid surface is strong, the fluid is in a bound or immobile state, and the

T2 relaxation time is small on the NMR. On the contrary, the fluid in the large pore, when the force on the solid surface of the pore is weak, this part of the fluid T2 relaxation time is larger. Therefore, NMR T2 spectrum can be used to analyze the occurrence of crude oil in core pores, and give quantitative evaluation parameters such as oil saturation and utilization degree at each stage of displacement.

According to the NMR data, the oil phase recovery degree of each interval after water flooding and chemical flooding is shown in Table 4. According to the different signal amplitude of T2 spectrum NMR in different states, the size of pore throat was divided into three sections. Signal values with T2 relaxation time less than 10ms reflect small pores; signal values with T2 relaxation time between 10-50ms reflect medium pores; signal values with T2 relaxation time greater than 50ms reflect large pores.

Table 4. Oil recovery degree in different intervals of T2 spectrum after water flooding/binary flooding (%)

Plan	All intervals		<10ms			10-50ms			>50ms		
	Water	Binary	Water	Binary	Growth	Water	Binary	Growth	Water	Binary	Growth
1	30.05	52.41	1.42	10.53	9.11	15.16	22.64	7.48	13.47	19.24	5.77
2	29.98	56.83	1.40	10.12	8.72	15.13	26.12	10.99	13.45	20.58	7.13
3	30.05	59.53	1.42	9.16	7.74	15.16	29.44	14.28	13.47	20.93	7.46
4	30.17	67.03	1.46	11.23	9.77	15.22	31.34	16.12	13.49	24.45	10.96
5	30.17	68.16	1.46	11.64	10.18	15.22	31.94	16.72	13.49	24.58	11.09

Compared with schemes 1, 2 and 3, it can be seen that under the condition of constant surfactant concentration (0.15%), with the increase of polymer concentration, the recovery degree of the middle pore increases rapidly, the large pore only increases slightly, and the small pore decreases slightly. The analysis shows that in the polymer/surface binary flooding after polymer flooding, the polymer mainly uses the remaining oil in the middle pore which has not been affected. Due to the relatively high utilization degree of macropores in the early stage and insufficient development potential in the later stage, the increase of recovery degree of binary flooding is low. Due to the increase of polymer concentration, its hydrodynamic size increases, its injection in small pores decreases, and the recovery degree of binary flooding decreases slightly.

Compared with schemes 2, 4 and 5, it can be seen that under the condition of a constant polymer concentration (2000mg/L), with the increase of surfactant concentration, the recovery degree of each pore is improved, and the increase order is as follows: medium pore > large pore > small pore. The analysis shows that the surfactant can improve the oil washing efficiency in the affected area, and the middle and large pore sweep volume is relatively high, so the oil washing capacity of surfactant can be fully brought into play. Similarly, due to the relatively high utilization degree of large pores in the early stage, the increase of recovery degree of dual flooding is less than that of middle pores.

3.3 Contribution rate of large/medium/small pores to recovery degree

The contribution rates of different pore intervals to the improvement of recovery degree in the binary composite flooding stage are shown in Table 5.

Table 5. Contribution rate of binary flooding to the improvement of recovery degree in different pore intervals

Plan	Recovery degree contribution rate		
	Small pore (%)	Medium pore (%)	Large pore (%)
1	40.74	33.45	25.81
2	32.49	40.95	26.56
3	26.26	48.44	25.31
4	26.51	43.74	29.74
5	26.80	44.01	29.19

As can be seen from Table 5, except for Scheme 1, the contribution rate of middle pores is the largest in the binary compound flooding stage, which is all above 40% or even 48.44%, while the contribution rate of small pores and large pores is relatively low. It can be seen that the binary composite flooding mainly displaces the remaining oil in the middle pores, and small pores and large pores can also achieve a certain effect. Due to the high degree of recovery in the water flooding stage, the contribution rate of the binary compound flooding stage is reduced. In Scheme 1, the polymer concentration is low, the molecular dynamics radius of the system is relatively small, and it is easy to enter small pores, so the recovery degree of small pores contributes relatively high. However, due to the low concentration of poly/surface binary, the oil displacement effect on the large pores is relatively insufficient, so the final oil recovery rate is low.

3.4 Polymer/surfactant contribution to recovery

A large-scale physical model was used to conduct oil displacement simulation experiment. The steps included water flooding to 98% water cut, 1500mg/L polymer flooding to 0.25PV, binary composite flooding to 0.4PV, and subsequent water flooding to 98% water cut. The binary flooding scheme was 0.2PV (Cp=2000mg/L, Cs=0.25%) + 0.2PV (Cp=1500mg/L, Cs=0.2%)

combined slug. The contribution rates of mobility control and increase of capillary number to recovery after polymer flooding were analyzed. Table 6 and Table 7 respectively compare the statistical table of stage recovery degree results and the contribution rate of each layer recovery degree in chemical flooding stage.

Table 6. Statistical table of recovery degree at each stage

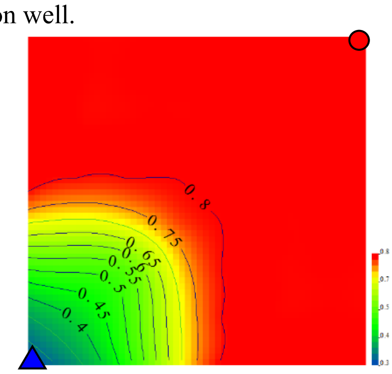
Plan	Porosity (%)	Oil saturation (%)	Oil recovery factor (%)		
			Water	Chemical drive	Total
6	29.55	77.48	37.09	33.15	70.23

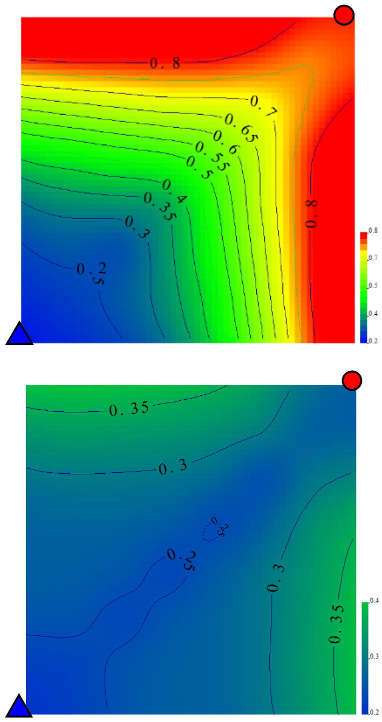
Table 7. Contribution rate of recovery degree of each layer in chemical flooding stage

Plan	Contribution rate of recovery degree of each layer in chemical flooding stage (%)		
	Low permeability layer	Medium permeability layer	High permeability layer
6	42.36	51.34	6.30

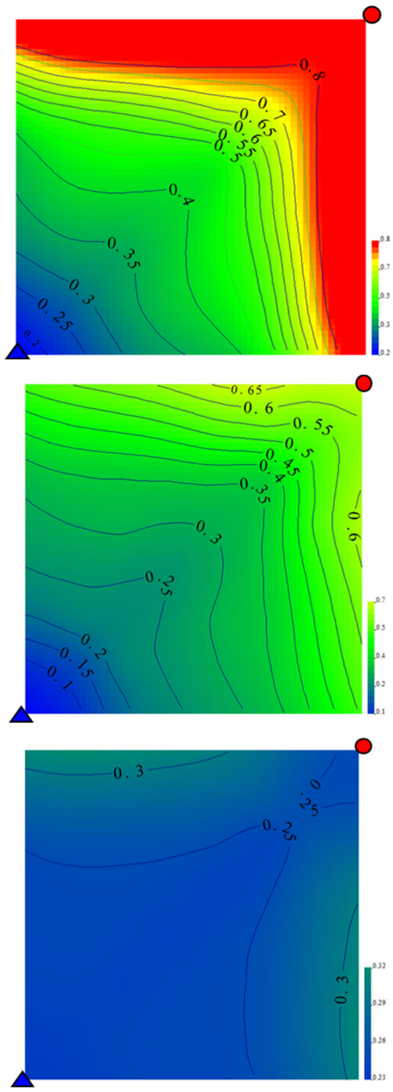
As can be seen from Table 6 and 7, chemical flooding can further increase the oil recovery rate by 30 percentage points on the basis of water flooding, indicating that the remaining oil after water flooding still has great development potential. During chemical flooding, the contribution rate of recovery degree of middle and low permeability layer is relatively high. The analysis shows that the high permeability layer has developed most of the crude oil in the water flooding and polymer flooding stage, which has formed the dominant channel, and the remaining oil potential is insufficient. On the contrary, the middle and low permeability layer is continuously deployed in the binary flooding stage, and the recovery degree changes greatly in this stage.

The remaining oil saturation electrode test results of each layer at the end of each displacement stage are shown in Figure 4. In the figure, ▲ is the injection well and ● is the production well.





a. End of polymer flooding



b. The end of the polytable binary drive

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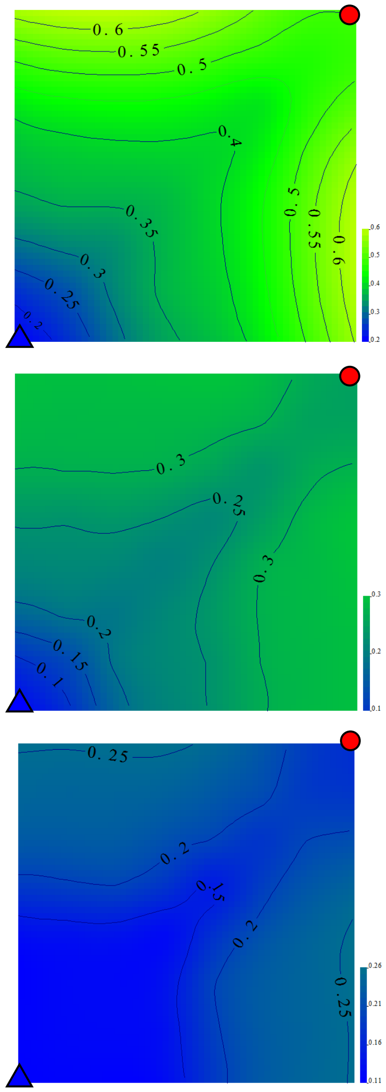

c. End of follow-up watet

Low permeability layer Medium permeability layer

High permeability layer

Figure 2. Distribution of remaining oil saturation in each layer

As can be seen from Figure 2, the remaining oil saturation of each layer gradually decreases with the progress of displacement, especially the middle permeability layer. Further analysis shows that the saturation of the high permeability layer does not change much, while the saturation of the middle and low permeability layer decreases rapidly. It shows that the high concentration polymer/surface binary can further block the hyperpermeability layer on the basis of the earlier polymer flooding. At the same time, the system enters the medium and low permeability layer to improve the emulsification and oil washing effect of the remaining oil in the affected area. In the subsequent water stage, the sealing effect of the dual system on the high permeability layer still exists, and the displacement water diffuses in the middle and low permeability layer, further reducing the remaining oil saturation in this area.

Table 8 shows the changes of oil saturation and sweep coefficient in different permeable layers.

Table 8. Variation of sweep coefficients at different horizons

Each small layer	Oil saturation, %			Coefficient of sweep, %		
	Polymer flooding	Two element drive	Drop	Polymer flooding	Two element drive	Growth
300 mD	65	36	29	21.09	90.63	69.54
900 mD	56	20	36	59.38	100	40.62
3000 mD	20	15	5	100	100	0

As can be seen from Table 8, after polymer flooding to binary flooding, the sweep coefficient of the high permeability layer has reached 100%, the oil saturation has decreased by 5 percentage points, and the oil displacement mechanism mainly focuses on improving the oil displacement efficiency. The sweep coefficient of the middle permeability layer increased by 40.62 percentage points, and the oil saturation decreased by 36 percentage points. The oil displacement mechanism was mainly based on the synergistic effect of expanding sweep volume and improving oil displacement efficiency. The sweep coefficient of low permeability layer increased by 69.5 percentage points, and the oil saturation decreased by 29 percentage points. The oil displacement mechanism mainly expanded sweep volume. From the increase of sweep volume, it can be seen that the enhancement ability of low permeability layer is the greatest, and that of medium permeability layer is the least. From the point of view of oil saturation decline, the middle permeability layer has the largest decline, the low permeability layer, the high permeability layer is the smallest, which also shows that the dual flooding mainly starts the remaining oil in the middle permeability layer.

4. Conclusion

(1) The improvement range of polymer flooding is very limited, and the improvement range is all below 10%. The oil displacement efficiency can be increased by 12%~29% by binary flooding.

(2) With the increase of surfactant concentration, the oil displacement efficiency increases, and the recovery degree of large and medium pores increases obviously. When the concentration is higher than 0.25%, the increase of oil displacement efficiency slows down, indicating that the concentration has reached the maximum oil washing efficiency, and further improving the oil displacement efficiency needs to expand the coordination of sweep volume.

(3) In the binary composite flooding stage, the contribution rate of recovery degree of middle pores is the largest, which is more than 40% or even 49%, while the contribution rate of small pores and large pores is relatively low. It can be seen that poly/surface binary composite flooding mainly acts on the remaining oil in the middle pores, and also has a certain effect on the small pores and large pores.

(4) In the large physical simulation experiment, the oil displacement mechanism of the low permeability layer is mainly based on expanding the swept volume, the middle permeability layer is mainly based on the synergistic effect of expanding the swept volume and improving the oil displacement efficiency, and the dual displacement mainly starts the remaining oil of the middle permeability layer.

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