Formation mechanism and distribution characteristics of micro residual oil in ultra-high water cut reservoirs a case study of yangsanmu oilfield

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Abstract. The formation mechanism and distribution characteristics of microscopic remaining oil are the basis for efficient development and enhanced oil recovery of heavy oil reservoirs in ultra-high water cut stage. This paper takes Yangsanmu heavy oil reservoir in Huanghua depression as an example, micro-displacement simulation experiment based on microscopic pore structure analysis. Through parallel experiments, the remaining oil displacement effects of water flooding combined with polymer flooding, water flooding and surfactant polymer system combination, water flooding and poly-alkaline ternary composite flooding were compared. The formation mechanism and distribution pattern of remaining oil under different displacement medium conditions were studied to find a reasonable displacement medium system. The experimental results show that the formation of microscopic remaining oil in the study area is related to the stripping effect, the flow around, the pinch action occurs, the run through effect and the adherent flow. The distribution types of remaining oil are mainly angular type, pore wall oil film type, throat retention type, dispersed oil drop type and porphyritic remaining oil in macropores. The analysis of residual oil saturation under different displacement media shows that the combined flooding effect of water flooding and poly-alkaline ternary composite flooding are the best, followed by water flooding and surfactant polymer system combination flooding. This study provides guidance for the remaining oil exploration plan of the ultra-high water cut stage heavy oil reservoir in this area.

1. Introduction
Most of the old oilfields in eastern China have entered high (extra-high) water cut stage[1,2], facing fine adjustment of secondary oil recovery and transformation from secondary oil recovery to tertiary oil recovery. However, people's understanding of the complex distribution of remaining oil is unclear, which restricts the economical and efficient potential tapping of reservoirs [3,4]. This paper takes the typical ultra-high water cut period reservoir of Yangsanmu heavy oil reservoir in Huanghua as an example. Through micro-displacement simulation experiment [5-9], the formation mechanism and model of micro-residual oil are explored[10-12], and different "two-three combination" development schemes are compared to provide basis for reservoir development.

2. Micro-displacement simulation experiment
Based on the data of the new airtight coring well Y11 in the research area and the method of glass etching simulation model, microscopic remaining oil simulation in the ultra-high water cut stage was
carried out. The method can realize the visual observation of the whole process of micro-displacement and can quantitatively analyze the remaining oil.

2.1. Reservoir microscopic characteristics and sample selection

Typical reservoir sections of Y11 sealed coring in the study area are selected for model making. The depth of the sample is 1482.05 m, and the lithology is medium sandstone. Braided river channel bar sedimentary are developed. The sample has a porosity of 38.05%, a permeability of 5182×10-3 μm² and an average pore throat radius of 15.96 μm. The pore type is mainly composed of primary porosity, and a small amount of intergranular dissolution porosity and intragranular dissolution porosity are developed. Figure 1 shows the throat is mainly a pore-reducing throat and a neck-reducing throat, with large pore-throat coordination number and good connectivity. From the capillary pressure curve, the median pressure of the discharge pressure saturation is small, the pore throat distribution is uniform and the large pore throat is dominant.

(a)Slices of castings, Primary intergranular pore and a small amount of granular corrosion pore; (b)scanning electron microscope; (c)Slices of castings, Pore throat characteristics; (d)Characteristics of capillary pressure curve of core samples.

Figure 1. Characteristics of pore throat structure of well Y11 reservoir in Yangsanmu Oilfield.

2.2. Experimental methods and schemes

Three sets of parallel tests were carried out on the etching simulation model of the same structure, and the effect of "two-three combination" oil recovery was verified by experiments. In the first group, water flooding is carried out first, and after the water flooding 2PV, it was converted into a polymer flooding. The flow of the second and third sets of experiments is consistent with the above, the
difference is that the replacement of the displacement medium in the polymer flooding stage, respectively, using "water flooding - surfactant polymer system combination "and "water flooding - poly-alkaline ternary composite flooding ". These three experimental schemes are three types of displacement oil recovery schemes that are often used in oil field sites. As shown in Table 1.

**Table 1.** Formulation of experimental displacement media and displacement parameters.

| Displacement medium 1 | BHHP-113 | 1125 | BHS-01(B) | 0.05 |
| Displacement medium 2 | BHHP-113 | 1125 | BHS-01(B) | 0.2  |
| Displacement medium 3 | BHHP-113 | 1125 | BHS-01(B) | 0.1  | 0.4  | 0.05 |

The experimental temperature and pressure conditions were based on the actual conditions of the underground oil layer, and the simulated formation temperature was 63°C and the formation pressure was 13.34 MPa. The real crude oil in the study area was used in the experiment, and the viscosity of crude oil was consistent with that of underground crude oil. The water salinity used in the displacement is actually adjusted according to the study area. The water type is NaHCO₃ type, and the total salinity is 5462mg/L. The polymer and surfactant used in the displacement medium are taken directly from the oil field production site. According to the actual displacement speed of the development of the study area, the experiment used a displacement speed of 0.05mL/min.

Figure 2 shows the experimental device used for real-time observation and recording of thin sections in the experimental kettle through the camera-connected microscope. The pressure of the whole system meets the formation pressure condition through the annular pressure device. The experiment first carried out the model saturated water process to simulate the reservoir fluid distribution before the reservoir formation, and then carried out the crude oil filling and flooding to simulate the reservoir formation process. After these two processes, the oil-water distribution in the model reached the original reservoir state before development. Then three groups of parallel experiments are carried out according to the development process simulation scheme of "water flooding - tertiary oil recovery".

**Figure 2.** Micro-displacement experimental device for remaining oil simulation model.
3. Experimental results and analysis

3.1. Formation mechanism of microscopic remaining oil

During the experiment, in the different development stages of the simulation, there are oil-water two-phase flow and oil-water-displacement medium multi-phase flow. There are five main forms of fluid movement on a microscopic scale at different stages of displacement: the stripping effect, the flow around, the pinch action occurs, the run through effect and the adherent flow. These five different movements and modes of action are combined in different pore structures and stages, which are the main factors for the formation of complex residual oil.

Figure 3(a) shows the stripping effect often occurs at the beginning of the displacement. Water flows at the edges of the particles and briefly occupies the throat, creating a brief aqueous phase plug flow. With the passage of time, the crude oil on the wall of the hole is gradually stripped down to form microscopic channels, and this process repeats repeatedly, and finally realizes the effective displacement of crude oil.

Figure 3(b) shows the flow around is often found in reservoirs with large pore coordination numbers and complex pore throat structures. Fluid resistance due to different sizes of pore throat is different. Therefore, the displacement fluid will preferentially enter the relatively thick area of the throat, avoiding the thinner throat area.

Figure 3(c) shows the run through effect usually occurs in the area with larger pore throat radius. Because the resistance of oil-water flow is relatively small, the displacement fluid tends to break through quickly, forming a channel.

Figure 3(d) shows the pinch action occurs when the crude oil in the displacement pore enters the throat with a reduced radius. The sudden increase in fluid resistance causes the crude oil plunger or large oil droplets to become pinched. Thus, the continuous oil phase is broken by the formation of discrete oil droplets, resulting in a decrease in displacement efficiency.

Figure 3. Microscopic residual oil displacement mechanism.
Figure 3(e) shows the wall-attached flow is that after displacement fluid displaces the crude oil in the middle of the pore throat, the crude oil left on the pore throat wall flows slowly on the pore throat wall in the form of thin film.

3.2. Distribution model of microscopic remaining oil

Under the above five effects, the distribution of microscopic residual oil presents three different types of distribution patterns.

Figure 4(a) shows the first type is a discrete residual oil, which mainly includes remaining oil in the form of dispersed oil drop type. It is mainly caused by the remaining oil in the pores caused by the run through effect, and the oil droplets are small in scale.

Figure 4(b, c) shows the second type is semi-bound remaining oil, which mainly includes angular type remaining oil and pore wall oil film type remaining oil film. The angular type remaining oil mainly exists in the corner of pore throat. Especially in the irregular pore and elongated throat corner, the distribution scale is small. The main reason for this kind of remaining oil is that the complex shape of pore throat corner makes it difficult for displacement fluid to sweep and cause oil retention. The pore wall oil film type remaining oil of the pore wall is formed by a part of crude oil attached to the surface of the particle by the formation of a film.

Figure 4(d, e) shows the third type is bound remaining oil, mainly including throat retention type and porphyritic remaining oil. The throat retention type remaining oil remaining in the throat refers to the remaining oil distributed in the fine throat. The main reason for this kind of remaining oil is that the fluid resistance is large, and the displacement fluid is difficult to enter, and the flow around is often caused to cause such crude oil to stay in the throat. The porphyritic remaining oil mainly occurs in the macropore where the pore throat intersects, and its shape is more regular. This kind of remaining oil exists mainly for two reasons. On the one hand, the local patchy crude oil formed by bypass flow has...
not been displaced, on the other hand, when the crude oil enters a larger pore from a narrow throat, the flow rate decreases, which leads to the decrease of displacement ability, thus resulting in the formation of patchy remaining oil.

3.3. Microscopic remaining oil distribution of different displacement schemes

In this study, the images of displacement experiment are processed in real time, and the remaining oil saturation at different stages is calculated by automatically identifying the pixels of crude oil, so as to quantify the remaining oil saturation at different displacement schemes and different development stages, and to analyze and compare the effects of different displacement schemes.

3.3.1. Microscopic remaining oil distribution types of different displacement schemes. Table 2 shows that the average remaining oil content of the three groups of water flooding is 42.34%, of which the highest is the bound remaining oil content of 34.19%, followed by the semi-bound remaining oil. By comparing the remaining oil distribution types under different displacement schemes after water flooding, we can know that: Under the polymer flooding scheme, the discrete remaining oil remains unchanged, the semi-bound remaining oil increases, the throat remaining oil in the bound remaining oil increases by 1%, and the porphyritic remaining oil decreases greatly. Under the polymer surface displacement scheme, the discrete remaining oil decreased by 2.11%, the semi-bound middle corner remaining oil decreased by 0.65%, the pore wall oil film increased by 0.91%, and the bound remaining oil decreased significantly. The discrete remaining oil decreased by 3.61% and the semi-bound remaining oil remained unchanged, while the bound remaining oil decreased by 21.19% under the poly-alkaline ternary composite flooding displacement scheme.

|                      | Discrete | Semi constrained type | Bound type          | Remaining oil saturation |
|----------------------|----------|-----------------------|---------------------|-------------------------|
|                      | Dispersed oil drop type | Angula r type | Pore wall oil film type | Throat retention type | Porphyr itic |
| Water flooding       | 5.91%    | 1.95%                 | 0.29%               | 6.00%                   | 28.19%     | 42.34%    |
| Polymer flooding     | 5.80%    | 2.40%                 | 2.30%               | 7.00%                   | 22.40%     | 39.90%    |
| Surfactant polymer system combination | 3.80% | 1.30%                 | 1.20%               | 0.60%                   | 15.30%     | 22.20%    |
| Poly-alkaline ternary composite flooding | 2.30% | 1.80%                 | 0.40%               | 0.70%                   | 12.30%     | 17.50%    |

Under different schemes, the content of patchy remaining oil and dispersed oil drop type remaining oil decreased, but they are still the main types of micro-residual oil distribution. Under the three displacement schemes, the displacement effect of porphyritic remaining oil is the best and that of angular type remaining oil is the worst.

3.3.2. Remaining oil saturation under different displacement schemes. Through figure 5 the microscopic remaining oil saturation histogram, we can know that the remaining oil saturation is 43.70% after the first scheme of water flooding, and the polymer flooding effect is not obvious, the decline is only 3.8%. In the second scheme, the remaining oil saturation of water flooding is 40.33%, and that of the polymer surface drive is 22.20%. The displacement effect is obvious. In the third scheme, the remaining oil saturation of water flooding is 42.99%, that of ternary flooding is 17.50%, and the decline is 25.49%. The displacement effect is the most remarkable. It can be known from this that for the future development of the Sanmu heavy oil reservoir in the Huanghua depression, a combination scheme of polybasic ternary displacement can be selected.
4. Conclusions
The microscopic residual oil is mainly formed under the action of the stripping effect, the flow around, the snap-off, the run through effect and the adherent flow. These different roles exist at all stages of displacement, but the pore throat parts of the roles are different.

The main types of microscopic residual oil distribution include discrete type of oil drop type remaining oil, semi-bound type of angular type and pore wall oil film type remaining oil, the throat retention type and porphyritic remaining oil of bound micro-remaining oil.

Among the three displacement schemes, the displacement effect of the poly-alkaline ternary composite flooding is the best, and the effect of the poly-surface flooding is second.

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