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A Study on the Distribution of Remaining Oil in Daqing S, P, and G Oil Layers at Different Flooding Stages

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Abstract: Extensive research has been conducted on remaining oil in the Daqing Oilfield during high water cuts' late stage, but few studies have offered multi-level analyses from both macro and micro perspectives for remaining oil under varying formation conditions and displacement methods. This article focuses on the remaining oil in the S, P, and G reservoirs of Daqing Oilfield by employing the frozen section analysis method on the cores from the S, P, and G oil layers. The research identifies patterns among them, revealing that the Micro Remaining Oil types in these cores primarily include pore surface thin film, corner, throat, cluster, intergranular adsorption, and particle adsorption. Among these, intergranular adsorption contains the highest amount of remaining oil (the highest proportion reaches 60%) and serves as the main target for development potential. The overall distribution pattern of the Micro Remaining Oil in the S, P, and G oil layers shows that as flooding intensity increases, the amount of free-state remaining oil gradually decreases, while bound-state remaining oil gradually increases. The study also examines eight typical coring wells for macroscopic remaining oil, finding four main types in the reservoir: interlayer difference, interlayer loss, interlayer interference, and injection-production imperfect types. Among these, the injection-production imperfect type has the highest remaining oil content and is the primary target for development potential. Analyzing the reservoir utilization status and oil flooding efficiency reveals that as water flooding intensifies, the oil displacement efficiency of the oil layer gradually decreases, while the efficiency of oil layer displacement improves. Strongly flooded cores exhibit less free-state remaining oil than weakly flooded cores, making displacement more challenging. This study aims to provide a foundation and support for the development of remaining oil in the S, P, and G oil layers.

Keywords: Micro remaining oil; Macro remaining oil; Remaining oil type; Flooding degree

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1. Introduction

In the later and middle stages of water injection development in most oil fields, the difficulty of extraction becomes a prominent issue. This challenge arises essentially from factors including high water cut, remaining oil dispersion, and heterogeneity within the oil layer. These factors together pose the biggest obstacle to further developing the remaining oil [1]. In the 1980s, engineers addressed this issue by adding polymers to the injected water. This increased the fluid's viscosity, which helped stabilize the displacement front and expand the affected volume, ultimately improving the recovery rate. Composite flooding, which involves adding alkali and surfactants to a polymer base, further increases the swept volume and reduces the interfacial tension between water and oil. This combination significantly enhances recovery efficiency [2]. After years of applying polymer flooding, composite flooding, and water flooding, the physical properties of the oil layers and the distribution of remaining oil in the Daqing Oilfield have evolved. The complex structure of these oil layers now plays a pivotal part in the development of remaining oil [3,4]. Therefore, understanding the distribution characteristics of the remaining oil in the Daqing Oilfield is crucial for its effective development.

In 1997, Yu recognized that extracting the remaining oil would become increasingly challenging as the oilfield development progressed. He speculated that research would need to shift towards a micro-level focus. Han [5,6] suggested that studying the distribution of remaining oil requires the establishment of precise predictive models. Guan *et al.* [7] divided remaining oil research into two scales: Micro Remaining Oil in cores and Macro Remaining Oil in oil layers. Various research methods [8], including geological research, indoor experiments, oil layer engineering, on-site monitoring technology, and dynamic analysis, are used depending on the situation. The main factors affecting the distribution of remaining oil include both geological and developmental factors [9]. Despite years of research, significant challenges remain in addressing complex and variable geological conditions. Fang *et al.* [10] found that water flooding impacts the type of remaining oil. As water flooding intensifies, the amount of free-state oil decreases, while bound-state oil increases. Heydari-Farsani *et al.* discovered a direct relationship between remaining oil saturation and rock pore size. Li *et al.* [11,12] identified that the microscopic flow characteristics of fluids in core pores are closely related to the throat pore structure and layer heterogeneity. Wu *et al.* [13] employed a complex stratigraphic structure model to study the variation patterns of millimeter-level remaining oil in different structural parts under various development methods. In addition, Gheshlaghi *et al.* [14] found that polymer flooding improves the recovery of free-state oil. However, the displacement effect is poor in narrow spaces. Although the well network in the old area of Daqing Oilfield is relatively complete, challenges arise during water injection development. When the front edge of the water injection reaches the first productive well array, it can create a closure effect. This leaves behind the remaining oil that is difficult to access. A similar effect occurs during polymer flooding, where flooding stops beyond the pressure relief range of the first productive well array, leaving the remaining oil behind. An unreasonable difference in oil-water viscosity ratio can also lead to incomplete displacement and premature water breakthrough in oil wells. This exacerbates oil layer heterogeneity. Due to the combined effects of oil layer heterogeneity and differences in fluid physical properties, the remaining oil formed by finger and bypass flow is commonly found in the S and P oil layers of Daqing Oilfield.

This study combines physical experiments with on-site data to examine the remaining oil in typical wells within the Daqing S, P, and G oil layers at both micro and macro scales. To streamline the workload, cores from various representative oil layers and wells are used. The findings aim to provide a comprehensive understanding of the remaining oil distribution in the northern Daqing region. This research will offer a solid theoretical foundation for the future development of the Daqing oil field.

2. Microscopic remaining oil experiment and results

2.1. Introduction to experimental methods

This study primarily employs frozen section analysis to examine remaining oil, integrating casting image microscopes, polarizing microscopy, and fluorescence microscopy capabilities. By utilizing the ultraviolet light emission from a high-pressure mercury lamp and the distinct fluorescence characteristics of various crude oil components, we observe the positions of fluorescence residual oil and rock minerals to analyze the distribution characteristics of the remaining oil.

2.2. Experimental principles

Frozen sectioning technology is utilized to cut and ground samples in a low-temperature environment, ensuring that the original form of fluid within the pores remains intact during the process. By combining the strengths of the casting image analysis microscope, polarizing microscope, and fluorescence microscope, we extract pore throat characteristic parameters and rock particle features using the casting image analysis microscope. The polarizing microscope helps identify mineral properties, and the fluorescence microscope, with an ultraviolet fluorescence filter, distinguishes the oil-water boundary. The remaining oil analysis software is then used to extract data on remaining oil saturation and occurrence. By observing fluorescence images, we can distinguish the distribution status of remaining oil within the pores, characterizing its micro-distribution.

2.3. Experimental steps

(1) Frozen section of rock core samples:

Preparation process: slice → seal with glue → polish slice → adhere slice → grind thin slice → label.

Sample Requirements: Samples selected for remaining oil identification must not be soaked in organic solvents before preparation. Preparation requirements: Oil-bearing rock samples need to be drilled and sliced under freezing conditions.

(2) Microscopic observation:

After examining the rock structure, composition, evolution, and pores under a polarizing microscope, fluorescence observation is performed to assess the distribution of oil and water. Finally, laser confocal observation is utilized to analyze the distribution of crude oil components across different pores.

(3) Image analysis

After identifying the Micro Remaining Oil types, the independent remaining oil is extracted. In the resulting binary image, we statistically calculate the target pixels to obtain the size and shape parameters of the remaining oil.

Oil area: Count the number of foreground pixels corresponding to the remaining oil area.

Water area: Count the number of foreground pixels corresponding to the water area.

Perimeter: Calculate the number of foreground pixels at the edge of the remaining oil.

Remaining oil type: Calculate the number of foreground pixels corresponding to each type.

Oil-water ratio: Determine the ratio of the oil-containing area to the water-containing area.

The ratio of remaining oil type: Calculate the ratio of remaining oil for different types.

2.4. Collection of core samples

The core samples in this study consist of oil-bearing fine sandstone. Samples are taken from the SII10+11 oil layer, PI1-7 oil layer, and GII1+2 oil layer at depths of 999.62–1007.88m, 1050.03–1058.55m, and 1174.88–1183.20m, respectively. We collected three sections each from the weak and medium flooding layers, and two sections from the strong flooding layer, totaling eight sections.

2.5. Distribution characteristics of remaining oil

Fluorescence images obtained from the frozen sections provided a detailed view of the remaining oil distribution, revealing the main types and distribution patterns of remaining oil in the northern region of the S oil layer. **Figure 1** is the schematic diagram of the main Micro Remaining Oil types.

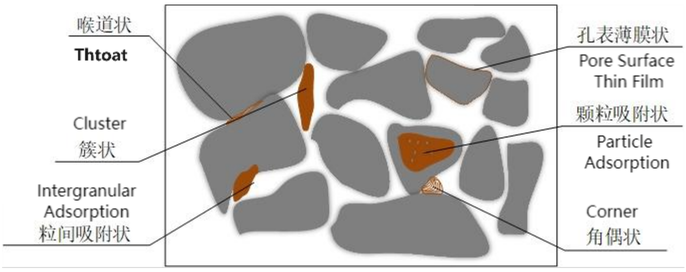

Figure 1. Main types of Micro Remaining Oil

2.6. Analysis of Micro Remaining Oil data in rock cores

For the 8 cores collected in 2.4., conduct the frozen sections experiment using the steps in 2.3. The Micro Remaining Oil position was determined under the microscope based on the fluorescence characteristics of crude oil. Then determine the Micro Remaining Oil type. By measuring and calculating the ratio of the Micro Remaining Oil area to the total area in the sections. It is possible to collect the relative content data of different Micro Remaining Oils in each core.

(1) Remaining oil types and quantitative analysis of the SII 10+11 oil layer after composite flooding

Statistical analysis was conducted on the formation and type of Micro Remaining Oil in the core of the SII10+11 oil layer under different flooding conditions (**Figure 2**). The bound state includes Pore Surface Thin Film, Particle Adsorption, and Slit-Shaped residues. The semi-bound state includes Corner and Throat residues. The free state includes Clusters, Intragranular Morphology, Intergranular Adsorption, and Light Mist.

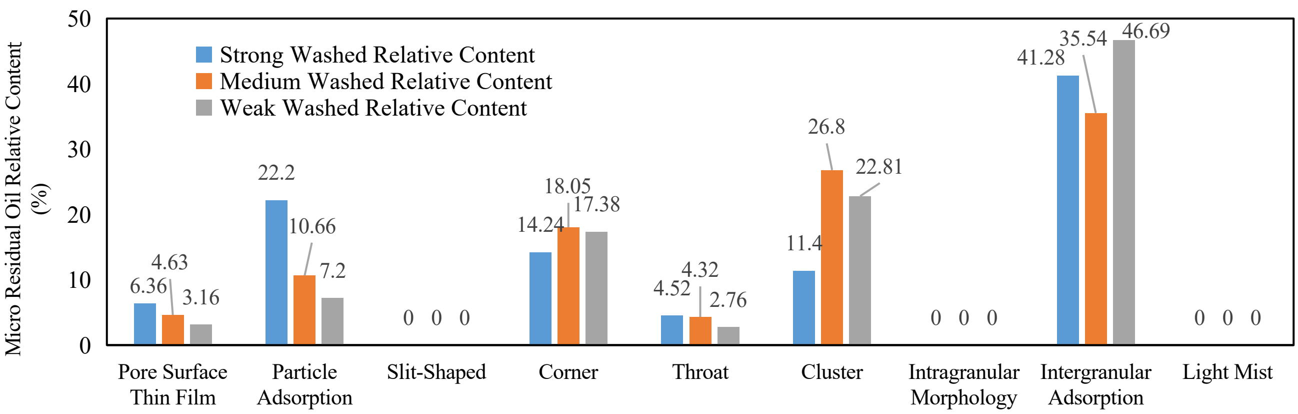

Figure 2. Distribution characteristics of the remaining oil in strong, medium, and weak flooding core of SII10+11 oil layer

An analysis of the remaining oil distribution in the cores of the SII 10+11 oil layer under various degrees of flooding revealed that the remaining oil content of strong flooding after combination flooding was the lowest, with an oil area of 4.12%. The primary remaining oil types in this scenario included intergranular adsorption (including newly formed types during the combination flooding process) and particle adsorption. In contrast, medium flooding resulted in a remaining oil content of 12.27%, predominantly consisting of clustered and intergranular adsorption types. Weak flooding showed the highest remaining oil content, with a relative content of 17.29%, where intergranular adsorption and cluster distribution were the main types.

Figure 3 below illustrates the main types of Micro Remaining Oil observed in the SII10+11 oil layer cores subjected to strong, medium, and weak flooding.

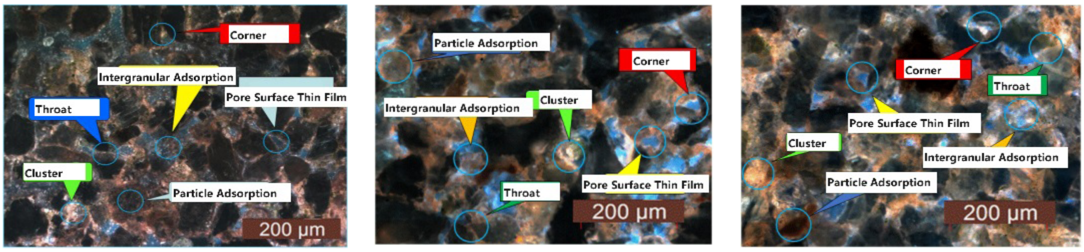

Figure 3. Main types of Micro Remaining Oil in strong, medium, and weak flooding cores of the S oil layer

(2) Type and quantitative analysis of remaining oil in the PI1-7 oil layer after Polymer Flooding

Statistical analysis was conducted on the formation and type of Micro Remaining Oil in the core of the PI1-7 oil layer under different flooding conditions (**Figure 4**).

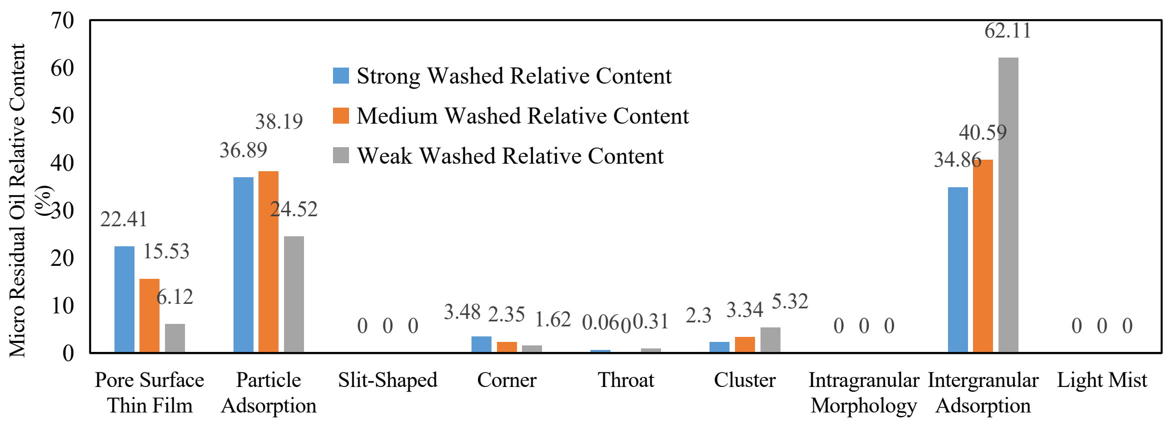

Figure 4. Distribution characteristics of the remaining oil in strong, medium, and weak flooding cores of the PI1-7 oil layer

An analysis of the distribution variances of the remaining oil in cores of the PI1-7 oil layers with varying degrees of flooding revealed that after polymer flooding, the remaining oil content in strongly flooded cores was relatively low, at 2.54%. This remaining oil mainly existed as particle adsorption, intergranular adsorption, and a thin film on the pore surface. In medium-flooded cores, the remaining oil content was higher, at 9.06%, primarily distributed as inter-particle adsorption, particle adsorption, and pore surface thin film. Weakly flooded cores had the highest remaining oil content, at 20.30%, with the remaining oil predominantly appearing as inter-particle adsorption and particle adsorption.

The main types of Micro Remaining Oil in the cores of the PI1-7 oil layer after strong, medium, and weak flooding (**Figure 5**: from left to right are strong, medium, and weak flooding).

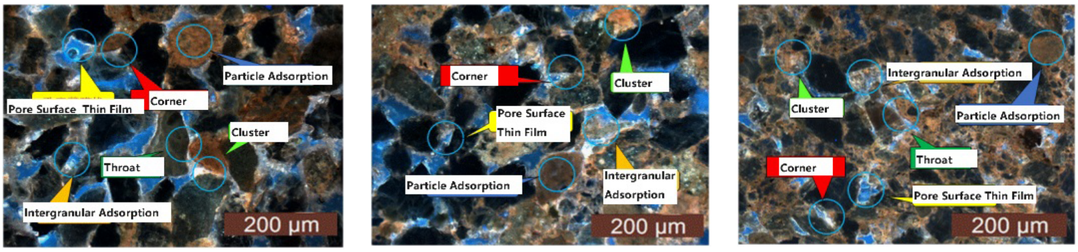

Figure 5. Main types of Micro Remaining Oil in strong, medium, and weak washed cores of the PI1-7 oil layer

(3) Observation and quantitative analysis of remaining oil types in the GII 1+2 after Water Flooding

Statistical analysis was conducted on the Micro Remaining Oil types and their distribution within the cores of the GII 1+2 oil layer under different flooding conditions (**Figure 6**).

The GII1+2 oil layer exhibited a higher remaining oil content after water flooding compared to polymer and combination flooding. In medium-flooded cores, the bound state remaining oil content reached 33.51%, the highest among the different flooding types. For semi-bound remaining oil, the content was slightly higher in medium-flooded cores compared to weak-washed cores. Free state remaining oil showed relatively low content in medium-flooded cores, at 57.47%, while weakly flooded cores had the highest content, at 75.01%. An analysis of the differences in remaining oil distribution across cores subjected to varying degrees of flooding revealed that remaining oil content following water flooding amounted to 18.46%. The remaining oil predominantly exists as inter-particle adsorption and particle adsorption. In weakly water-flooded cores, the remaining oil content was higher, at 24.86%, mainly appearing as intergranular adsorption and clusters.

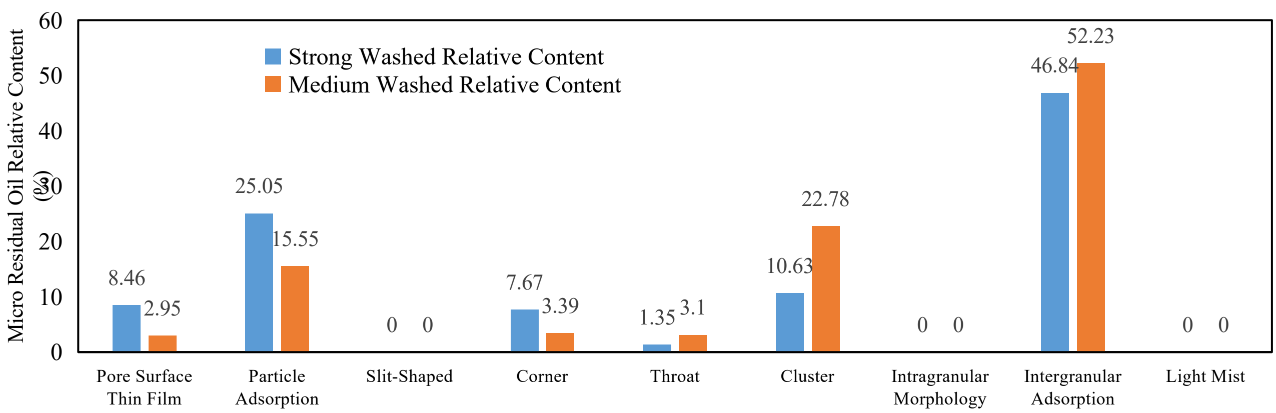

Figure 6. Distribution characteristics of the remaining oil in strong, medium, and weak washed cores of the GII 1+2

The main types of Micro Remaining Oil in the cores of the GII 1+2 oil layer after flooding (**Figure 7**):

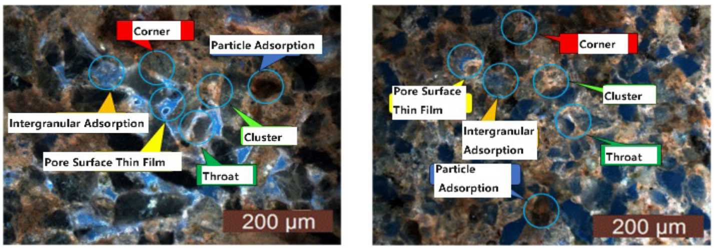

Figure 7. Main types of Micro Remaining Oil in weakly and medium water flooded cores of the GII 1+2 oil layer

After combination flooding, the content of remaining oil in the form of inter-particle adsorption is the highest. This is likely due to the formation of a new type of remaining oil (petroleum-clay (feldspar and debris) mixed remaining oil) during the flooding process, which accumulates between particles and pore throats, increasing the proportion of inter-particle adsorption remaining oil. For the remaining oil after polymer flooding, as the degree of flooding increases, bound remaining oil content gradually rises, while free remaining oil content gradually decreases. Compared to combination flooding, the proportion of newly formed remaining oil (petroleum-clay (feldspar and debris) mixed remaining oil) decreases. However, the remaining oil content that existed as inter-particle adsorption remains the highest, followed by particle adsorption. In the case of water flooding, as the flooding intensity increases, the remaining oil content in the core gradually diminishes. Among them, the remaining oil content in the bound state shows a gradual increase, while the remaining oil content in the free state exhibits a gradual decrease. Notably, the remaining oil content in the form of inter-particle adsorption ranks the highest, followed by the remaining oil that exists as particle adsorption and clusters.

3. Macro Remaining Oil analysis and results

An analysis was conducted on the macroscopic remaining oil in the main oil layers of eight wells. By thoroughly analyzing the differences in permeability between oil layer structural units, the flow line relationship between wells, the development characteristics of interlayers, and the degree of injection-production efficiency, the macroscopic remaining oil types, distribution characteristics, and occurrence layers in each well were summarized and analyzed.

3.1. Main types of Macro Remaining Oil

Macro Remaining Oil is primarily classified into two categories: planar and vertical remaining oil.

Planar remaining oil can be further divided into two subcategories: (1) The remaining oil in the detention zone between injection and production wells. This type forms due to small pressure gradients, insufficient coverage, or hindered crude oil flow, primarily found in the SII13+14a oil layer of the typical WELL-7#. (2) Sedimentary microfacies-controlled remaining oil: variations in sedimentary microfacies give rise to planar heterogeneity, leading to the presence of remaining oil. There are many types of remaining oil. For instance, the remaining oil in the WELL-1# typical well within the SII10+11b oil layer primarily consists of abandoned river channel-blocked remaining oil. In the case of the typical well WELL-5# in the SII7+8 reservoir, the predominant remaining oil type is a thin layer of remaining oil. Lastly, the remaining oil in the typical WELL-9# of the PII6 reservoir mainly originates from the riverside.

Vertical remaining oil can also be divided into two subcategories: one is interlayer interference type remaining oil. Due to vertical differences in the physical properties of each layer, remaining oil accumulates in layers with relatively poor physical properties, even when the injection-production relationship is optimal. This phenomenon is exemplified by typical WELL-10# and 2#. The second is the heterogeneous remaining oil within the layer. This phenomenon is exemplified by typical wells WELL-11# and 12#.

Among the eight types of remaining oil in the well plane, the proportion of remaining oil in the inter-well retention zone is relatively large, with an average value of 53.63%. In terms of vertical remaining oil types, heterogeneous remaining oil within the layer dominates, with an average value of 68.88%.

In terms of genesis, core wells can be subdivided into four types: remaining oil with incomplete injection and production, remaining oil with interlayer differences, remaining oil with interlayer losses, and remaining oil with interlayer interference. The study delves into the types of remaining oil in the eight selected wells (**Figure 8**). Among them, imperfect injection production is the highest reason. In this area, targeting remaining oil from imperfect injection production is crucial for enhancing development potential.

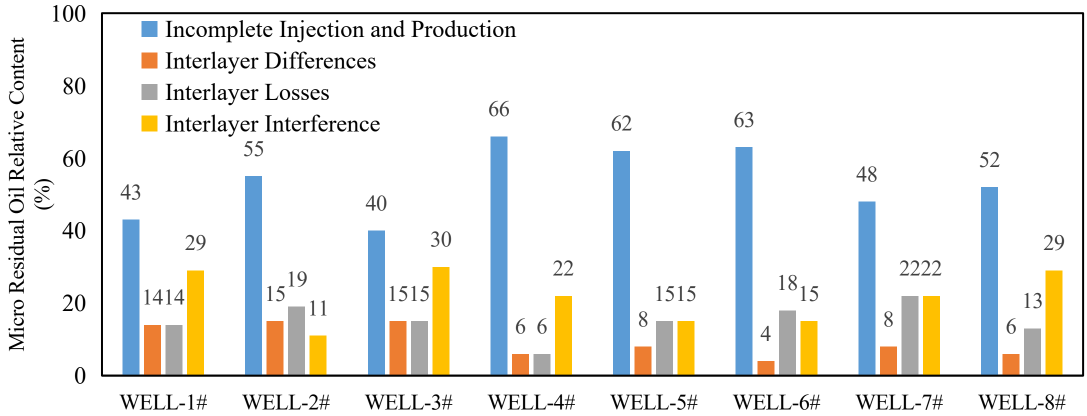

Figure 8. Distribution of Remaining Oil Types in typical wells

3.2. Analysis of the origin of remaining oil in typical wells under different chemical flooding

This article examines the oil displacement efficiency across a variety of oil layers in the WELL-7# core well following combination flooding and polymer flooding.

The results indicate that among the SI 2, SII 2+3a, and SIII 2-4a oil layers, the SII 2+3a oil layer exhibits the highest oil displacement efficiency, reaching 49.62%. After combination flooding, the oil film on the solid-phase surface of the water flow channels in the S oil layer is replaced by an emulsion due to the action of surfactants and alkalis. This process reduces the amount of remaining oil in both free and bound states, leading to high oil displacement efficiency. However, the sweep efficiency in low-permeability layers between high-permeability zones remains inadequate, resulting in weaker flooding and higher free-state remaining oil content, which lowers oil displacement efficiency. This is because, in low-permeability layers without combination flooding, the remaining oil tends to remain in small oil flow channels and forms an oil film on the solid surface of the water flow channels, existing in a bound state.

For the PI2 and PII3 oil layers after polymer flooding, as the degree of flooding increases, the oil saturation in these layers gradually decreases, leading to an overall increase in oil recovery efficiency. The oil recovery efficiency in the strongly flooded sections of the PI2 and PII3 oil layers is 36.3% and 38.1% higher, respectively, compared to the weakly flooded sections. The dynamic remaining oil in the strongly flooded core is not only less than that in the weakly flooded core but also more challenging to displace. This is because, in strongly flooded cores, the remaining oil persists in a semi-bound state within small and weak flow channels, and it forms an oil film on the solid surface of large water flow channels, existing in a bound state. Therefore, when targeting remaining oil in strongly flooded areas, combination flooding offers a superior oil displacement effect.

4. Conclusion

The analysis of Micro Remaining Oil in the S, P, and G oil layers shows that the main types of Micro Remaining Oil in the core include pore surface thin film, corner, throat, cluster, intergranular adsorption, and particle adsorption. Among these, the content of adsorbed remaining oil between particles, particularly in the intergranular mud matrices or areas with high clay mineral content, is relatively the highest. This type of remaining oil is the primary target for micro-remaining oil exploration. The high content of intergranular adsorption of remaining oil may be due to the formation of a new type of remaining oil (petroleum-clay (feldspar and debris) mixed remaining oil) distributed between particles and pore throats, leading to an increase in its proportion.

Experimental research on Micro Remaining Oil reveals that in the S, P, and G oil layers, as the degree of flooding increases, the movable free-state remaining oil (e.g., intergranular adsorption and clusters) gradually decreases, while the immovable bound-state remaining oil (e.g., pore surface thin film and particle adsorption) gradually increases. Therefore, during extraction, it is essential to prioritize the recovery of free-state remaining oil, followed by the extraction of bound-state remaining oil. The experiments indicate that the remaining oil content in the free state, specifically in the form of inter-particle adsorption, is the most prominent initially. As the extraction process advances, there is a decline in free-state remaining oil and a concurrent rise in bound-state remaining oil.

A macroscopic analysis of remaining oil in the reservoir identifies four primary types of typical in the wells: interlayer difference type, interlayer loss type, interlayer interference type, and injection-production imperfect type. While each well's macroscopic remaining oil has distinct distribution characteristics, the injection-production imperfect type remaining has the highest content, making it the main target for enhancing development potential. In addition, the analysis of reservoir utilization and oil displacement efficiency demonstrates that as flooding intensity increases, the reservoir's oil saturation gradually decreases, and oil displacement efficiency improves. The dynamic remaining oil in strongly flooded cores is not only less than in weakly washed cores but also more challenging to displace.

In summary, for the development of the S, P, and G oil layers in the Daqing Oilfield, it is crucial to implement targeted measures based on specific geological characteristics and the content of various types of remaining oil to maximize recovery and profitability.

Disclosure statement

The author declares no conflict of interest.

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