Distribution characteristics of movable fluid in tight sandstone based on nuclear magnetic resonance

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Abstract. Movable fluid parameter is an important index to evaluate the seepage characteristics of tight sandstone reservoir. Combined with high-pressure displacement and nuclear magnetic resonance movable fluid testing principle, the nuclear magnetic resonance movable fluid characteristics of six typical tight sandstone core samples of Xujiahe Formation in Central Sichuan Basin were studied. Based on mercury injection capillary pressure curve, the nuclear magnetic resonance T2 spectrum distribution was converted into pore throat According to the radius distribution, the minimum pore throat radius of the movable fluid and the contribution of different pore sizes to the movable fluid are determined. The research shows that the movable fluid saturation of the tight sandstone reservoir in the second member of Xujiahe Formation in Central Sichuan is closely related to the pressure difference, with good logarithmic correlation, and the main contribution to the movable fluid saturation is the reservoir space > 0.1 μm. 70% of the total movable fluid saturation is injected at a lower pressure (about 5MPa). In the later stage, high pressure injection can only enter the reservoir pore with small pore size, and the total amount is small and increases slowly. Therefore, the total contribution of high pressure drive to gas saturation in the later stage is small.

1. Introduction

In recent years, with the depletion of conventional oil and gas resources, the exploration and development of tight oil and gas in the world has been intensified [1-2]. Tight oil and gas accounts for a large proportion of China's oil and gas composition, so it is of great significance to study the accumulation mechanism of tight oil and gas and improve the development effect of tight oil and gas reservoirs for ensuring national energy security. Because tight sandstone reservoir has lower physical properties and pore throat structure than conventional sandstone reservoir, it is widely defined that the porosity of tight sandstone is less than 10%, the surface air permeability is less than 1md or the overburden matrix permeability is less than 0.1md [3-7]. Due to the lower porosity and permeability,
the movable fluid parameter is an important index to evaluate the proportion of movable fluid in tight sandstone development. Therefore, it is of great significance for the exploration and development of tight sandstone gas reservoir to analyze the movable fluid in tight sandstone with the new method.

Nuclear magnetic resonance (NMR) technology is based on the spin characteristics of hydrogen nucleus and the principle of interaction with external magnetic field, which is sensitive to the size of pore body. The pore structure of rock is studied by measuring the NMR relaxation time spectrum of fluid in pores of different sizes [8-10]. NMR detection involves two relaxation times: the longitudinal relaxation time (T1) refers to the time after the hydrogen nucleus spin absorbs energy. The characteristic time for the system to recover equilibrium, transverse relaxation time (T2) and the time for energy exchange between nuclear spin and spin to recover equilibrium are widely used in laboratory because T2 spectrum can quickly and nondestructively detect the hydrogen containing fluid in pores. The occurrence state of fluid in tight sandstone pores can be divided into movable fluid and bound fluid. Movable fluid refers to the fluid under certain pressure. The free fluid (the surface force of pore and throat is weak) which overcomes the capillary pressure to participate in the flow, while the bound fluid (the surface force of pore and throat is strong) which exists in micro pore and dead pore and cannot flow under certain pressure.

2. Sample collection and test analysis
The second member of Xujiahe Formation in Central Sichuan is mainly composed of feldspar lithic sandstone, lithic feldspar sandstone, and lithic quartz sandstone. Based on the high-pressure displacement and nuclear magnetic resonance T2 spectrum experiments of six core samples, further analysis is carried out (Table 1).

| Serial number | Sample | porosity /% | permeability /mD | lithology | Maximum displacement pressure difference (MPa) |
|---------------|--------|-------------|-----------------|-----------|-----------------------------------------------|
| 1             | JH2-61 | 7.2         | 0.24            | Sandstone | 18                                            |
| 9             | Y12-183| 7.8         | 0.28            | Sandstone | 23                                            |
| 11            | PL7-56 | 12.6        | 0.57            | Sandstone | 23.2                                          |
| 15            | JH2-103| 6.4         | 0.12            | Sandstone | 17                                            |
| 20            | HC5-254| 6.5         | 0.02            | Sandstone | 21.5                                          |
| 37            | Y12-186| 8.49        | 0.16            | Sandstone | 31.1                                          |

High pressure displacement+NMR T2 The spectrum experiment is completed on the visual dynamic simulation system of natural gas accumulation and development (macormr12-150h-hthp-i) developed by China Petroleum Exploration and Development Research Institute. The nuclear magnetic detection part adopts the large-diameter low field nuclear magnetic resonance instrument with the resonance frequency of 12 MHz. The sample processing and nuclear magnetic detection experiment methods refer to SY / t5336-2006 core analysis method and SY / t6490-2014 rock sample nuclear magnetic resonance method. The sampling parameters of NMR relaxation measurement: waiting time $T_W = 3500\text{ms}$; echo interval TE = 0.2ms; echo number $n_{ech} = 5000$; cumulative times $n_s = 64$; the experiment was carried out at 22 °C.

3. Determination of NMR movable fluid
By using the method of displacement+on-line detection, the best displacement pressure of each sample is taken as the displacement pressure when the sample is displaced to a small change of movable fluid saturation, so as to calculate the movable fluid saturation and analyze its influencing factors. According
to the nuclear magnetic resonance T2 spectrum morphology of 6 typical tight sandstone samples in the second member of Xujiawe Formation in the study area, there are some differences in T2 spectrum distribution of different samples under saturated simulated formation water state. There are four types of spectrum distribution: bimodal, unimodal and transitional. The on-line detection of six samples after displacement experiment shows that, except for the T2 of hs5-254 sample, there are four types of spectrum distribution: bimodal, unimodal and transitional. The results show that the content of mobile fluid in hs5-254 sample is very low no matter in macropores, mesopores or micro pores, the connectivity of pores is poor, there are many dead pores, and the right peak of macropores does not drop obviously. However, the left and right peaks of double peak jh2-61 sample are decreased obviously, and there is no significant difference the large amplitude indicates that the mobile fluid is distributed in micro pores, macropores and mesopores. The T2 peak of single peak and transitional samples y12-183, y12-186, pl7-56 and jh2-103 decreases greatly, and the spectrum after the decrease is mainly in the left peak state, indicating that the mobile fluid mainly exists in macropores and mesopores, and dead pores and pores appear in small and medium pores. The proportion of blocked throat is high and the connectivity is poor, which may be directly related to the type, content and occurrence mode of clay minerals in the rock.

4. Results and Discussion

4.1. Distribution characteristics of movable fluid

T2 cut-off value is the key parameter to divide the movable fluid and bound fluid in sandstone pores in conventional centrifugal NMR experiments. The main calculation method is to find a point on the T2 spectrum distribution curve of saturated water, so that the area of the left curve and the coordinate axis is equal to the area of the whole T2 spectrum curve and the coordinate axis after centrifugal experiment. This point is defined as T2 Cut off value, that is, the fluid within the pore diameter whose relaxation time is greater than the cut-off value is movable fluid, and the fluid whose relaxation time is less than the cut-off value is bound fluid. However, the T2 cut-off value of tight sandstone is widely distributed, which has poor correlation with porosity and permeability of tight sandstone, that is, the quality of reservoir physical properties has no direct relationship with T2 cut-off value.

According to the experimental results of NMR (Fig. 1, Fig. 2), the mobile fluid percentage of six typical core samples is 23.74% - 88.99%, with an average of 61.25%. The movable fluid parameters of six typical core samples are widely distributed and different, which reflects the heterogeneity of the second member of Xujiawe Formation in the study area.
Fig 1. Nuclear magnetic resonance T2 spectra of typical core samples from tight sandstones of Xujiahe.

Fig 2. Variation of movable fluid saturation with pressure difference.
Before and after the displacement experiment of 6 core samples from Xujiahe Formation (Fig. 1). For example, after the displacement experiment of pl7-56, y12-186 and y12-183 samples in Fig. 1, the mobile fluid in micro micro pore, medium pore and macropore decreases greatly, indicating that the connectivity of micro micro pore, medium pore and macropore is good, and there are a large amount of mobile fluid in them; while in Fig. jh2- After displacement experiments, the movable fluid in macropores and mesopores of 61, he5-254 and jh2-103 samples decreased to a certain extent, but the movable fluid in micro micro pores decreased to a small extent, indicating that most of the movable fluid in the samples occurred in macropores and mesopores In the samples with poor connectivity, the fluid in the macropores and mesopores cannot flow even under high displacement pressure, and finally appears as bound fluid. This is the reason for the wide distribution of mobile fluid percentage.

4.2. The main contribution radius of movable fluid
At present, the minimum pore throat radius of mobile fluid is widely used to determine the minimum pore throat radius that can flow in tight sandstone under external force. Generally, the corresponding pore throat radius is calculated by using the determined optimal centrifugal force to define the minimum pore throat radius of mobile fluid. However, according to the displacement + NMR experimental results conducted by the author, even the large pore throat radius in the core can be determined Therefore, if this method is used to calculate the minimum pore throat radius of movable fluid, it may be less than the real value, which has certain limitations.

Previous studies have shown that NMR detection is more sensitive to the pore structure of rock. T2 spectrum and mercury injection (capillary pressure) curve are effective methods to study the pore structure of rock. When the pore is assumed to be a sphere, both can be used to reflect the pore structure characteristics of rock, and there is a positive correlation between pore throat radius R and relaxation time T2 [8-10]:

\[ r = f \cdot T_2 \]  

In formula (1), f is the conversion coefficient. The author uses the conversion method of formula (1) to calculate the pore throat radius distribution corresponding to the NMR T2 spectrum distribution, and then analyzes the main contribution of the pore throat radius by the movable fluid saturation of the whole core and the movable fluid saturation corresponding to different pore radius. Plot the T2 spectrum porosity cumulative distribution curve and mercury injection cumulative mercury saturation curve of typical core samples in the same logarithmic coordinate system, try to ensure that the T2 spectrum cumulative curve coincides with the mercury saturation curve, and use formula (1) to fit and convert the sample relaxation time and pore throat radius, so that the conversion coefficient f can be determined as 0.035 μm/ ms

Through the calculation of the conversion coefficient, the experimental data are processed, the core NMR aperture is divided into different intervals, the gas saturation of different interval aperture and the overall gas saturation of the core are counted, the results show that, as a whole, with the increase of pore radius, the movable fluid saturation becomes larger, that is, the pores with relatively large pore radius have better connectivity, and the dead fluid saturation increases There are relatively few pores. The lower limit of pore size that makes the greatest contribution to the movable fluid saturation can be determined by comparing the whole movable fluid saturation of the core with the movable fluid saturation of pores in each pore area. For all samples in this experiment, regardless of porosity and permeability, the movable fluid saturation of pores larger than 0.1 μm is greater than the whole movable fluid saturation of the core (Fig 1 red line in the figure), and less than 0 Based on the above understanding, 0.1 micron is regarded as the lower limit of pore radius which is mainly contributed by the movable fluid saturation of Xujiahe Formation in Central Sichuan. That is to say, pores larger than 0.1 micron contribute the most to the movable fluid saturation, while pores smaller than 0.1 micron contribute the least to the movable fluid saturation.
Fig 3. Comparison of whole movable fluid saturation of core samples and movable fluid saturation of different pore sizes.

5. Conclusion
The movable fluid saturation of the tight sandstone reservoir in the second member of Xujiahe Formation in Central Sichuan is closely related to the pressure difference, and has a good logarithmic correlation. The main contribution to the movable fluid saturation is the reservoir space > 0.1 μ M. 70% of the total movable fluid saturation is injected at a lower pressure (about 5MPa). In the later stage, high pressure injection can only enter the reservoir pore with small pore size, and the total amount is small and increases slowly. Therefore, the total contribution of high pressure drive to gas saturation in the later stage is small.

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