Study on Oil-water Two-phase Migration Mechanism of Low Permeability Fractured Core based on the Online NMR Testing

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Abstract. Understanding the dynamic migration mechanism of oil-water two-phase is the key to improve the effect of water injection development in low permeability fractured reservoir. Based on artificial fracturing of core and basic physical parameter testing, the online NMR displacement experiments of cores with different fracture widths are conducted to analyze the oil-water dynamic distribution characteristics and migration mechanisms. The experimental results show that when water breaks through at the outlet, oil volume in the small pores is basically unchanged. In the large pores it decreases to a certain extent, while in the fracture it decreases greatly. When the displacement is over, oil volume in the small pores still changes little, while it decreases greatly in the large pores, and it is almost zero in the fracture. With the decrease of fracture width, the recovery ratio when waterflooding front breaks through and the final recovery ratio after displacement increase gradually. The contribution proportion of recovery ratio in the fracture decreases as a whole, while in the large pores it increases gradually, and in the small pores it decreases slightly. The research results lay a foundation for the optimal design of fracture parameters and the adjustment of water injection development technology policy in low permeability fractured reservoir.

1. Introduction

Low permeability reservoirs are widely distributed in China, especially in Changqing oilfield [1-2]. In the recent 20 years, the production rate of low permeability oil reservoir is increasing continuously. Low permeability reservoir plays an increasingly important role in the development of oilfield and it is becoming the main body of development. Micro fractures and artificial fractures are often developed in low permeability reservoir, which is often called low permeability fractured reservoir [3-4]. Low permeability reservoir is characterized by low permeability, small reserve abundance, low pressure coefficient, low natural productivity and great development difficulty. Water injection is still one of the main development methods of low permeability reservoir [5-7]. In the process of waterflooding in low permeability fractured reservoirs, water channeling, changes of fracture morphology and reservoir physical parameters will happen, which have great impacts on waterflooding development [8-10].

Many scholars conducted oil-water two-phase flow mechanism and water displacement experiments of low permeability fractured reservoir. Because of the particularity of fractured core, it cannot be taken out in the process of displacement experiment, otherwise the fluid in the fracture of core cannot be preserved, so conventional NMR technology cannot meet the requirements of fractured core displacement experiment, and the online NMR displacement experiment can monitor the fluid distribution and migration characteristics in the process of water displacement [11-12]. Based on nuclear magnetic theory and technology, the online nuclear magnetic displacement experiments of low
permeability fractured core are conducted in this study. The influences of fracture widths on
distribution characteristics and dynamic migration mechanisms of oil-water two phases in the cores
with different fracture widths at different displacement stages are analyzed and the differences are
compared. The study is of great significance to improve the waterflooding effect of low permeability
fractured reservoir.

2. Experimental principle and steps
The mechanism of nuclear magnetic resonance (NMR) shows that when the pore is full of fluid, H⁺
makes transverse relaxation movement in the pore. H⁺ will collide with the pore wall, causing energy
loss of H⁺ and making H⁺ return from high energy state to low energy state, which is the transverse
relaxation process of H⁺. The more frequent the collision, the faster the energy loss of H⁺. Obviously,
the pore size determines the number of collision process between H⁺ and pore wall. The smaller the
pore, the greater the probability of collision between H⁺ and pore in the process of transverse
relaxation. It can be considered that the size of the pore is inversely proportional to the relaxation rate
of H⁺. That is, the smaller the pore, the higher the transverse relaxation rate of H⁺ and the shorter the
the corresponding relaxation time. The larger the pore, the lower the transverse relaxation rate of H⁺
and the longer the corresponding relaxation time. At the same time, the wider the distribution range of
NMR relaxation spectrum, the lower the amplitude, the worse the pore throat sorting.

Online NMR displacement experiment can scan the core and form T₂ spectrum in the displacement
process without affecting the displacement experiment. By analyzing the signal amplitude
corresponding to different relaxation time in T₂ spectrum, the volume of fluid under a certain pore size
can be obtained.

Because T₂ value and corresponding signal amplitude represent the size and quantity of the pore
space where the hydrogen nucleus is located, the T₂ spectrum can represent the distribution of fluid in
the core. In the online NMR experiment of this study, the core holder containing core is put in the
NMR instrument together for testing, so that the core and fluid in it can keep high pressure online
displacement state. For each core, the NMR testing is repeated three times to confirm the reliability of
testing results. Because both water and oil contain H⁺, they will produce certain magnetic signals,
which will cause interference in the process of experiment. In order to study oil distribution in the core
and keep the property of oil unchanged, brine containing MnCl₂ is used to saturate the core, which can
shield the magnetic signal produced by H⁺ in water. Therefore, the T₂ spectrum tested in the
experiment only represents the distribution of oil in the core. Three cores are used to conduct the
experiment. The experimental temperature is 20 °C. For core 1, core 2 and core 3, the confining
pressures are 5MPa, 10MPa, 15MPa and the fracture widths are 0.04mm, 0.027mm, 0.023mm
respectively. The experimental steps are as follows:

①Measure the basic size of core without fracture, put it into the core holder after weighing, connect the vacuum pump with the outlet end and close the valve at the inlet end of core holder, then use the vacuum pump to vacuum for more than 48 hours.

②The core is saturated with brine containing MnCl₂ after vacuum pumping. After saturation, the core is taken out and weighed. The porosity of core is calculated according to the weight difference before and after saturation.

③The weighted core is put into the core holder, and the core is saturated with standard white oil with flow rate of 0.1mL/min until there is no water flowing out at the outlet. The volumes of produced oil and water are measured and the irreducible water saturation is calculated.

④The core with saturated oil and water is split and fractured by cutting machine and fixed by thermoplastic rubber sleeve.

⑤The permeability of the fractured core is tested and the fracture width is calculated under corresponding confining pressure.
Inject the brine containing MnCl₂ into the core with injection rate of 0.02 mL/min to displace oil. When waterflooding front breaks through at the outlet, NMR is tested again to determine oil distribution in the core.

Continue to inject the brine containing MnCl₂ for oil displacement until water cut of produced liquid reaches up to 100%, and conduct NMR testing again to determine the residual oil distribution at the end of water displacement.

3. Analysis of experimental results

According to online NMR displacement experimental methods and steps, the T₂ spectrum curves of three cores at initial state, water breakthrough state and residual oil state are obtained. According to the T₂ spectrum curve, the distribution characteristics of oil in the core and the influence of fracture on it are analyzed. In order to better compare the characteristics of fluid distribution in the cores with different fracture widths, frequency is used to describe corresponding amplitude under different relaxation times.

\[
f = \frac{A_i}{\sum A_i}
\]

where, \( f \) is the frequency of an amplitude;
\( A_i \) is the amplitude corresponding to a certain relaxation time;
\( \sum A_i \) is the sum of amplitudes corresponding to all relaxation times.

According to the experimental results and Eq.(1), the NMR T₂ spectra of three cores at initial state, water breakthrough state and residual oil state are obtained, as shown in figure 1 ~ figure 4.

The fracture width of core 1 is 0.04mm. The T₂ spectrum curves at initial state, water breakthrough state and residual oil state are shown in figure 1. The results show that in the initial state before displacement, the T₂ spectrum curve presents a three peak shape, and the height of the three peaks decreases from left to right. The left peak represents oil distribution in the small pores of core; the middle peak represents oil distribution in the large pores, and the right peak represents oil distribution in the fracture. When water breaks through at the outlet, the volume of oil in the small pores is almost the same. In the large pores, oil volume is slightly reduced, while in the fracture it is greatly reduced. When the displacement is over, the volume of oil in the small pores still changes little, while in the large pores it decreases obviously, and in the fracture it is almost zero. At this time, the T₂ spectrum curves change from three peaks to two peaks.

Figure 1. T₂ spectrum curves of oil distribution at different stages of core 1
The fracture width of core 2 and core 3 are 0.027 mm and 0.023 mm. The T$_2$ spectrum curves at initial state, water breakthrough state and residual oil state are shown in figure 2 and figure 3. The results show that in the initial state before displacement, the T$_2$ spectrum curve presents a three peak shape from left to right, which represents the distribution of oil in the small pores, large pores and fracture of core. The displacement characteristics of core 2 and core 3 are basically the same as that of core 1. When water breakthrough occurs at the outlet, oil volume in the small pores is basically unchanged. In the large pores oil volume decreases to a certain extent, and in the fracture it decreases greatly. When the displacement is over, the volume of oil in the small pores still changes little, while in the large pores it decreases greatly, and in the fracture it is almost zero. At this time, the T$_2$ spectrum curves change from three peaks to two peaks.

![Figure 2. T$_2$ spectrum curves of oil distribution at different stages of core 2](image)

![Figure 3. T$_2$ spectrum curves of oil distribution at different stages of core 3](image)
Figure 4 shows the comparison of $T_2$ spectrum curves of three cores in the initial state. From core 1 to core 3, confining pressure gradually increase and fracture width gradually decreases. It can be seen that the value on the right end of $T_2$ spectrum curve gradually decreases with the increase of confining pressure. As the relaxation time represents the pore space size of fluid, the fracture space scale decreases with the increase of confining pressure, which verifies the feasibility of controlling fracture width by confining pressure.

![Comparison of initial oil distribution in different fractured cores](image)

Figure 4. Comparison of initial oil distribution in different fractured cores

The sum of the frequency values in different peaks represents the total volume of fluid in corresponding pore sizes, therefore the corresponding recovery ratios in the small pores, large pores and fracture can be calculated. Figure 5 shows the comparison of recovery ratio in the small pores, large pores and fracture when waterflooding front of different fractured cores breaks through. The results show that: (1) With the decrease of fracture width, the recovery ratio when waterflooding front breaks increases gradually. For the cores with fracture widths of 0.04mm and 0.023mm, the recovery ratios when water breaks are 8.07% and 16.62% respectively. (2) With the decrease of fracture width, the recovery ratio from the large pores increases gradually. For the cores with fracture widths of 0.04mm and 0.023mm, the recovery ratio from the large pores are 2.98% and 11.97% respectively. (3) With the decrease of fracture width, produced oil volume in the large pores of matrix increases gradually before water breakthrough. This is mainly because the smaller the fracture width is, the lower the fracture conductivity is, and the greater the displacement pressure difference between two ends of the core is. Under the effect of displacement pressure difference, the oil in the large pores is easier to be displaced.

Figure 6 shows the contribution proportion of recovery ratio in the small pores, large pores and fracture to the total recovery ratio when waterflooding front of different fractured cores breaks through. It can be seen that with the decrease of fracture width, the contribution proportion of recovery ratio in the fracture decreases as a whole, and that in the large pores increases gradually, while in the small pores it decreases gradually. This shows that the larger the fracture width is, the more serious the injection water channeling is, the smaller the pressure difference between two ends of the core is, and the less oil can be displaced from the large pores. However, the contribution proportion of recovery ratio in the small pores decreases with the decrease of fracture width. It is because some oil in the large pores is displaced out, but there is still a small amount of oil left, which is identified as oil in the small pores when testing with NMR.
Figure 5. Comparison of recovery ratios when waterflooding front breaks in different fractured cores

Figure 6. Comparison of recovery contribution proportion when waterflooding front breaks in different fractured cores

Figure 7. Comparison of recovery ratios at the end of displacement in different fractured cores
Figure 7 shows the final recovery ratio at the end of displacement in the small pores, large pores and fracture of different fracture cores. The results show that the final recovery ratio increases with the decrease of fracture width. For the cores with fracture widths of 0.04mm and 0.023mm, the final recovery ratios are 19.00% and 25.19% respectively at the end of displacement. Meanwhile, with the decrease of fracture width, the oil recovery ratio from the large pores increases gradually. For the cores with fracture widths of 0.04mm and 0.023mm, the recovery ratios from the large pores at the end of displacement are 9.37% and 18.6%. With the decrease of fracture width, the recovery ratio from the fracture decreases as a whole. For the cores with fracture widths of 0.04mm and 0.023mm, the recovery ratio from the fractures are 5.47% and 2.77% respectively. This shows that the larger the fracture width, the more difficult the oil in the matrix pore to be displaced. When the displacement is over, the oil in the fracture is basically all recovered, which results in the greater the fracture width, the larger the fracture volume, the more oil stored in the fracture, and the greater the recovery ratio from the fracture.

Figure 8 shows the contribution proportion of recovery ratio in the small pores, large pores and fracture to the total recovery ratio at the end of displacement of cores with different fractures widths. It can be found that with the decrease of fracture width, the contribution proportion of recovery ratio in the fracture decreases as a whole, while the contribution proportion in the large pores increases gradually, and that in the small pores decreases slightly. For the cores with fracture widths of 0.04mm and 0.023mm, the contribution proportions of recovery ratios in the fractures are 28.81% and 11.02% respectively, whose differences are more than twice. It shows that the larger the fracture width is, the more difficult it is to displace the oil in the matrix, and the contribution proportion of oil produced from the fracture is larger. However, when the fracture width is smaller, most of the produced oil comes from the matrix because of the weak oil storage capacity in the fracture. One part of the oil comes from the pressure difference displacement and the other part comes from the imbibition.

4. Conclusions
(1) Online nuclear magnetic displacement technology overcomes the defects of conventional nuclear magnetic technology. It can not take out the fractured core in the experimental process, hold the fluid in the fracture, and monitor the fluid distribution and oil-water two-phase migration characteristics in the core during water displacement.
(2) When water breaks through at the outlet, oil volume in the small pores is basically unchanged. In the large pores it decreases to a certain extent, while in the fracture it decreases greatly. At the end
of the displacement, oil volume in the small pores still changes little, while it decreases greatly in large pores, and it is almost zero in fracture.

(3) With the decrease of fracture width, water channeling in the fracture is weakened. The recovery ratio when waterflooding front breaks through and the final recovery ratio at the end of displacement increase gradually. The contribution proportion of recovery ratio in the fracture decreases as a whole, while in the large pores it increases gradually, and in the small pores it decreases slightly. In the field practice, the optimal fracture scale should be designed, which can avoid rapid flooding and channeling of fracture, but also effectively produce the oil in the matrix.

References
[1] Ran, X., Li, A., Zhao, J., et al. (2013) Classification and evaluation of ultra-low permeability reservoirs in the Changqing oilfield. In: International Petroleum Technology Conference. Beijing, China. IPTC-16603-MS.
[2] Hu, W., Song, Z., Liu, H., et al. (2000) Experimental research on development fracturing technology of Changqing ultra-low permeability reservoirs. In: International Oil and Gas Conference and Exhibition in China. Beijing, China. SPE-64787-MS.
[3] Zhang, A., Yang, Z., Li, X., et al. (2020) An evaluation method of volume fracturing effects for vertical wells in low permeability reservoirs. Petroleum Exploration and Development, 47(2): 441-448.
[4] Denney, D. (2013) Optimizing fracture stimulations in low-permeability oil reservoirs in the Ordos Basin. Journal of Petroleum Technology, 65(3):112-117.
[5] Lei, Z., Zhu, Z., Liu, S., et al. (2018) Waterflooding optimization using improved streamline simulation for the biggest fractured low-permeability reservoir in China. In: SPE Kingdom of Saudi Arabia Annual Technical Symposium and Exhibition. Dammam, Saudi Arabia. SPE-192402-MS.
[6] Wang, X., Dang, H., Gao, T. (2018) Method of moderate water injection and its application in ultra-low permeability oil reservoirs of Yanchang Oilfield, NW China. Petroleum Exploration and Development, 45(6): 1094-1102.
[7] Qian, G., Jiang, X., Zhang, H. (2000) Numerical simulation study of water injection development in an extra-low-permeability fractured reservoir, Xiaoguai oilfield. In: International Oil and Gas Conference and Exhibition in China. Beijing, China. SPE-64794-MS.
[8] Pu, C., Jing, C., He, Y., et al. (2016) Multistage interwell chemical tracing for step-by-step profile control of water channeling and flooding of fractured ultra-low permeability reservoirs. Petroleum Exploration & Development, 43(4): 679-688.
[9] Shangguan, Y., Zhang, Y., Xiong, W. (2015) The effect of physical property change on the water flooding development in Changqing oilfield Jurassic low permeability reservoir. Petroleum, 1(4):300-306.
[10] Wang, Y., Song, X., Tian, C., et al. (2015) Dynamic fractures are an emerging new development geological attribute in water-flooding development of ultra-low permeability reservoirs. Petroleum Exploration & Development, 42(2):247-253.
[11] Dai, C., Cheng, R., Sun, X., et al. (2019) Oil migration in nanometer to micrometer sized pores of tight oil sandstone during dynamic surfactant imbibition with online NMR. Fuel, 245: 544-553.
[12] Liu, Z., Cheng, H., Xu, C., et al. (2018) Effect of lithology on pore-scale residual oil displacement in chemical flooding using nuclear magnetic resonance experiments. In: SPE EOR Conference at Oil and Gas West Asia. Muscat, Oman. SPE-190450-MS.