Research Article

Microscale Pore Throat Differentiation and Its Influence on the Distribution of Movable Fluid in Tight Sandstone Reservoirs

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1. Introduction

In recent years, with the development of the economy, people’s demand for energy consumption has been promoted, and the improvement of oil and gas exploration and development technology and theoretical innovation have been promoted, thus expanding the field of unconventional oil and gas exploration and development [1]. Tight sandstone reservoirs are currently one of the “hot spots” in petroleum exploration and development. Their microscopic geological characteristics, pore throat genetic mechanisms, distribution heterogeneity characteristics, and fluid seepage mechanisms are different from those of conventional and general low permeability reservoirs [2, 3]. In view of the characteristics of tight reservoirs, such as strong heterogeneity, fine pore throats, and difficult fluid flow, previous researchers have conducted much effective work, mainly focusing on the pore structure characterization of tight reservoirs, movable fluid saturation evaluation, and influencing factors of reservoir effectiveness [4, 5]. Presently, the heterogeneity of conventional reservoirs is
characterized by "a large number of" test data using parameters such as the coefficient of variation, sorting coefficient, and mean coefficient [6]. Compared with conventional reservoirs, tight reservoirs have small pore throat sizes and low dispersion degrees, and their pore throat radii may be concentrated in a relatively narrow numerical interval. As a result, the pore throat sorting coefficient is close to 0, and the pore throat size distribution can be regarded as qualitatively uniform, which is contradictory to the essential characteristics of tight sandstone reservoirs with complex microscopic pore structures and strong heterogeneity. Obviously, these parameters cannot accurately reflect the heterogeneity of the micropore structure of tight sandstone reservoirs. In recent years, two different conclusions have been drawn about pore throat heterogeneity. Some scholars believe that the more complex the small pore structure is, the worse the physical properties of the reservoir are [7, 8]. Some scholars believe that macropores have a more obvious effect on pore throat heterogeneity [9]. At present, there is a lack of quantitative studies on the heterogeneity of pore distribution in porous media, and the mechanism of porous media affected by microscale pore heterogeneity needs to be further understood. A large number of studies have shown that there is an obvious heterogeneity of the pore throat structure at the micro-/nano-meter scale [10]. Meanwhile, a complex sedimentary model has created the pore structures of clastic rock reservoirs with multiple modes [11, 12]. There are great differences in the occurrence rules of the movable fluid in the cores of different modes at the micro level, and the development characteristics are obviously different at the macro level. Nanoscale pore throat systems are widely developed in the pore throat of tight reservoirs. The pore throat structures of different microscales are complex and diverse with obvious microscale effects, which causes different seepage laws of fluid in the micro- and nanopores [13–19]. Therefore, taking the Chang 6 tight sandstone reservoir in the Huaqing area of the Ordos Basin as an example, the microscale pore throat differentiation of different reservoirs and its influence on the distribution of movable fluid in tight sandstone reservoirs are analyzed based on casting thin sections, nuclear magnetic resonance (NMR) experiments, modal analysis, and information entropy theory. This study has important theoretical and practical significance for promoting the efficient development of tight oil and gas reservoirs.

2. Experiments and Methods

In this study, nine samples of the Chang 6 tight sandstone reservoir in the Huaqing area of Ordos Basin were selected to carry out casting thin section observation, NMR, and other experiments. Based on the information entropy theory, quantitative characterization of microscale pore throat differentiation and its influence on the distribution of movable fluid were discussed.

2.1. Experimental Samples and Test Methods. A plunger sample with a diameter of 2.5 cm was drilled from the core and used for casting thin section grinding, physical properties, and NMR testing.

2.1.1. Before Testing. The Sample Was Washed with Oil. The sample was washed with methanol and dichloromethane mixture in the Soxhlet extractor. When the fluorescence of the washing fluid was very low and unchanged, the washing oil was considered to be finished, and the sample was dried continuously by microwave at 100°C for 24 h.

2.1.2. Casting Sheet Observation. After the treatment, the samples were injected into the red casting body, and the thin slices with a thickness of 0.03 mm were ground. Under a polarized light microscope, the statistics and study of petrology and pores were carried out by the point meter method (300 points were counted for each sample). The experimental methods were strictly carried out in accordance with SY/T 5913-2004 "Rock thin section preparation" [20].

2.1.3. NMR Experiment. The nuclear magnetic resonance $T_2$ spectrum was measured by the MicroMR20-025 instrument of Newmai Company. The main frequency intensity was 23 MHz, the core diameter was 25 mm, the length was 2-4 cm, the echo interval was 0.2 ms, the waiting time was 6 s, and the echo number was 8000. The experimental method is strictly in accordance with GB/T29172-2012 "Core analysis method" [21] and SY/T6490-2014 "laboratory measurement specification for nuclear magnetic resonance parameters of rock samples" [22]. The experiment was carried out at 22°C.

2.2. Quantitative Characterization of Variation Law of Microscale Pore Throat. Information entropy, first proposed by Shannon, the father of information theory, is mainly used to measure the uncertainty of information and can be used to represent the complexity of a system. The higher the entropy of a system is, the more complex the system is. The essence of information entropy is the quantitative analysis of distribution uniformity [23–25]. Based on the information entropy theory, a new concept of microscale pore throat radius entropy is introduced to quantitatively characterize the variation law of microscale pore throat. The specific steps are as follows:

(a) The $T_2$ relaxation time is converted into a pore throat radius. There is a positive correlation between pore throat radius and relaxation time [26]:

\[ r = C \times T_2. \]

In Formula (1), $T_2$ is the relaxation time (ms), $r$ is the pore throat radius ($\mu$m), and $C$ is the conversion factor ($\mu$m/ms). Among them, a certain amount of representative rock samples in the Chang 6 tight sandstone reservoir of the study area should be selected for C-value calibration.

(b) Based on the frequency data of pore throat radius distribution, the interval of pore throat radius distribution is intercepted

(c) Taking a certain pore throat radius distribution interval as the object and assuming that it contains $m$ pore throats, the frequency of different pore throat radius
is normalized and the sequence is generated. The sequence generated each time is calculated according to Formula (2) to calculate the information entropy of different pore throat radius intervals. That is what we call the entropy of the microscale pore throat radius:

\[ H = -\sum_{i=1}^{m} z_i \ln z_i \]  

(2)

Among them, \( z_i \) is the standard value of the occurrence frequency of the \( i \)th pore throat radius in the pore throat radius interval. In a certain pore throat interval, when the frequency of different pore throat radii is the same \((t z_1 = z_2 = \cdots = z_m = 1/M)\), the entropy value reaches the maximum value, indicating that the pore throat size distribution has reached a uniform state.

3. Discussion

3.1. Structure Type and Distribution Characteristics of Pore Throats. The NMR experimental data were processed to obtain the pore throat radius distributions of the Chang 6 tight sandstone reservoir in the study area, and the pore throat radius distribution frequency map was drawn, as shown in Figure 1.

The peak frequency of the pore throat radius of the wide bimodal mode (rock sample nos. 1, 2, and 3) is usually two; the difference between the primary peak and the secondary peak is small, the curved shape is strongly irregular, the peak distribution band is wide, and the average value of the pore throat radius is 0.14 \( \mu m \). The peak frequency of the pore throat radius of the asymmetrical bimodal mode (rock sample nos. 4–9) is usually two, with a large difference between the main peak and the secondary peak; the main peak usually has a dominant peak with a very high peak, with a corresponding pore throat radius of approximately 0.02 \( \mu m \), and a weak secondary peak with a very low peak, with a corresponding pore throat radius of approximately 0.7 \( \mu m \).

3.2. Reservoir Space Combination Characteristics of Reservoirs with Different Modal Pore Throat Structures. Because different pore networks have different percolation characteristics, their overlay combination also affects the overall physical performance of the reservoir. Casting thin section analysis of the representative rock samples of the Chang 6 reservoir in the Huaqing area (Figure 2) shows that the Chang 6 tight sandstone in the study area is mainly feldspathic sandstone and feldspar lithic sandstone, and the reservoir space mainly consists of primary intergranular pores, solution pores, and micropores, which exist in the form of overlay combinations.

Not only does the difference in reservoir spatial composition affect the physical properties of the reservoir but also the difference in pore development and distribution also leads to strong heterogeneity. The results of the casting thin sections and the modal characteristics of the pore throat structure were compared. The wide bimodal mode (rock sample no. 1) mainly developed intergranular pores, dissolved pores, and a small number of micropores, and the asymmetrical bimodal mode (rock sample no. 9) mainly developed micropores and small numbers of intergranular pores and dissolution pores.

3.3. Variation Law of the Microscale Pore Throat. Pores with different origins have different pore sizes and shapes, and the
The entropy of the microscale pore throat radius of reservoirs with different modal pore throat structure types is significantly different (Figure 3). The main manifestations are as follows: There are obvious differences in the entropy of the pore throat radius at different scales, mainly manifested in the following ways. The entropy of the pore throat radius decreases on the order of $0.01-0.1\,\mu m$, $>0.1\,\mu m$, and $<0.01\,\mu m$, which means that the complexity of the pore throat structure in turn decreases.

3.4. Distribution Characteristics of Movable Fluid in Pore Throats of Different Scales. The spatial combination of different types of pores determines the connectivity of micropore throats, which further affects the direction and ability of microseepage in tight sandstone reservoirs. The average movable fluid saturations of the wide bimodal mode and asymmetrical bimodal mode reservoirs are 49.06% and 28.51% (Table 1), respectively. The high saturation of movable fluid in the wide bimodal mode reservoirs is because the reservoir space has mainly intergranular pores and dissolved pores. Contrary to the conclusion that "the water displacement efficiency of the two-mode conglomerate reservoir is low" [27], there are significant differences between tight sandstone reservoirs with the same mode pore throat structure and conglomerate reservoirs in terms of their microscopic seepage characteristics and their control mechanisms.

As shown in Figure 4, there are obvious differences in the pore throat radius distribution characteristics of different modalities of pore throat structures and the distribution characteristics of movable fluids within different throat radius intervals. The wide bimodal mode and asymmetrical bimodal mode reservoir seepage capacities are mainly provided by $t$ pore throats of $0.01-0.1\,\mu m$ and $>0.1\,\mu m$, in which the movable fluid saturation corresponding to the radius of $0.01-0.1\,\mu m$ pore throat is 25.49% and 16.27%; the movable fluid saturation corresponding to the radius of $>0.1\,\mu m$ pore throat is 22.52% and 13.49%, and the movable fluid saturation corresponding to the radius of $<0.1\,\mu m$ pore throat is very small, which is 3.49% and 0.81%.

3.5. Influence of Microscale Pore Throat Differentiation on the Distribution of Movable Fluid. The tight sandstone reservoir has a spatial scale, and the flow of fluid in the reservoir at different spatial scales also has a scale effect [28]. Meanwhile, the ability of pores at different scales to be reformed by stress and other factors is different, resulting in a different distribution of movable fluids. The appearance of dissolved pores provides favorable conditions for the deposition of movable fluid, but micropores often occupy the throat, thus affecting fluid flow and negatively affecting the saturation of movable fluid. Analyzing the relationship between the entropy of the pore throat radius and the movable fluid saturation of the Chang 6 reservoir in the Huaqing region shows that the higher the entropy of the pore throat radius, the higher the movable fluid saturation will be (Figure 5(a)). However, there are differences in the correlation between the distribution of movable fluid in pore throats of different scales and the entropy of the pore throat radius, which mainly manifest in the following ways. In the $>0.1\,\mu m$ and $0.01-0.1\,\mu m$ range, the positive correlation between the entropy of the pore throat radius and the number of the movable fluid

![Figure 2: Reservoir space characteristics of different modal pore throat types. No. 1: wide bimodal mode. The main development of intergranular pore, dissolved pores, and a small number of micropores. No. 3: wide bimodal mode. The main development of dissolution pore and a small amount of intergranular pore and micropores. No. 9: asymmetry bimodal mode. The main development of micropores and a small number of dissolved pores.](image1)

![Figure 3: Entropy of microscale pore throat radius of different types of modal pore throat structure reservoirs.](image2)
occurrences in the wide bimodal mode reservoir is better than that in the asymmetrical bimodal mode reservoir (Figures 5(b) and 5(c)). However, in the pore throat radius range of <0.01 μm, the entropy of the pore throat radius in two types of reservoirs is negatively correlated with the depositional quantity of movable fluid, but the correlation is weak (Figure 5(d)). The main reason is that the more uniform the distribution of small pores is, the less obvious the aggregation phenomenon is, the larger the specific surface area of rock particles is, and the greater the wall friction resistance of fluid flowing through porous media is. Therefore, the pore throats of >0.1 μm and 0.01–0.1 μm of the Chang 6 tight sandstone reservoir in the study area have a controlling effect on the complexity of the pore throat structure and the occurrence state of movable fluid.

4. Conclusions

(1) The concept of “the entropy of microscale pore throat radius” is first proposed to characterize the microscale pore throat variational characteristics of different pore throat structure types of reservoirs, and its influence on the distribution of movable fluid in tight sandstone reservoirs is deeply analyzed. This is of great significance for the efficient development of tight sandstone reservoirs

(2) Based on the analysis of the characteristics of the pore throat radius frequency distribution curve, the pore throat structure of the tight sandstone reservoir in the Chang 6 study area is divided into two types: wide bimodal mode and asymmetrical bimodal mode. The reservoir space combination, reservoir physical properties, and microscopic seepage characteristics of reservoirs with different modal pore throat structure types are completely different from those of conventional reservoirs and conglomerate reservoirs

(3) The pore with different origins has different pore sizes and shapes, and its developed position, configuration relationships, development direction, and development characteristics determine the differentiation of microscale pore throat. There are obvious differences in the entropy of the pore throat radius in different scales, which showed that the entropy of the pore

| Sample number | Length (cm) | Diameter (cm) | Porosity (%) | Permeability (×10^{-3} μm²) | Movable fluid saturation (%) | Reservoir types |
|---------------|-------------|---------------|--------------|-----------------------------|----------------------------|----------------|
| 1             | 2.704       | 2.498         | 12.31        | 0.6561                      | 55.94                      | Wide bimodal mode |
| 2             | 2.753       | 2.498         | 11.97        | 0.5682                      | 45.67                      |                |
| 3             | 2.783       | 2.498         | 11.05        | 0.4983                      | 45.57                      |                |
| 4             | 2.489       | 2.498         | 11.54        | 0.3426                      | 34.19                      |                |
| 5             | 3.296       | 2.501         | 10.07        | 0.2032                      | 36.42                      |                |
| 6             | 2.673       | 2.501         | 8.04         | 0.0692                      | 27.28                      |                |
| 7             | 2.554       | 2.500         | 9.18         | 0.1516                      | 33.32                      |                |
| 8             | 2.609       | 2.501         | 8.06         | 0.0795                      | 20.98                      |                |
| 9             | 2.998       | 2.501         | 6.14         | 0.0597                      | 18.85                      |                |

Table 1: Physical properties and dynamic fluid saturation information of the sample.
throat radius decreased successively at 0.01~0.1 μm, >0.1 μm, and <0.01 μm. In other words, the complexity of the pore throat structure decreases in turn.

(4) Based on nuclear magnetic resonance technology, the distribution of pore throat and the occurrence law of dynamic fluid in the study area of the Chang 6 tight sandstone reservoir are studied. The seepage capacity of the reservoir is mainly provided by pore throats of 0.01~0.1 μm and >0.1 μm, and the saturation of the movable fluid in the range of 0.01~0.1 μm, >0.1 μm, and <0.01 μm decreased successively. Therefore, pore throats of >0.1 μm and 0.01~0.1 μm play a controlling role in the complexity of the micropore throat structure of the Chang 6 tight sandstone reservoir and the occurrence state of movable fluid in the study area.

**Data Availability**

The experimental data used to support the findings of this study are included within the manuscript.

**Conflicts of Interest**

The authors declare that they have no conflicts of interest.

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