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Study on Microscopic Distribution Law of Remaining Oil after Polymer Flooding based on Polymer Flooding Control Degree

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Abstract. There are many factors that affect the distribution of remaining oil after polymer flooding, and different geological conditions, production methods and production systems will affect the distribution characteristics of remaining oil. In this paper, the control degree parameters of polymer flooding are used to quantitatively measure the remaining proportion of four types of microscopic residual oil after polymer flooding, namely cluster, membrane, blind end and corner, and it is concluded that different types of microscopic residual oil have different reduction ranges after polymer flooding. The microscopic remaining oil distribution law of different displacement intensity positions at high, medium and low levels is summarized. After polymer flooding, the remaining oil distribution is more concentrated, and the oil saturation in the remaining oil-rich area is higher, which is distributed in strips and sheets. The main enrichment areas of remaining oil are near faults and sandstone pinchouts. The residual oil for polymer drive has a limited effect, and the development difference in the subsequent water drive stage still exists.

1. Introduction

With the main oil layers of each polymer flooding development block in the oilfield entering the subsequent water flooding development stage, the comprehensive water cut of the oilfield is increasing year by year, so it is urgent to study the distribution law of microscopic remaining oil after polymer flooding. The key to tapping the potential of remaining oil after polymer flooding is to accurately analyze the development effect of polymer flooding and determine the distribution law of remaining oil. The distribution characteristics of remaining oil after polymer flooding are different from those after pure water flooding. Macroscopically, due to the influence of inaccessible pore volume of polymer, the injection pore volume multiple of polymer solution is very small or zero, so it is difficult to see polymer flooding effect. In the parts with high permeability, the injection-production relationship is imperfect due to the change of facies belt, sand body pinchout, faults, etc., and there is residual oil in some parts due to pressure gradient. Polymer flooding uses the high viscosity of polymer to improve the viscosity of injected water, improve the water-oil mobility ratio and expand the swept volume of injected water [1]; Using the viscoelasticity of polymer solution, the carrying efficiency of residual oil at the blind end is improved, and then the overall oil displacement efficiency is improved, so as to achieve the purpose of enhancing oil recovery [2].

Compared with other methods, polymer flooding can not only greatly improve sweep efficiency, but also improve microscopic oil displacement effect through viscoelasticity [3-4]. Reservoir



geological conditions are one of the important factors affecting polymer flooding effect besides injection parameters [5]. Therefore, aiming at the serious heterogeneity of the second-class reservoir, the concept of polymer flooding control degree was established. According to the polymer flooding control degree, the polymer flooding parameters of the second-class reservoir were determined. Two sets of fluorescence pictures of the same position profile after water flooding and polymer flooding were taken respectively, and the saturation of different types of micro remaining oil was measured. The changes of micro remaining oil after polymer flooding were quantitatively analyzed, and the distribution law of micro remaining oil after polymer flooding was given.

2. Occurrence State of Microscopic Remaining Oil

2.1. Bound residual oil

Film-like residual oil on the pore surface is mainly distributed on the lipophilic pore channel surface of rock particles. Because of the lipophilicity of rock, it is difficult to displace this kind of residual oil by the shear stress of water. The thickness of oil film varies with the physical properties of rock particles forming pore channels, and it is widely distributed [6]. When a substance molecule is irradiated by a special light source to absorb light quantum, the electrons in the ground state are excited to transition, and when these excited transition electrons return to the ground state, they emit fluorescence [7]. Reservoir structure, physical properties and horizontal and vertical connectivity are complex. According to the distribution of production wells and water injection wells in each layer, and considering the reasonable simulation workload, Cartesian coordinate system is established, and corner grid is used to mesh the simulation area. Calculate porosity; Permeability measured by water; Oil drive water, measure oil saturation and calculate irreducible water saturation; Then carry out water flooding until the water content at the outlet reaches 100%. From the fluorescence analysis picture of remaining oil, the remaining oil of water-displaced cores is mostly oil-in-water, and oil-water mixture; After polymer flooding, the amount of remaining oil in the core is greatly reduced, the rock skeleton is clear, and more remaining oil is scattered.

2.2. Semi-bound residual oil

Physical properties play an important role in controlling oil-water seepage in oil layers. The recovery degree and water flooding in different parts of the sublayers in the study area and the distribution of remaining oil in each flow unit in the longitudinal direction are affected by physical properties, showing different characteristics. On the premise of knowing the actual oil field data, the calculation performance is consistent with the actual performance by adjusting the parameters that affect the development performance. A cross section is taken from the middle of each section to make a grinding plate, and five lines are evenly selected on each grinding plate. Using the fluorescence analysis technology of grinding plate, the pictures are scanned and made into continuous images, and several pictures are selected to calculate the remaining oil saturation. However, in a sufficiently small passage, polymer solution is difficult to pass through, and the blind residual oil is still stuck at the throat. In another case, the liquid-oil interface at both ends of the remaining oil in the pore is parallel to the streamline direction of the polymer displacement fluid, and the remaining oil cannot flow under the action of capillary force.

Because some small pores in the reservoir do not allow polymer molecules to pass through, the swept volume of polymer solution in the reservoir is reduced, so the concept of polymer control degree is put forward to characterize the ratio of the swept pore volume of polymer solution with a certain relative molecular mass to the total pore volume of the reservoir. The formula of polymer flooding control degree is [8]

$$\eta_{\text{polymer flooding}} = V_{\text{polymer flooding}} / V_{\text{total}} \times 100\% \quad (1)$$

Where: $\eta_{\text{polymer flooding}}$ is the control degree of polymer flooding, %; $V_{\text{polymer flooding}}$ polymer is the pore volume of oil layer that polymer molecules can sweep, m³; V_{total} is the total pore volume, m³.

With the help of 3D geological modeling, taking the unit grid as the research object, not only the connectivity of plane section is considered, but also the pore volume that polymer molecules can enter is refined. The calculation formula of total pore volume and reservoir pore volume that polymer molecules can sweep is as follows

$$V_{\text{total}} = \sum_{j=1}^m [\sum_{i=1}^n V_{\text{cell}} \times \varphi] \quad (2)$$

$$V_{\text{polymer flooding}} = \sum_{j=1}^m [\sum_{i=1}^n V_{\text{cell}} \times \varphi_p] \quad (3)$$

Where: V_{cell} is the reservoir volume of unit grid, m³; φ is porosity; φ_p is the sweep porosity of polymer.

The porosity correction formula after polymer flooding is

$$\varphi_p = (1 - P)\varphi \quad (4)$$

In which P is inaccessible pore volume coefficient of polymer.

However, the influence of reservoir heterogeneity must be considered when actually calculating the swept pore volume of polymer flooding, that is, there are some areas where polymer is difficult to sweep during polymer flooding.

In moderate and strong water washing, only narrow throat is distributed. Precipitated residual oil in the center of pores is a high-molecular and high-viscosity residual oil with gum and asphaltene as main components, which mostly precipitates in the center of pores. The practice of polymer flooding in the main reservoirs of oil field shows that to ensure good polymer flooding effect, it is not only necessary to have a large reservoir connection thickness between injection-production wells, but also to ensure the perfection of injection-production relationship on the plane. Considering that some small pores in the reservoir only allow water to pass but not polymer molecules to pass, the swept volume of polymer solution in the reservoir is reduced. While considering porosity correction after polymer flooding, geological research is made on the middle and low permeability layers which cannot be affected by polymer and some areas far away from both wings of mainstream line. Finally, effective thickness less than 0.5m is taken as filtering condition for correction calculation. The high permeability layer has a large liquid absorption, and its permeability and fluidity decrease greatly, which in turn causes the liquid absorption or liquid moving speed of the high permeability layer to decrease greatly, thus achieving the purpose of adjusting the liquid absorption profile.

2.3. Free remaining oil

The statistical results of field tests at home and abroad show that under the premise of similar average permeability, there will be obvious differences in injection and flooding capacity and liquid absorption profile, so permeability classification is very important. There is little difference for the well-developed reservoirs, but the second-class reservoirs with strong plane and longitudinal heterogeneity can not reflect the true control degree of polymer on reservoirs. Intragranular residual oil is mostly distributed in the layers with low maturity of clastic components and developed intragranular dissolution pores, and exists in intragranular pores. During water flooding, this residual oil remains in isolated drops at the dead angle of pores swept by water injection. After polymer flooding, the remaining oil is pulled and stripped by polymer molecules, and some of it is displaced, but there is still a certain amount of remaining oil. The flooding degree in high permeability area is relatively serious, the remaining oil saturation is low and the recovery degree is high; On the contrary, low permeability areas have lower recovery degree and higher oil saturation. Due to the "stripping" effect of polymer solution, this kind of remaining oil will be greatly reduced after polymer flooding, and after polymer

flooding, the rock surface will change from lipophilic to hydrophilic, and the oil displacement effect will be further enhanced, so the remaining amount of this remaining oil is less.

3. Microscopic Remaining Oil Distribution after Polymer Flooding

3.1. Microscopic remaining oil distribution in high-intensity displacement site

According to the statistics of fluorescence analysis pictures, the proportions of different types of microscopic remaining oil after polymer flooding are shown in Table 1. It can be seen from the table that in pores with residual oil saturation below 20%, corner residual oil accounts for the largest proportion, followed by cluster residual oil, and membrane residual oil is the least. Due to the viscoelastic effect of polymer, polymer can pull out a part of this kind of residual oil. However, in a sufficiently small passage, polymer solution is difficult to pass through, and the blind residual oil is still stuck at the throat. After polymer flooding, the remaining potential distribution is relatively concentrated, mainly distributed in the middle and high water washing section, accounting for 70.1% of the total remaining reserves; If the strong water washing level is unchanged, the displacement efficiency of other water washing levels will increase to the average value of the previous level.

Table 1. Proportion of various remaining oil types after polymer flooding (%)

Oil saturation	Type of remaining oil				Total
	Membrane-like	Clustered	Blind shape	Corner corner	
Under 20%	4.92	20.36	20.84	53.88	100.00
20%-40%	5.53	21.28	12.91	60.28	100.00
Over 40%	9.83	28.11	13.20	48.86	100.00

High-intensity displacement sites refer to those with water saturation above 80% and oil saturation below 20%. There are two situations: one is that pores have reached strong water washing in water flooding stage before polymer flooding, the other is that pores have been displaced by polymer solution with high injection times, and the remaining oil saturation has been very low. After polymer flooding, the remaining oil in cross section and longitudinal section has been basically displaced clean. Compared with the pictures after water flooding, the remaining oil has been washed strongly but still exists after water flooding, and the remaining oil basically does not exist after polymer flooding. After water flooding, the remaining oil saturation in the high oil saturation area at the core edge is also greatly reduced. The main difference between sweep efficiency of polymer flooding and water flooding lies in the top simulation layer. This is mainly due to the high viscosity of polymer flooding injection fluid, which reduces the oil-water mobility ratio, blocks the bottom water flooded layer, and promotes the injection water to push to the top. Although the recovery degree of crude oil in the middle and high permeability layers is relatively high, the oil saturation of each layer has little difference, which is due to the low initial oil saturation of the low permeability layer. It can be seen that the potential of crude oil production after water flooding is still in the medium and high permeability layer.

3.2. Microscopic remaining oil distribution in medium flooded area

The water flooded part refers to the part where the water saturation is 0.6 ~ 0.8 and the oil saturation is 0.2 ~ 0.4. The remaining oil in the corner still accounts for the largest proportion, followed by cluster remaining oil, and film remaining oil is the least. Compared with high flooding, the proportion of remaining oil in film and corner increased, while that in cluster and blind decreased. In the pores with residual oil saturation of 20%-40%, the proportion of corner residual oil is still the largest, followed by cluster residual oil and membrane residual oil is the least. Compared with high-intensity displacement sites, the proportion of remaining oil in membrane and corner increased, while that in cluster and blind decreased. On different heterogeneous physical models, with the increase of permeability variation coefficient, the gap between water flooding recovery in high permeability layer and low permeability layer gradually increases; The recovery ratio of polymer flooding in low permeability layer increases gradually, but when the coefficient of variation of permeability increases to more than 0.62, the increase value of recovery ratio will decrease.

3.3. *Microscopic remaining oil distribution in low flooded area*

It can be seen from Table 1 that in pores with residual oil saturation greater than 0.4, the relative proportion of cluster and film-like residual oil increases, while the relative proportion of blind and corner residual oil which is difficult to use decreases, which is due to the formation of microscopic residual oil in low-strength polymer flooding mainly due to narrow pore channels, inaccessible pores, polymer adsorption, low pressure gradient, capillary force and so on, which makes the available film-like and cluster-like residual oil difficult to use. Moreover, polymer injection in polymer injection block is stopped and subsequent water flooding ends when the water cut is about 96%, rather than when the water cut in laboratory experiment reaches 100%. Because of the narrow pore channel, although water can enter, it is difficult for polymer to enter. In the laboratory core displacement experiment with high permeability, this kind of remaining oil exists in large quantities in actual reservoirs, although it is very small. And many parts, including those not driven by water flooding, have shown the color characteristics of rock skeleton, which also shows that polymer flooding not only improves oil displacement efficiency, but also expands swept volume. Before and after polymer injection, the enhanced oil recovery has a large range, but the difference between polymer flooding and water flooding prediction in each layer is small, so the intra-layer effect of polymer flooding is stronger than the inter-layer effect.

In the process of polymer flooding, for the positive rhythm and anti-rhythm models, the oil phase saturation of each layer is evenly distributed around the injection well, with no sudden or slight sudden, which is similar to the oil phase saturation distribution characteristics of the planar homogeneous model. With the increase of water washing and oil displacement, the proportion of light components decreases obviously, while the proportion of heavy components increases. In the composition of residual oil saturation in low-intensity displacement pores, the film-like and cluster-like residual oil saturation increases greatly. Compared with the composition of residual oil in high-intensity and medium-intensity displacement pores, it is considered that this part of residual oil can be injected by increasing the pore volume multiple of polymer flooding. It can be seen that due to the comprehensive influence of heterogeneity and well pattern in the longitudinal direction of the reservoir, the crude oil production of different flow units is not consistent. The flow units with better physical properties and well pattern conditions have higher recovery rate, but the flooding situation is also serious.

3.4. *Changes of light and heavy components in crude oil under different water washing conditions after polymer flooding*

Hydrocarbons have fluorescence characteristics, and the performance of hydrocarbons with different compositions and viscosities on laser confocal scanning excitation fluorescence images can be completely different and very clear. The oil displacement efficiency is seriously uneven in spatial distribution, and the polymer injection in polymer injection block is stopped, and the subsequent water flooding ends when the water cut is about 96%, rather than when the water cut reaches 100% in laboratory experiment. On the one hand, the injected polymer solution first flows to the high permeability layer, which makes the polymer adsorb on the pore wall and reduces the seepage channel of the high permeability layer. On the other hand, the polymer solution increases the viscosity of the whole fluid flow, which leads to the increase of seepage resistance, forcing the displacement agent to enter the middle and low permeability layer and spread from the high permeability layer to the adjacent middle and low permeability layer, thus improving the utilization degree of crude oil in the middle and low permeability layer [8].

When the reservoir enters the stage of strong water washing, the change between them is more obvious, and the content ratio of light and heavy components decreases rapidly from over 1.2 in medium water washing to 0.8-0.6 (Figure 1). The reason for this result may be determined by the pore structure.

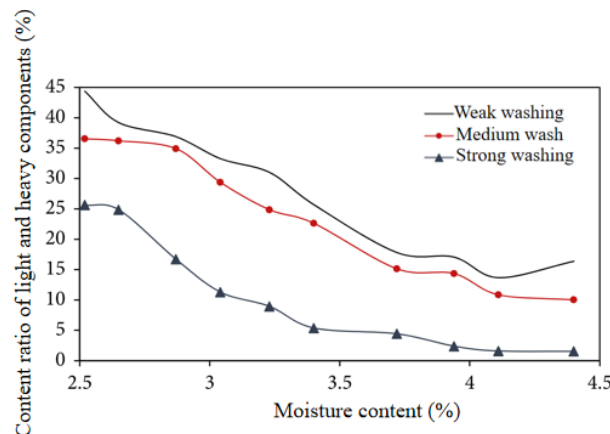


Figure 1. Proportion change of light and heavy components in rock samples with different water content

Clay mineral content and dispersed occurrence are the main factors affecting the micro-distribution of residual oil. Driven by reservoir development fluid, especially under the condition of high injection-production intensity, these particles are easily transported out of the reservoir to the surface along with the produced fluid, which reduces the relative content of kaolinite in the formation. Table 2 shows the clay content of reservoirs with different water washing degrees after polymer flooding.

Table 2. Clay content of reservoirs with different water washing degrees after polymer flooding

Degree of washing	Gas permeability/ D	Clay mineral content/ %	Relative content of clay minerals/%				
			Illite	kaolinite	Chlorite	Illite/montmorillonite mixed layer	Chlorite/montmorillonite mixed layer
Unwashed water	0.033	8.63	7	70	7	1	14
Weak washing	0.814	7.81	14	66	8	3	9
Medium washing	1.637	6.08	9	71	14	3	7
Strong washing	4.128	6.67	8	80	7	2	2

There are many factors affecting the distribution of remaining oil after polymer flooding. Combined with the actual situation, according to the main influencing factors of remaining oil, the distribution of remaining oil can be divided into five types: sandstone pinchout, fault control, pressure balance, imperfect well pattern (isolated oil-bearing area without well production) and microstructure high point. Because irreducible water can't flow, this part of elastic energy is released in the form of pure oil, which causes the decrease of oil saturation in the formation equal to the expansion of irreducible water. Unused remaining oil in polymer flooding is caused by inaccessible pore volume of polymer. Because of narrow pore channel, although water can enter, polymer is difficult to enter. After polymer flooding, the decrease range is different. Film-like residual oil affected by polymer friction is greatly reduced, cluster and blind end residual oil affected by small friction and capillary force is second, and corner residual oil is affected by polymer friction and blocked by unconnected pores. After polymer flooding, the decrease range is the smallest.

4. Summary

The control degree of polymer flooding takes into account the number of communication directions in the reservoir plane, the permeability of the reservoir and the pore space that polymer molecules can enter, which adapts to the geological characteristics of the second-class reservoir and can be used as the injection-production well spacing of polymer flooding in the second-class reservoir. By using the parameters of polymer flooding control degree established in this paper, the parameters of polymer dry powder dosage, injection speed, production and injection allocation and so on can be more

scientifically guided, which is beneficial to further improve the polymer flooding effect in conglomerate reservoirs. The distribution of microscopic remaining oil in high, medium and low intensity displacement sites is also different, and the remaining oil in high intensity displacement sites is less in membrane, cluster, blind end and corner; The medium-intensity displacement site is mainly composed of the residual oil at the blind end and corner; There are more four types of remaining oil in the low-intensity displacement area, especially the film-like and cluster-like remaining oil.

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