EXPERIMENTAL STUDY ON POST-FRACTURE OIL-WATER DISPLACEMENT MECHANISM OF TIGHT SANDSTONE RESERVOIR WITH NUCLEAR MAGNETIC RESONANCE

by

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In this paper, three different fracturing fluids are used as replacement working fluids, and nuclear magnetic resonance technology is used to study the oil-water replacement law of tight sandstone cores in the field, revealing the main influencing factors of oil-water replacement in the process of tight oil fracturing flow back.

Key words: *tight sand reservoir, fracturing fluid, oil-water displacement, NMR technique, pore size*

Introduction

Tight reservoirs usually have a long return period after fracturing, and after fracturing, they are usually produced in a well-controlled manner, so that the return fluid can replace oil and water in the propped fracture and the crude-oil in the reservoir matrix. The main mechanism of oil-water replacement is osmotic oil recovery. Previous studies have shown that surfactants can reduce the interfacial tension between oil and water and change the wettability of the rock surface, thus improving the efficiency of oil recovery by osmosis in tight reservoirs [1-5].

In this paper, the impact of the breaker fluid of slick-water fracturing fluid, guar fracturing fluid and cross-linked guar fracturing fluid on the oil-water displacement efficiency and microscopic oil and water migration law in tight sand oil reservoirs were studied with nuclear magnetic resonance technology. The main influencing factors of oil-water displacement during the fracturing fluid-flow back process were revealed, which can provide a theoretical basis and reference for the optimization of the post-fracture flow back system for tight oil reservoirs [6-10].

Experimental procedure

The eight cores are dried, vacuumed and saturated formation water containing 25000 mg per L $MnCl_2$. The dried cores are saturated with oil by displacing water until the core outlet contains 100% oil. The cores saturated with oil are tested by NMR to obtain the original oil distri-

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Figure 1. Core soaking for oil-water displacement

bution. At the reservoir temperature, the core is immersed in the working fluid, and the type of working fluid, additives and soaking time are changed, as shown in fig. 1. After soaking for a certain period of time, the core was tested by nuclear magnetic resonance again to obtain the oil distribution after oil-water displacement. According to the T_2 distribution curve before and after oil-water displacement, the displacement efficiency in various pores are analyzed.

Experimental materials and experimental scheme

The simulated reservoir crude-oil was used as the experimental oil, and the crude-oil viscosity was 2.2 mPa·s at 353.15 K. The displacement time was 24 hours with normal pressure. The displacement fluid includes formation water, gel breaking liquid and surfactant solution. The core physical properties, displacement fluid properties and experimental conditions were shown in tab. 1.

Table 1. Experimental material properties and experimental scheme

Core number	Permeability [10^{-3} μm^2]	Displacement fluid type	Oil-water interfacial tension [mNm^{-1}]
1	0.68	Formation water	19.506
2	0.35	0.3% OC-I surfactant	0.055
3	0.492	0.3% GMQ-6 surfactant	1.633
4	0.214	0.1% microemulsion	2.325
5	0.235	0.3% Hetero-gemini surfactant	0.131
6	0.301	Slippery water breaking fluid	0.613
7	0.26	linear gel breaking fluid	0.059
8	0.358	Cross-linked guar gum breaking fluid	0.065

Experimental results and analysis

In this experiment the oil-water displacement efficiency is calculated using the difference of T_2 spectrums before and after the oil-water displacement:

$$R = \frac{S_o - S}{S_o} \tag{1}$$

where R is the displacement efficiency, S – the the area covered by the NMR T_2 spectrum and the T_2 axis after oil-water displacement, and S_o – the area surrounded by the NMR T_2 spectrum, and the T_2 axis when the core is saturated with oil.

The core saturated water used in the experiment as well as the submerged replacement solution are water containing $MnCl_2$. Since Mn^{2+} can effectively shield the H nucleus in the water, after the oil-water replacement, the area surrounded by the T_2 spectrum and the T_2 axis decreases by how many proportions, which represents how many proportions of the oil have been replaced.

Effect of physical properties of core sample on oil-water displacement efficiency

According to the common classification method of T_2 spectrum of tight reservoirs, the pore radius is divided into four categories on the base of T_2 distribution interval, namely micropore ($T_2 < 1$ ms), small pore (1 ms < T_2 < 10 ms), and medium pore (10 ms < T_2 < 100 ms) and macropore ($T_2 > 100$ ms).The displacement efficiency of various pores can be calculated by calculating the superposition of signal amplitudes in various pores, and the calculation results are shown in tab. 2.

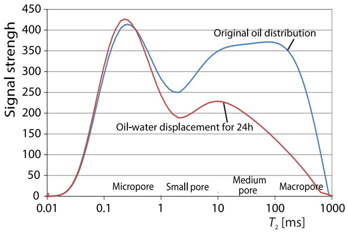

Figure 2. The T_2 spectrum of core 1#

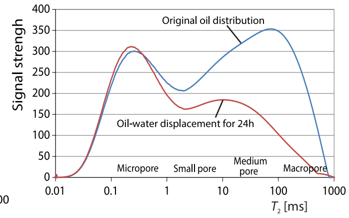

Figure 3. The T_2 spectrum of core 2#

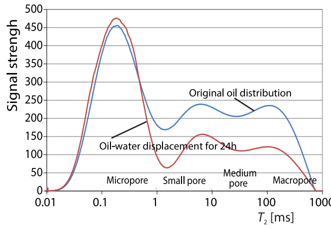

Figure 4. The T_2 spectrum of core 3#

Table 2. The oil-water displacement efficiency of core 1#, 2#, and 3#

Core number	Oil-water displacement efficiency [%]				
	Micropore (<1 ms)	Small pore (1-10 ms)	Medium pore (10-100 ms)	Macropore (>100 ms)	Synthesis
1#	–1.23	18.79	41.07	41.38	31.21
2#	–1.27	25.29	51.96	78.99	34.80
3#	–3.20	45.26	44.51	49.22	23.62

From figs. 2-4, it can be seen that T_2 spectral curves decreased significantly after 24 hours of oil-water replacement, especially the most obvious decrease in the T_2 spectra in the small, medium and large pore regions, which indicates that the oil displaced from the core mainly comes from these pores. The T_2 spectrum in the microporous region slightly increased, indicating that the secondary migration of crude-oil occurred during the replacement process, which led to an increase in the concentration of oil in the microporous. From tab. 2, it can be seen that the largest pores have the most oil replacement, followed by the mesopores, and the least oil in the micropores. Theoretically, oil in small pores should be more easily displaced because of the greater capillary forces, the experimental results show a higher oil displacement efficiency in large pores, which may be due to the lower seepage resistance of large pores, which makes it easier for water to displace the oil upon entry.

We can see from tab. 2 that the oil-water displacement efficiency of core samples #1 and #2 is significantly higher than that of core sample #3. By analyzing the reasons, the crude-oil displacement efficiency is closely related to the pore size distribution of core sample, which is macroscopically represented by the permeability. From tab. 3 we can find the proportion of medium and large pores (45% and 48%) of core samples #1 and #2 is higher than that of core sample #3 (34%), which is the main reason for the difference in displacement efficiency. Although the pore size distributions of core samples #1 and #2 are close to each other, and the permeability of core sample #2 is smaller than that of core sample #1, the oil-water displacement efficiency is higher than that of core sample #1. This is due to the addition of surfactant in the replacement fluid of core sample #2, which makes the replacement efficiency reach 34.8%. It can be seen that the addition of surfactant to the replacement fluid can reduce the interfacial tension between oil and water, thus improving the replacement efficiency of oil and water.

Table 3. Original distribution of crude-oil in various pores of three rock samples

Core number	Distribution of crude-oil in various pores [%]			
	Micropore (<1 ms)	Small pore (1-10 ms)	Medium pore (10-100 ms)	Macropore (>100 ms)
#1	33.61	21.47	27.18	17.74
#2	30.69	21.31	30.01	18.00
#3	45.42	20.15	21.02	13.41

Effect of oil-water interfacial tension on oil-water displacement efficiency

In order to further investigate the influence of oil-water interfacial tension on the oil-water displacement efficiency, two core samples #4 and #5 with similar permeability were used in the experiment.

From figs. 5 and 6, it can be seen that after 24 hours of oil-water displacement, the T_2 spectrum curve of small, medium and large pores decreased significantly. The T_2 spectrum curve of microporous interval increased slightly, indicating that oil-water displacement reduces the oil volume in small, medium and large pores, but also increases the crude-oil in micropores, which may be due to the secondary migration of oil and water in micropores. Compared with core sample #4, the T_2 spectral curve of core sample #5 after oil-water displacement decreases more, indicating that core sample #5 has higher oil-water displacement efficiency.

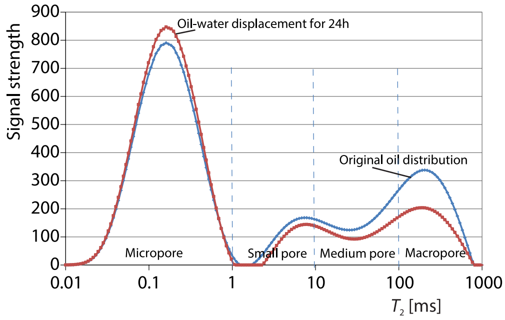

Figure 5. The T_2 spectrum distribution of core #4

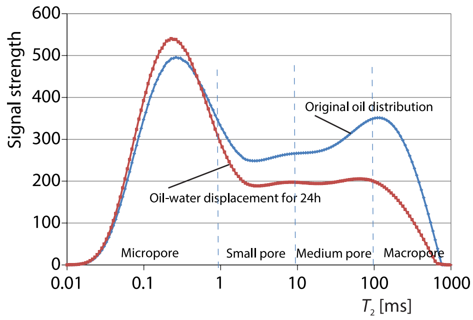

Figure 6. The T_2 spectrum distribution of core #5

Table 4. Displacement efficiency in various pores of two rock samples

Core number	Displacement efficiency [%]				
	Micropore (<1 ms)	Small pore (1-10 ms)	Medium pore (10-100 ms)	Macropore (>100 ms)	Synthesis
4	–6.49	25.55	27.29	39.56	9.22
5	–6.28	22.42	32.95	52.60	17.83

We can find from tab. 4 that the oil displacement efficiency in the medium pores and macropores of core sample #5 is higher than that of core sample #4 and the comprehensive oil displacement efficiency is 8.61% higher. From tab. 5 that crude oil is most distributed in micropores. Analyzing the reasons, firstly, the oil-water interfacial tension in the replacement fluid of core sample #5 is lower, which improves the replacement efficiency. Secondly, the pore throat distribution of core sample #5 is more uniform than that of core sample #4, which indicates better homogeneity and better pore throat connectivity, which is also the main reason for the difference in oil-water displacement efficiency.

Table 5. Distribution of crude-oil in various pores of two rock samples

Core number	Distribution of crude-oil in various pores [%]			
	Micropore (<1 ms)	Small pore (1-10 ms)	Medium pore (10-100 ms)	Macropore (>100 ms)
4	60.09	7.27	13.47	19.16
5	41.15	20.20	22.59	16.06

Effect of fracturing fluid type on oil-water displacement efficiency

To further guide field applications, three fracturing fluid breakers were used in this experiment, including a slick water fracturing fluid, a linear gel breaker, and a cross-linked guar breaker. The three core samples used in the experiment have similar permeability. This experiment mainly examines the oil-water displacement effect of three gel-breaking fluids with different interfacial tensions.

From figs. 7-9, it can be seen that after 24 hours of oil-water displacement, the T_2 spectrum curves of small pores, medium pores and macrospores have decreased significantly, while the T_2 spectral curves of the microspores changed slightly, indicating that the crude-oil in small pores, medium pores and macrospores was mainly produced by oil-water displacement. As can be seen from tab. 6, the larger the pore size, the higher the oil-water displacement efficiency.

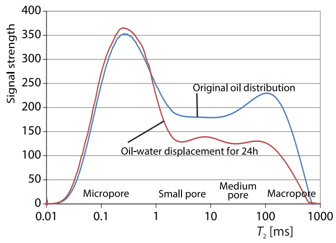

Figure 7. The T_2 spectrum of core #6

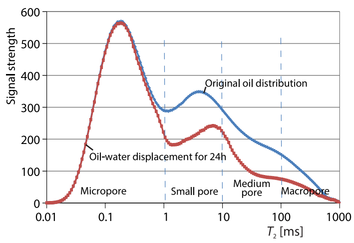

Figure 8. The T_2 spectrum of core #7

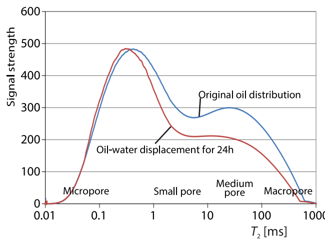

Figure 9. The T_2 spectrum of core #8

Table 6. Displacement efficiency in various pores of three rock samples

Core number	Displacement efficiency [%]				
	Micropore (<1 ms)	Small pore (1-10 ms)	Medium pore (10-100 ms)	Macropore (>100 ms)	Synthesis
6	–5.66	24.00	35.07	52.60	17.83
7	3.10	34.00	44.47	46.24	21.11
8	15.83	22.10	31.22	41.84	23.33

It can be seen from tab. 7 and the original T_2 spectrum curves of oil distribution that the pore size distribution and permeability of the three core samples are relatively close. The difference of oil-water displacement efficiency is mainly caused by the interfacial tension of the displacement fluid. Since the displacement fluid of core samples #7 and #8 is guan gum breaking fluid containing cleanup additive, the interfacial tension is significantly lower than that of slick water breaking fluid used in core sample #6, so the oil-water displacement efficiency of core samples #7 and #8 is higher than that of core sample #6, as can be seen from tab. 6. It can be concluded that the cleanup additive in guan gum fracturing liquid system can effectively reduce the interfacial tension of oil and water, and improve the oil-water displacement efficiency compared with the slippery water fracturing liquid.

Table 7. Distribution of crude-oil in various pores of three rock samples

Core number	Distribution of crude-oil in various pores [%]			
	Micropore (<1 ms)	Small pore (1-10 ms)	Medium pore (10-100 ms)	Macropore (>100 ms)
6	42.70	21.15	21.90	14.24
7	50.00	26.58	17.26	6.15
8	42.58	25.18	23.20	9.05

Conclusion

In the process of oil-water displacement, crude-oil has a secondary migration microspores, resulting in an increasing trend of oil in microspores. The displaced oil is mainly from small pores, medium pores and macrospores. The larger the pore size, the higher the oil-water displacement efficiency. The displacement efficiency of crude-oil is closely related to the pore throat distribution of core samples, which is actually manifested as permeability. Strong homogeneity of core samples and good pore-throat connectivity are the main reasons for the higher oil-water displacement efficiency. The oil displacement efficiency is related to the interfacial tension. The oil-water interfacial tension is low, and the displacement efficiency is improved. When the pore throat distribution of the sample is close, the oil-water interfacial tension can be reduced by adding surfactants to the displacement fluid, thus improving the oil-water displacement efficiency. The cleanup additive in guar gum fracturing fluid system can effectively reduce the oil-water interfacial tension and improve the oil-water displacement efficiency compared with the slick water fracturing fluid.

Nomenclature

R – displacement efficiency, [%]

S, S_o – area, [m^2]

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