Micro-scale investigation on the effect of waterflooding rate on oil recovery and residual oil distribution

Tongyao Zhang1*, Ke Chen1 and Xudong Zhang1

1 CNOOC Experimental Center (Bohai), CNOOC Ener Tech-Drilling & Production Co, Tianjin, 300452, China

*Corresponding author. Email address: zhangty2@cnooc.com.cn

Abstract Waterflooding is currently one of the most common and mature oil and gas development methods. However, when oil and gas fields enters the medium or high water-cut period, there is still a large amount of residual oil remaining untapped while residual oil characteristics and distribution could be complicated. Micromodel method is considered as a novel experimental method for studying residual oil characteristics and waterflooding. Unlike conventional core flooding, visualization of the whole process can be realized through micromodels. In this work, three different flooding rates were used to simulate the waterflooding process via micromodels. Consequently, oil recovery rates and residual oil distribution were obtained. It was observed that higher waterflooding rate increased the oil recovery. When the flooding rate was large, dispersed residual oil was observed after waterflooding. When the rate was small, residual oil exhibited more complicated configurations. For the trapped residual oil in the dead end pores in hydrophilic rock matrix, increasing the flooding rate or the viscosity of displacing phase could be beneficial to dislodge the residual oil.

1. Introduction

Waterflooding is widely used around the globe since its low cost and good oil displacement. Yet after long time of waterflooding, there is still a large amount of residual oil that remains untapped. Therefore, the formation mechanism and current state of residual oil are of great significance to the evaluation of reservoir development and subsequent enhanced oil recovery (EOR) technologies.

The research on waterflooding and residual oil is mainly divided into physical experiments and numerical simulations. The physical experiments mainly include micromodels, computed tomography (CT), and nuclear magnetic resonance (NMR). Meshless method and pore network method are mostly used in numerical simulations. As one of the emerging physical experimental methods for studying residual oil in recent years, the micromodel method has the advantages of process visualization, low cost and high efficiency, thus is widely used in the study of micro-scale multiphase flow.

Mattax et al. first proposed the concept of micromodel in 1962[1]. Since then, micromodels were widely used in the fields of biology, chemistry, engineering etc., and various materials such as glass, silicon, paper and polydimethylsiloxane (PDMS) were used to make the model. Nowadays, micromodels have become one of the important experimental methods for studying fluid phenomena.

Jamaloei et al. used the glass etching micromodels to study the phenomenon of viscous fingering during surfactant-alkali flooding of heavy oil[2]. The fingering process was recorded by a microscope. Their study found that fingering of heavy oil can be divided into three flow regimes based on pressure drop. Cao et al. studied the injection process of supercritical CO2 fluid using high-pressure resistant
micromodels[3]. The whole process was recorded under the condition of a back pressure of 8MPa. They found that the injectivity of CO2 in saline aquifers mainly depends on the seepage process.

Xu et al. produced 2.5-D micromodels with different pore-throat depths[4]. Chips made by a special hydrofluoric acid etching method have smaller throat depths and larger pore depths. Therefore, this type of chips has been used to observe 2.5-D fluid distribution.

Pu et al. produced micromodels with two different permeability regions to study the performance of polymer microspheres[5]. Experiments observed that the microspheres can move to the deeper part of the high permeability area for further sealing through elastic deformation. Yao et al. also studied the migration phenomenon of micron-sized polymer microspheres using three-dimensional micromodels by filling transparent quartz sand between polypropylene sheets[6].

Zhu et al. have made micro glass models with different injection-production angles to study the effects of angle on oil recovery[7]. And found that after changing the injection-production angle, clustered and columnar-shaped residual oil have been driven out. Xu et al. used core models with electrodes to describe the residual oil distribution based on the electrical resistivity[8]. They simulated water flooding, polymer flooding and evaluated the oil recovery of different displacement methods.

As mentioned above, researchers have conducted lots of research on the characteristics of multiphase flow and various displacement methods. Nevertheless, due to the continuous change of fluid properties and the complexity of the porous medium, there is still much need to be studied in waterflooding and residual oil.

In this work, micromodels are made based on the micro-structure of core slices, and different displacement rates are selected for waterflooding experiments. Each micromodel is waterflooded until the residual oil saturation no longer changes. Then by calculating the oil displacement rate, sweeping volume and recording residual oil status of the microchip, we attempt to evaluate and quantify the influence of displacement rate on oil displacement efficiency and residual oil shape.

2. Materials and methods
In order to better understand the interaction between oil and water in waterflooding, our experiment uses micron-size chips which is close to the scale of the formation pore throat. And the whole process is visualized and captured by microscopes for subsequent data processing and analyzing.

2.1. Micromodels fabrication
The microfluidic chip is designed from real core slices (Figure 1a). By extracting its pore structure, a binary picture (Figure 1b) is obtained, which is then processed by AutoCAD and the drawings are generated (Figure 1d). Based on the drawings, two pieces of glass is wet-etched and then bonded to form a chip (Figure 1c). Later, PEEK connectors are equipped (Figure 2).

Figure 1. The manufacturing process of microfluidic chips, where a) core slice; b) binary picture of the rock pore-throat structure; c) real-time image taken under a microscope; d) AutoCAD design.
2.2. Device operation
Main experimental devices are: inverted microscope, syringe pump, needles and connecting hoses, and
miniature pressure sensor. Figure 3 shows the complete set of experimental equipment.

There are mainly three steps in the waterflooding experiment. The first step is to saturate the chip
with water. This step simulates the process in which water first fills the rock pores under the original
geological conditions. The second step aims to simulate the process of oil displacing water after oil is
generated. And the last step is the waterflooding process in which the water is injected into the chip to
drive the oil out. The waterflooding rates used in the experiment were 0.2, 0.5 and 0.8 µL/min.

3. Results and discussion
The flooding process was recorded through a microscope. And the pictures were binarized as shown in
Figure 4 - the black part of the chip represents water, and the remaining white part is the rock and the
residual oil. Then ImageJ software was used to calculate the water saturation so that the residual oil
saturation can be calculated from it.
3.1. Effect of waterflooding rate on oil recovery

Through the binarization of all pictures, the oil recovery curves are obtained. It can be seen from Figure 5 that when the waterflooding rate is 0.2 µL/min, the displacement speed is relatively slow. As more water is injected, more oil is driven out, and the recovery rate increases rapidly at the beginning but then slows down until it reaches 56.8% when the waterflooding process ends.

![Figure 5. The oil recovery curve when the waterflooding rate is 0.2µL/min.](image)

Figure 5. The oil recovery curve when the waterflooding rate is 0.2µL/min.

Figure 6 shows the recovery curve when the waterflooding rate is 0.5 µL/min. Compared with 0.2µL/min, the initial slope of the recovery curve and the final recovery are both bigger. Moreover, there is a stepped recovery rate increases until it reaches about 85%. It can be concluded that when the flooding rate is increased by 2.5 times, the final recovery rate increases from 56.8% to 85%.

![Figure 6. The oil recovery curve when the waterflooding rate is 0.5µL/min.](image)

Figure 6. The oil recovery curve when the waterflooding rate is 0.5µL/min.

When we continue to increase the waterflooding rate to 0.8µL/min, it can be seen from Figure 7 that the final recovery is much higher. Comparing with Figure 5 and 6, it is found that when the waterflooding rate is larger, the time it takes for the recovery rate to reach stable is much shorter. However, it should be noted that the pore volume of the chip is smaller so that the sweep efficiency is higher than the actual field development. In addition, when the waterflooding rate is increased by 4 times from 0.2 to 0.8µL/min, the final recovery rate increases from 56.8% to 92.7%.
3.2. Effect of waterflooding rate on residual oil shape

The shape of residual oil can be roughly divided into contiguous type and dispersed type. The contiguous type can then be subdivided into contiguous and clustered shapes. And the dispersed type can be subdivided into columnar, angular, membranous and island shapes.

To better observe the shape of the residual oil, the pictures are color-processed as shown in Figure 8 in which blue represents the water phase, black represents the oil phase, and brown represents the rock.

The residual oil shapes observed are shown in Figure 9. When the waterflooding rate is as large as 0.8μL/min, the shape of the residual oil is mostly island-shaped (Figure 9a). And most of the oil exists in the dead end pores, making it difficult to sweep out. When the waterflooding rate is 0.5 μL/min, there are mainly three types of residual oil, including the trapped oil in the dead end pores (Figure 9a), free droplet oil (Figure 9b), and columnar oil in the connected pores (Figure 9c).

When the waterflooding rate is as small as 0.2μL/min, the residual oil distribution shapes are more complex and diverse. From Figure 10 it can be seen that the residual oil shapes include contiguous type (Figure 10c) and columnar shape (Figure 10a, 10b, 10c), membranous shape (Figure 10a), angular shape (Figure 10a), island shape (Figure 10a, 10b, 10c), etc.
4. Conclusions
In this work, a micromodel was fabricated to simulate the micro-scale waterflooding process, and the following conclusions are obtained after analyzing the oil recovery rate and residual oil distribution:

(1) Increasing the waterflooding rate can improve the oil recovery. When the waterflooding rate is 0.2μL/min, the oil recovery is low and its growth rate is slow. When the flooding rate is 0.5μL/min, the growth rate of the recovery increases so does the final oil recovery volume. When the displacement flow is 0.8μL/min, the final recovery volume is the highest, and the time required to reach the final recovery volume is the shortest.

(2) The waterflooding rate has effects on the residual oil shape and distribution. When the rate is large, there is mainly dispersed residual oil after waterflooding, including the trapped oil in the dead end pores, free droplet oil, and columnar oil in the connected pores. The first type of residual oil is difficult to drive out, which requires the flooding of vicious liquid.

(3) When the waterflooding rate is small, the residual oil shapes are complex and diverse. Continuous and dispersed types of oil both exist in pores and throats. The increase in flooding rate or the application of other EOR methods can improve oil recovery.

(4) For the residual oil trapped in the dead end pores, increasing the flooding rate helps to reduce the volume of the trapped oil in the hydrophilic rock structure. The greater the flooding rate, the thicker the water membrane between oil and rock, therefore the easier for residual oil to be driven out.

Acknowledgements
This research was funded by the National Science and Technology Major Project of China (No. 2016ZX05058).

References
[1] Mattax, C.C., Kyte, J.R. (1962) Imbibition oil recovery from fractured, water-drive reservoir. SPE Journal, 2(02): 177-184.
[2] Jamaloei, B.Y., Babolmorad, R., Kharrat, R. (2016) Visualization and analysis of viscous fingering in alcohol-assisted surfactant waterflooding of heavy oil in a two-dimensional sandstone micromodel. FUEL, 184(nov.15): 169-179.
[3] Cao, S.C., Dai, S., Jung, J. (2016) Supercritical CO₂ and brine displacement in geological carbon sequestration: micromodel and pore network simulation studies. International Journal of Greenhouse Gas Control, 44: 104-114.
[4] Xu, K., Liang, T., Zhu, P. et al. (2017) A 2.5-D glass micromodel for investigation of multi-phase flow in porous media. Lab on a Chip, 17(4): 640-646.
[5] Pu, W., Zhao, S., Wang, S. et al. (2018) Investigation into the migration of polymer microspheres (PMs) in porous media: Implications for profile control and oil displacement. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 540: 265-275.
[6] Yao, C., Lei, G., Lawrence, M. et al. (2014) Pore-scale investigation of micron-size polyacrylamide elastic microspheres (MPEMs) transport and retention in saturated porous media. Environmental Science & Technology, 48(9): 5329-5335.
[7] Zhu, W., Ma, Q., Li, B. et al. (2019) Influence of injection-production angle variation on oil displacement efficiency and microscopic remaining oil. Fault-Block Oil & Gas Field, 26(02): 220-224.

[8] Xu, B. (2020) Experimental study on distribution characteristics of remaining oil in vertical heterogeneous reservoirs by gel profile control. Petroleum Geology and Recovery Efficiency, 27(06): 71-80.