Analysis of movable fluid distribution in a clastic rock reservoir using nuclear magnetic resonance and computed tomography

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Abstract. Studying influence factors of movable fluid distribution is of significance for the development of clastic reservoirs. In this paper, the characteristics of movable fluid distribution in clastic core samples from Tarim Oilfield were studied with nuclear magnetic resonance (NMR) tests and computed tomography (CT) scanning. The movable fluid saturations of each core sample under centrifugal pressure of 3 psi, 10 psi, 50 psi, 100 psi, and 500 psi were measured, respectively. The main factors influencing the movable fluid saturation were analysed. The results show that the movable water saturation is strongly dependent on the centrifugal pressure used. When the centrifugal pressure increased to 100 psi, the movable fluid saturation increased sharply. The CT scanning indicates that the movable fluid saturation is mainly dominated by pore sizes of core samples, and the larger the average pore size is, the higher the fluid saturation will be.

1. Introduction

The characteristics of fluid distribution in clastic core samples are critical for evaluating the oil and gas production potential of reservoirs. Clastic rock is a kind of sedimentary oil-bearing strata widely distributed in the Tarim Basin, NW China[1]. Studying the movable fluid distribution is of great significance for the development of clastic rock reservoirs. At present, the test methods for pore-throat structure characterization include NMR[2, 3], CT scanning[4], mercury intrusion porosimetry (MIP)[5, 6], rate-controlled porosimetry (RCP) [7, 8], etc. Zhang et al. [9] applied NMR and RMICP to analyze the impact of pore-throat structure on the storage and seepage capacity of a tight clastic rock reservoir and found that the largest throat is the key parameter dominating permeability and movable water saturation. Wang and Zeng[10] analyzed the movable fluid distribution characteristics of tight sandstone using RCP and NMR and divided the fluid in tight sandstone into three parts, including completely unmovable fluid, partially movable fluid and completely movable fluids. Although much literature on the movable fluid distribution can be found, the studies on the distribution of movable fluids in the clastic rocks from Tarim Basin, NW China is rarely reported. In this paper, the movable
fluid saturation in the clastic rock reservoir was studied combining NMR and CT scanning. The main factors influencing the movable fluid saturation were analyzed.

2. Experiments

Five natural clastic core samples from the Tarim Basin were selected for NMR and CT scanning tests. The parameters of the core samples were shown in Table 1. The core permeability changes from $8.95 \times 10^{-3}$ $\mu$m$^2$ to $499.62 \times 10^{-3}$ $\mu$m$^2$, but the porosity varies little, from 16.18 % to 20.91 %. NMR utilizes the interaction between the magnetic field and hydrogen nuclei to obtain the information of the internal microstructure and fluid flow state[10]. First, the NMR T$_2$ spectra of five core samples under 100 % water saturation was measured. Then, the NMR T$_2$ spectra of each core sample with the centrifugal pressure of 3 psi, 10 psi, 50 psi, 100 psi, and 500 psi were measured. During the NMR measurement, 0.2 ms echo interval was adopted, and core samples were scanned with 128 times and 8192 echoes were obtained. Multiple centrifugal NMR T$_2$ spectra of the 5 core samples are shown in Figure 1. As the figure shows, the increasing centrifugal pressure increasing, more fluids are removed and the covered area of NMR spectra decreases. The shift of NMR spectra of micropores and mesopores is not caused by the movement of the fluid in macropores moving to micropores and mesopores but caused to the decrease of T$_2$ free relaxation and the increase of surface relaxation in micropores and mesopores.

| Sample | Well   | Formation                  | Depth (m) | Core diameter (cm) | Core length (cm) | Porosity (%) | Permeability ($10^{-3}$ $\mu$m$^2$) |
|--------|--------|----------------------------|-----------|--------------------|------------------|--------------|------------------------------------|
| 1      | TZ40   | CII16, Carboniferous        | 4339.06   | 2.505              | 2.396            | 16.18        | 54.49                              |
| 2      | TZ117  | SII3-1, Silurian            | 4442.05   | 2.502              | 2.570            | 16.90        | 12.45                              |
| 3      | TZ16-5 | CIII4-1, Carboniferous      | 3812.23   | 2.504              | 2.418            | 17.53        | 499.62                             |
| 4      | LN2-2J1| TIII1, Triassic             | 4868.45   | 2.504              | 2.459            | 20.91        | 281.00                             |
| 5      | LN31   | TIII2, Triassic             | 4917.52   | 2.502              | 2.441            | 17.99        | 8.95                               |

3. Methodology description

The movable fluid saturation of each core sample under centrifugal pressure of 3 psi, 10 psi, 50 psi, 100 psi, and 500 psi be calculated, respectively. Take the calculation of the movable fluid saturation of the core sample 1 under the centrifugal pressure of 500 psi as an example. First, the cumulative distribution curve of sample 1 under 100 % saturation and 500 psi centrifugal pressure is plotted, as shown in Figure 2. Then, make a horizontal line along the x-axis at the maximum value of the cumulative distribution curve of sample 1 under 100 % saturation. The T$_2$ value at the intersection of the horizontal line and the cumulative distribution curve of sample 1 under 100 % saturation is taken as the T$_2$ cutoff value of sample 1 under 500 psi centrifugal pressure. The ratio of the porosity greater than the T$_2$ cutoff value to the total porosity is the movable fluid saturation. Table 2 is the movable fluid saturation of five core sample under centrifugal pressure of 3 psi, 10 psi, 50 psi, 100 psi, and 500 psi. The average movable fluid saturation with 100 psi centrifugal pressure is a little less than 30 %, but when centrifugal pressure increases to 500 psi, the average movable fluid saturation increases to more than 50 %.
Figure 1. NMR T2 spectra of the 5 core samples under 100% saturation and centrifugal pressure of 3 psi, 10 psi, 50 psi, 100 psi, and 500 psi.

Table 2. The movable fluid saturation of five core sample under centrifugal pressure of 3 psi, 10 psi, 50 psi, 100 psi, and 500 psi.

| Sample | Movable fluid saturation (%) |
|--------|------------------------------|
|        | 3 psi | 10 psi | 50 psi | 100 psi | 500 psi |
| 1      | 0.00  | 0.00   | 13.40  | 13.40   | 66.56   |
| 2      | 0.00  | 0.00   | 23.75  | 30.42   | 43.46   |
| 3      | 1.77  | 10.54  | 24.69  | 50.98   | 55.50   |
| 4      | 0.00  | 11.93  | 29.38  | 38.25   | 57.52   |
| 5      | 0.00  | 0.00   | 2.28   | 13.67   | 36.20   |
| Average| 0.35  | 4.49   | 18.70  | 29.34   | 51.85   |
Figure 2. Movable fluid calculation based on T2cutoff in sample 1 under 500 psi centrifugal pressure.

4. Analyse and discussion
The linear conversion method usually used to convert NMR T2 spectra into pore size distribution:

\[ r = CT_2 \]  

where \( r \) is pore throat radius and \( C \) is the conversion coefficient, and \( C = 0.0133 \mu m/ms \) is used in this paper.

Figure 3 shows the distribution frequency of the pore throat radius of 5 core samples converted from NMR spectra. The pore throat sizes of sample 3 mainly distribute 1 \( \mu m \)-10 \( \mu m \), but the pore throat sizes of sample 5 mainly distribute 0.01 \( \mu m \)-1.3 \( \mu m \). Figure 4 shows the CT images of sample 3 and sample 5, the average pore sizes of sample 3 are significantly larger than those of sample 5. Although the porosity of sample 3 and sample 5 differed by only 0.46 %, the permeability of sample 3 was about 56 times higher than that of sample 5. Figure 5 shows a comparison of the percent area, volume, and pore number of samples 3 and 5. It can be found that the pore size and volume of sample 3 are much greater than those of sample 5, especially for the pores with the equivalent pore diameter in the range of 1 \( \mu m \)-200 \( \mu m \). Although for pores with diameters in the range of 200-500 \( \mu m \), the percentage of area and volume of sample 5 is greater than that of sample 3, while according to Figure 5 (e) and (f), the pores are mainly distributed between 1 and 50 \( \mu m \).

It shows that the pore size is the main factor influencing core permeability and affecting the movable fluid saturation in clastic rock reservoirs. The changes in movable fluid saturation with increasing centrifugal pressure are shown in Figure 6. the movable fluid saturation increased sharply when the centrifugal pressure increased to 100 psi, but the increase in movable fluid saturation with centrifugal pressure increasing from 100 psi to 500 psi, except for sample 1.

Figure 3. Distribution frequency of pore-throat radius of 5 core samples converted from NMR spectra.
Figure 4. Comparison of sample 3 and sample 5 CT scanning images. a: 2D CT image of sample 3; b: 2D CT image of sample 5; c: 3D CT image of sample 3; d: 3D CT image of sample 5.

Figure 5. Comparison of the area percentage, volume, and quantity of sample 3 and sample 5 obtained from CT scanning.
5. Conclusions
The characteristics of movable fluid distribution in clastic core samples from the Tarim Basin, China were studied with NMR and CT scanning. The results show that the average movable fluid saturation with 100 psi centrifugal pressure is a little less than 30 \%, but when centrifugal pressure increases to 500 psi, the average movable fluid saturation increases to more than 50 \%. The CT scanning indicates that the permeability and movable fluid saturation are mainly dominated by pore sizes. The larger the average pore size is, the higher the clastic core permeability, and the movable fluid saturation will be.

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