Visualization Study of Produced Oil Based on Magnetic Resonance Imaging Technology

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ABSTRACT: In recent years, visualization technology based on magnetic resonance imaging has been widely used in core flooding experiments and mechanism research. In this research, the visualization of produced oil is realized by subtracting from image signals collected in different displacement stages. The distribution images of the produced oil can be used to clearly analyze the oil displacement characteristics of cores with different permeabilities and chemical agents with different functions. The distribution image of the produced oil shows advantageous and hard-to-reach areas of water flooding in cores with different permeabilities. The SMG dispersion by blocking the dominant water pathway produced remaining oil areas that were difficult to be swept water flooding and then enlarged the swept volume. The produced oil is concentrated at both ends and dispersed in the middle of the core. The polymer flooding by improving the viscosity of water flooding sharply increased the injection pressure and then swept all areas. The distribution image of the produced oil has the characteristics of filamentous continuous advancement.

1. INTRODUCTION

In recent years, core fluid visualization technology based on magnetic resonance imaging (MRI) has rapidly developed in the petroleum field.1−3 Compared with visualization technologies such as CT and microscopic models,4,5 MRI visualization technology has obvious advantages. It can not only provide the characteristics of fluid saturation distribution and the pore throat structure in the core but also directly observe the internal displacement process of the porous medium and track the changes in the fluid migration process online.6−9 MRI technology is also one of the methods to study the oil displacement mechanism.8,9,10−12 Zhou et al.8 reported the oil saturation changes in the process of oil migration in the core by MRI technology. Cheng et al.9 reported the changes in fluid distribution during core displacement using oil−water distribution images acquired by MRI technology. Di et al.10 used nuclear magnetic resonance to visually characterize the distribution of polymer and soft gel flooding in cores and study the characteristics of oil displacement. Zhang et al.11 visually observed the oil displacement characteristics of the foam through MRI technology and found that it is difficult to distinguish the similarities and differences in the oil displacement characteristics of the two foam systems with direct acquisition in two foam systems with different performances. In previous research work, MRI visualization was limited to collecting fluid distribution images inside the core at different displacement stages. By directly analyzing the fluid change characteristics in the core before and after the displacement, it is difficult to accurately reflect the fluid change characteristics in the core due to the core type and imaging quality.

Both SMG dispersion and polymer solution contribute to improving oil recovery, and the study of their oil displacement mechanism has also achieved a certain understanding.13−17 Wu, Sun et al.14,15 studied the oil displacement mechanism of the SMG dispersed phase and the polymer continuous phase using a microscopic displacement model, and the results showed that the continuous-phase displacement fluid relied on the increase of the viscosity of the injected water to achieve mobility. The microgel particle water dispersion system reduces the relative permeability of the injected water and relatively increases the oil phase permeability to achieve efficient adjustment of convection. Bai et al.16 used mechanical analysis methods to characterize the viscoelastic oil displacement mechanism of polymers.

This work explores the visualization feasibility of the produced oil by subtracting from the obtained different MRI signals. Using low-field nuclear magnetic resonance (LF-NMR) imaging technology combined with core displacement equipment, four sets of core flooding experiments with different permeabilities and agent flooding experiments with two different functional chemical solutions were carried out. The visualization method of the produced oil provides...
guidance for enhanced oil recovery and is a new method for the study of oil displacement mechanism.

2. RESULTS AND DISCUSSION

2.1. Experimental Results and Analysis of Core Flooding with Different Permeabilities. 2.1.1. Changing Characteristics of the NMR T_2 Spectrum. The NMR T_2 spectrum variation curves of the four sets of core flooding experiments with different permeabilities are shown in Figures 1 and 2. In the figures, the NMR T_2 spectrum signals of the 500-1 core are mainly distributed between 1 and 120 ms, while the NMR T_2 spectrum signals of the other three groups of cores are mainly distributed between 10 and 500 ms. This shows that there are many small and medium pores in the 500-1 core, while the other three groups of cores are mainly large pores. After water flooding, the NMR T_2 spectrum peak area of the four core experiments decreased in different ranges, indicating that the crude oil in the core was driven out by water flooding and its content decreased. The NMR T_2 spectrum of the 500-1 core decreases at the P_1, P_2, and P_3 peaks. The NMR signal changes of the other three core experiments are mainly concentrated on the P_3 peak.

In the 1500-1 core flooding experiment, the P_1 peak appeared after water flooding, indicating that there were small pores in the core. In the stage of saturated crude oil, the crude oil failed to enter, and then the injection pressure increased during the water flooding process and the crude oil entering small pores could not be displaced after water flooding. From the change of peak area, the recovery ratio of water flooding in the four core flooding experiments can be calculated (shown in Table 1) (Figures 3, 4).

### Table 1. Water Flooding Recovery Rates of Core Oil Flooding Experiments with Different Permeabilities

| core no. | gas permeability/mD | core oil saturation/% | recovery ratio after water flooding/% |
|----------|---------------------|-----------------------|--------------------------------------|
| 500-1    | 468                 | 71.1                  | 41.73                                |
| 1000-1   | 989                 | 72.69                 | 37.50                                |
| 1500-1   | 982                 | 72.06                 | 39.38                                |
| 2000-1   | 2047                | 78.62                 | 44.4                                 |

2.1.2. Distribution Characteristics of MRI. The MRI images of the four groups of core displacement experiments with different permeabilities are shown in Table 2. In the comparison of the images of saturated oil and residual oil after water flooding, it can be concluded that the colors in the cores are all different and lighter, especially in the areas with high oil signal intensity. Although water flooding has largely recovered crude oil from areas with high oil saturation, a large amount of crude oil remains in the core after water flooding.
From the four sets of images, it can be seen that the image signal distribution of the 500-1 core is obviously weaker than that of other cores, especially the distribution of produced oil after water flooding is blurred. Combined with the NMR $T_2$ spectrum distribution of the core, it shows that the core has more small and medium pores. In addition, the TE time (5.885 ms) in NMR limits the application range of imaging, and it is difficult to collect image signals for small apertures.

In the image of the produced oil after water flooding, except for the 1000-1 core, the other three groups of cores have end-face effects during the process of core displacement, and the signal of the produced oil at the tail end is obvious. The produced oil in the 1000-1 core is evenly distributed, and the signal strength of the produced oil in the upper half of the outlet end is weak, indicating that the crude oil in this area has not been effectively produced. The produced oil in the 1500-1 core is mainly distributed in the first half of the core and the outlet end. There are large blue areas without signals in the core, indicating that there is a large dominant water pathway around the area, which cannot be swept by water flooding. The distribution of the produced oil in the 2000-1 core was mainly concentrated in the first half of the core and the outlet end and less on both sides of the middle and rear cores, indicating that the crude oil in this area of the core could not be effectively produced during the displacement. The distribution image of the produced oil after water flooding can clearly reflect the differences in oil displacement characteristics in cores with different permeabilities.

2.2. Results and Analysis of Flooding Experiment with SMG Dispersion or Polymer Solution.

2.2.1. Changing Characteristics of Pressure. Under the condition of a constant rate of 0.3 mL/min, the change of the injection pressure during the flooding experiment of SMG dispersion and polymer solution is shown in Figure 5; 0−2.0 PV is the water flooding process, 2.0−2.3 PV is the agent injection process (between dotted lines), and 2.3−4.3 PV is the subsequent water flooding process.

As shown in Figure 5, the injection pressure of the core (1000-2, 1000-3) increases with the increase of the injection volume during the water flooding stage, then drops after reaching the extreme value (about 0.04 MPa), and finally tends to be stable (0.02 MPa). After the polymer solution is injected, water flooding is continued, and the pressure increases rapidly to 0.15 MPa with the increase of the injected amount and then rapidly drops to 0.101 MPa. After the SMG dispersion is injected, water flooding is continued, and the pressure rise is small, reaching an extreme value of 0.034 MPa, which then slowly drops to 0.02 MPa. The results show that the polymer solution increases the injection pressure by improving the viscosity of the water flooding, but the pressure of a single injection polymer solution is difficult to maintain after the pressure rises. With the increase of the injection volume, the polymer cannot stay in the core for a long time and the pressure drops sharply.

2.2.2. Changing Characteristics of the NMR $T_2$ Spectrum. The characteristics of the $T_2$ spectrum changes of SMG and polymer flooding experiments are shown in Figures 6−7. The NMR $T_2$ spectrum signal in the figure is mainly distributed in the interval of 10−500 ms, and its changes are mainly concentrated at the $P_3$ peak. In the two experiments, the $P_3$
peak signal of the $T_2$ spectrum showed a decreasing trend, and the decreasing amplitude was roughly the same. Both water flooding and agent flooding produced different degrees of crude oil. The results in Table 3 show that the recovery ratio of

### Table 3. Recovery Rates in Each Stage of SMG and Polymer Flooding Experiments

| core no. | type of injected chemical | recovery ratio of water flooding/% | recovery ratio of chemical flooding/% | enhanced oil recovery/% |
|----------|--------------------------|-----------------------------------|-------------------------------------|------------------------|
| 1000-2   | SMG dispersion            | 34.3                              | 49.6                                | 15.8                   |
| 1000-3   | polymer solution          | 35.6                              | 51.4                                | 15.3                   |

Based on the change of the NMR $T_2$ spectrum peak area, the recovery factors of water flooding and agent flooding in the two core flooding experiments were calculated (shown in Table 3).

#### 2.2.3. Distribution Characteristics of MRI. The MRI images of SMG dispersion and polymer solution flooding experiments are shown in Figures 8–9. In the saturated oil image, residual oil image after water flooding, and residual oil image after agent flooding, the color gradually becomes lighter, and the oil signal intensity gradually decreases.

As shown in Figure 8, water flooding produces crude oil from areas with high signal strength in the core. In the image of the produced oil after water flooding, the oil used for water flooding is evenly distributed in the core, and there are blue areas at the entrance and middle and later sections of the core, indicating that water flooding in these areas has not been affected and crude oil has not been produced. Due to the low efficiency of water flooding, a large amount of crude oil remains in the core. In the produced oil image after SMG flooding, the produced oil is concentrated at the inlet and outlet ends, and the produced oil in the middle section is uniformly dispersed in blocks, and the whole oil is in a dispersed state. In addition, the produced oil of SMG flooding in the middle part of the core is in the blue area compared to the produced oil of water flooding. The results show that the two ends and the middle area of the SMG particles have blocked the dominant channel, enlarged the area that cannot be swept by water flooding, and expelled part of the remaining oil that is difficult for water flooding.

As shown in Figure 9, water flooding also produces crude oil from areas with strong signals in the core. In the water flooding produced oil image, the produced oil is mainly distributed in the first half of the core and the outlet end, and there is a large blue area in the middle of the second half. It shows that the water flooding failed to affect the area and no crude oil was produced. In the produced oil image of polymer flooding, the produced oil is advancing in a filamentary shape as a whole to maintain continuity. The more the oil is produced to the back of the core, the stronger is the signal. It shows that the polymer greatly increases the injection pressure by improving the water flooding fluidity and enters all swept areas without distinction.

Figure 6. 1000-2 Core NMR $T_2$ spectrum.

Figure 7. 1000-3 Core NMR $T_2$ spectrum.

Figure 8. MRI of the SMG flooding experiment.
Although the 1000-2 and 1000-3 cores are intercepted from the same core, and their NMR $T_2$ spectrum changes and recovery ratios are generally the same in the oil displacement experiment, under the same flooding conditions, there are differences in water flooding in core flooding experiments with similar physical properties, and the differences in flooding characteristics of different functional chemical agents are more obvious in MRI and produced oil distribution images.

### 3. CONCLUSIONS

Using magnetic resonance imaging (MRI) technology combined with a core displacement device, visualization of produced oil is achieved by subtracting from image signals collected at different displacement stages. The distribution images of the produced oil can clearly reflect the oil displacement characteristics of cores with different permeabilities and chemical agents with different functions. The dominant water pathway in different cores can be identified through the produced oil distribution images, as well as the areas in the cores that are difficult to be swept by water flooding.

Under the same conditions, both the SMG dispersion and the polymer solution enhance the oil recovery ratio by about 15%. It is difficult to distinguish the similarities and differences in the oil displacement characteristics of the two from the directly collected images and the NMR $T_2$ spectrum. But the distribution images of the produced oil can reflect the following: (1) SMG dispersion can adjust and block the dominant water pathway, so that subsequent water flooding can enter the remaining oil area that was difficult to be swept by the first water flooding, and can expand the swept volume. The distribution image of the produced oil has the characteristics of being concentrated at both ends and dispersed in the middle in the core; (2) polymer flooding greatly increases the injection pressure by improving the water flooding viscosity and enters all areas without distinction. The distribution image of the produced oil has the characteristics of filamentous continuous advancement distribution. Therefore, the visualization of the produced oil based on MRI technology provides a new method for the study of the oil displacement mechanism.

### 4. EXPERIMENTAL SECTION

#### 4.1. Materials

The core is taken from artificial sandstone (the artificial core is produced by the manufacturer, and the specific production method is similar to the method of Xie et al.\textsuperscript{18–20}) with a diameter of 2.5 cm, a length of 4.9–5.0 cm, and a gas permeability of 460–2050 × 10$^{-3}$ μm$^2$, and the pore size of cores is 4.3–215 μm; the parameters are shown in Table 4. Other materials used are as follows: deuterium water, purchased from Beijing Funuo Technology Development Co., Ltd., with a purity of 99.9 ± 0.02%; crude oil in a block from Bohai Sea, with a viscosity of 23.26 mPa·s at 60 °C; SMG dispersion, prepared from SMG particles and deuterium water, with an average particle size of 32.99 μm and mass fraction of 0.3%; polymer solution, made of a polymer prepared with acrylamide and deuterium water, with a mass fraction of 0.18%, molecular weight of 20 million, and viscosity of 75.45 mPa·s at 60 °C.

#### 4.2. Experimental Apparatus

The low-field nuclear magnetic resonance (LF-NMR) displacement equipment is shown in Figure 10, which is mainly composed of a displacement device, a nuclear magnetic device, and a metering device. The displacement device is composed of an MR-dd-type high-temperature and high-pressure displacement device, produced by Nantong Huaxing Petroleum Instrument Co., Ltd.; the nuclear magnetic device is composed of a MesoMR23-060H-HTHP core LW-NMR analyzer, produced by Shanghai NIUMAG Electronic Technology Co., Ltd.; and the RS600 controlled-stress rheometer, produced by Thermo Haake Company, adopts a double-slit rotor.

#### 4.3. Principle of Nuclear Magnetic Resonance

When a core sample of a hydrogen-containing proton ($^1$H) fluid is placed in a uniform static magnetic field, the hydrogen nuclei ($^1$H) in the fluid interact with the magnetic field to generate a magnetization vector. The radio frequency unit applies radio frequency pulses to the nuclear magnetic resonance unit. The hydrogen nucleus ($^1$H) in the fluid will produce NMR signals\textsuperscript{21,22} by detecting the NMR signal of the $^1$H proton fluid and then mathematical inversion, the distribution of the transverse relaxation time is obtained, that is, the NMR $T_2$ spectrum. The NMR $T_2$ spectrum curve can reflect the spatial distribution of the $^1$H proton-containing fluid in the core.\textsuperscript{22}

MRI also requires the gradient pulse generated by the gradient unit to determine the spatial positioning of the target object.\textsuperscript{23} The gradient unit in the nuclear magnetic device is divided into three independent channels (X, Y, and Z are perpendicular to each other), such as independent DAC, gradient amplifier, and gradient coil.\textsuperscript{9,23} Three mutually vertically controllable linear gradient magnetic fields are

### Table 4. Core Data\textsuperscript{a}

| core no. | diameter/cm | length/cm | gas permeability/mD | porosity/% |
|----------|-------------|-----------|---------------------|------------|
| 500-1    | 2.51        | 4.95      | 468                 | 19.48      |
| 1000-1   | 2.51        | 4.98      | 989                 | 26.23      |
| 1000-2   | 2.51        | 4.94      | 982                 | 27.60      |
| 1000-3   | 2.51        | 4.90      | 982                 | 27.87      |
| 1500-1   | 2.51        | 4.87      | 1502                | 27.63      |
| 2000-1   | 2.51        | 4.74      | 2047                | 32.95      |

\textsuperscript{a}Note: Core 1000-2 and Core 1000-3 are cut from a 10 cm core.

Figure 9. MRI of the polymer flooding experiment.
applied to the target object to accurately locate the target object in a three-dimensional space, establish the relationship between the resonance frequency of the NMR signal and the nuclear position, and obtain MRI signals using techniques such as Fourier transform and image reconstruction.10,23

The main parameters of the nuclear magnetic device are as follows: magnetic field strength 0.5 T, resonance frequency 21 MHz, and probe coil diameter 70 mm. Main imaging parameter settings: TR time 500 ms, TE time 5.885 ms, and accumulation times 32.

4.4. Distinction of Nuclear Magnetic Signals between Water, Chemicals, and Crude Oil. The 2H signal of deuterium water is not produced by nuclear magnetic resonance, and the chemical properties of deuterium water are basically the same as those of ordinary water. Although there are some 1H protons in the chemical agent, its NMR T2 spectrum curve basically overlaps the T2 spectrum curve of pure deuterium water, when the low-concentration chemical agent solution prepared with deuterium water is tested in the nuclear magnetic equipment. This indicates that the low-concentration chemical agent solution prepared with deuterium water has basically no effect on the nuclear magnetic signal in the core. Therefore, with the use of deuterium water instead of ordinary water and the preparation of chemical solutions with deuterium water, the nuclear magnetic signal of crude oil can be distinguished. The nuclear magnetic signal detected during the entire displacement experiment is the crude oil signal, and the amount of change is the reduction of the crude oil signal.

4.5. Establishment of a Visualization Method for the Produced Oil. During the experiment, the image signals collected by MRI are all crude oil signals contained in the core. Through the MRI processing software to subtract the image signals collected in different displacement stages, the image signals of the distribution of the produced oil in the original core before and after the different phases of displacement can be obtained, that is, the distribution position of the produced oil in the original core. ROI extraction, unified mapping, and false-color imaging are performed on the collected core region image signal, and finally a clear color image is obtained (shown in Figure 11).

In this flooding experiment, three-stage MRI signals are collected, including the image signals acquired at the end of the saturated crude oil (saturated oil image), the image signals acquired after water flooding (residual oil image after water flooding), and chemical image signal collected by the water flooding after the chemical agent injection (residual oil image after agent flooding). Image processing software is used to subtract the image signal collected from saturated crude oil and the image signal collected at the end of water flooding to obtain the distribution image of the produced oil after water flooding. The same method can be used to obtain the distribution image of the produced oil after agent flooding.

Figure 11 shows the MRI of the saturated crude oil and the residual oil after water flooding in flooding experiment with the high-permeability core, as well as the produced oil distribution image after water flooding obtained by signal subtraction processing. The left side is the injection end, and the right side is the outlet end. In the images of saturated simulated oil and remaining oil in water flooding, the blue background represents the oil-free area and other colors represent the oil-bearing area. The darker the color, the stronger the signal, indicating that the higher the oil saturation in this area. In the image of the produced oil after water flooding, blue means that there is no oil produced in this area and other colors represent that there is oil produced in this area. The darker the color, the stronger the signal, and the higher the degree of produced oil in this area.

4.6. Experimental Steps. The experiment is divided into two groups. One group is a core displacement experiment with different permeabilities (500-1, 1000-1, 1500-1, 2000-1 cores) for which only water flooding is carried out. The purpose of this experiment is to investigate the characteristics of the produced oil by water flooding in cores with different permeabilities. The other group stands for SMG dispersion and polymer solution flooding experiments (1000-2, 1000-3
cores), in which chemical agents (SMG dispersion, polymer solution) are injected on the basis of water flooding. The purpose of this experiment is to investigate the characteristics of the produced oil by flooding of different functional chemical agents. The displacement process is carried out on the LW-NMR displacement equipment, and the temperature is maintained at 60 °C throughout.

Before the oil displacement experiment, the cores (500-1, 1000-1, 1000-2, 1000-3, 1500-1, 2000-1) were dried and vacuum-saturated with deuterium water. The crude oil was injected at 1.0 and 2.0 mL/min to displace the deuterium water in the core until the NMR T2 spectrum curve no longer changed. After 24 h of aging, the saturated oil NMR T2 spectrum curve (black lines in the NMR T2 spectrum representation) and the saturated oil distribution image were obtained. In the analysis of the experimental results, the injection of deuterium water to replace the crude oil in the core is referred to as water flooding, the water flooding after the injection of SMG dispersion is referred to as SMG flooding, and the water flooding after polymer solution injection is referred to as polymer flooding.

The experimental procedure for core flooding with different permeabilities is as follows: deuterium water is injected at a constant rate of 0.5 mL/min to displace the crude oil in the core, and the injection is continued until the NMR T2 spectrum curve no longer changes; the NMR T2 spectrum curve of water flooding (blue lines in the NMR T2 spectrum representation) and the residual oil image after water flooding are obtained, and the distribution image of the produced oil after water flooding is obtained by subtracting the image signal.

SMG dispersion and polymer solution flooding experiment steps are as follows: (1) deuterium water is injected at a constant rate of 0.3 mL/min to displace the crude oil in the core, and the injection is stopped after displacement to 2.0 PV (the multiple of pore volume) to obtain the water flooding NMR T2 spectrum curve (blue lines in the NMR T2 spectrum representation) and the residual oil image of water flooding. The oil distribution image after water flooding is obtained by subtracting the image signal; (2) after injecting 0.3 PV SMG dispersion or polymer solution at a constant rate of 0.3 mL/min, injection of deuterium water (2.0 PV) is continued at a constant rate of 0.3 mL/min to displace the deuterium water in the core until the NMR T2 spectrum curve no longer changes; the NMR T2 spectrum curve of SMG flooding (red lines in the NMR T2 spectrum representation) and the residual oil image after SMG flooding are obtained, and the distribution image of the produced oil after water flooding is obtained by subtracting the image signal.

SMG dispersion and polymer solution flooding experiment steps are as follows: (1) deuterium water is injected at a constant rate of 0.3 mL/min to displace the crude oil in the core, and the injection is stopped after displacement to 2.0 PV (the multiple of pore volume) to obtain the water flooding NMR T2 spectrum curve (blue lines in the NMR T2 spectrum representation) and the residual oil image of water flooding. The oil distribution image after water flooding is obtained by subtracting the image signal; (2) after injecting 0.3 PV SMG dispersion or polymer solution at a constant rate of 0.3 mL/min, injection of deuterium water (2.0 PV) is continued at a constant rate of 0.3 mL/min to obtain the SMG flooding or polymer flooding NMR T2 spectrum curve (red lines in the NMR T2 spectrum representation) and residual oil image, and produced oil images after water flooding and produced oil images after agent flooding are obtained through image signal subtraction.

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