Hindawi
Geofluids
Volume 2021, Article ID 6654773, 7 pages
https://doi.org/10.1155/2021/6654773

Research Article

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

Fengjuan Dong[1,2] **Xuefei Lu,**[3] **Yuan Cao,**[4] **Xinjiu Rao,**[5] **and Zeyong Sun**[1,2]

[1]*College of Petroleum Engineering, Xi'an Shiyou University, Xi'an, Shaanxi 710065, China*
[2]*Shaanxi Key Laboratory of Advanced Stimulation Technology for Oil & Gas Reservoirs, Xi'an Shiyou University, Xi'an, Shaanxi 710065, China*
[3]*College of Sciences, Xi'an Shiyou University, Xi'an, Shaanxi 710065, China*
[4]*China Petroleum Logging Co. Ltd, Xi'an, Shaanxi 710077, China*
[5]*Exploration & Development Research Institute of Petrol China Changqing Oilfield Company, Xi'an, Shaanxi 710018, China*

Correspondence should be addressed to Fengjuan Dong; dfj_1222@126.com

Received 1 December 2020; Revised 17 December 2020; Accepted 24 December 2020; Published 7 January 2021

Academic Editor: Feng Xiong

Tight sandstone reservoirs have small pore throat sizes and complex pore structures. Taking the Chang 6 tight sandstone reservoir in the Huaqing area of the Ordos Basin as an example, based on casting thin sections, nuclear magnetic resonance experiments, and modal analysis of pore size distribution characteristics, the Chang 6 tight sandstone reservoir in the study area can be divided into two types: wide bimodal mode reservoirs and asymmetric bimodal mode reservoirs. Based on the information entropy theory, the concept of "the entropy of microscale pore throats" is proposed to characterize the microscale pore throat differentiation of different reservoirs, and its influence on the distribution of movable fluid is discussed. There were significant differences in the entropy of the pore throat radius at different scales, which were mainly shown as follows: the entropy of the pore throat radius of 0.01~0.1 μm, >0.1 μm, and <0.01 μm decreased successively; that is, the complexity of the pore throat structure decreased successively. The correlation between the number of movable fluid occurrences on different scales of pore throats and the entropy of microscale pore throats in different reservoirs is also different, which is mainly shown as follows: in the intervals of >0.1 μm and 0.01~0.1 μm, the positive correlation between the occurrence quantity of movable fluid in the wide bimodal mode reservoir is better than that in the asymmetric bimodal mode reservoir. However, there was a negative correlation between the entropy of the pore throat radius and the number of fluid occurrences in the two types of reservoirs in the pore throat radius of <0.01 μm. Therefore, pore throats of >0.1 μm and 0.01~0.1 μm play a controlling role in studying the complexity of the microscopic pore throat structure and the distribution of movable fluid in the Chang 6 tight sandstone reservoir. The above results deepen the understanding of the pore throat structure of tight sandstone reservoirs and present guiding significance for classification evaluation, quantitative characterization, and efficient development of tight sandstone reservoirs.

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-/nanometer 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]:

$$r = C * T_2. \tag{1}$$

In Formula (1), T_2 is the relaxation time (ms), r is the pore throat radius (μm), and C is the conversion factor (μm/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

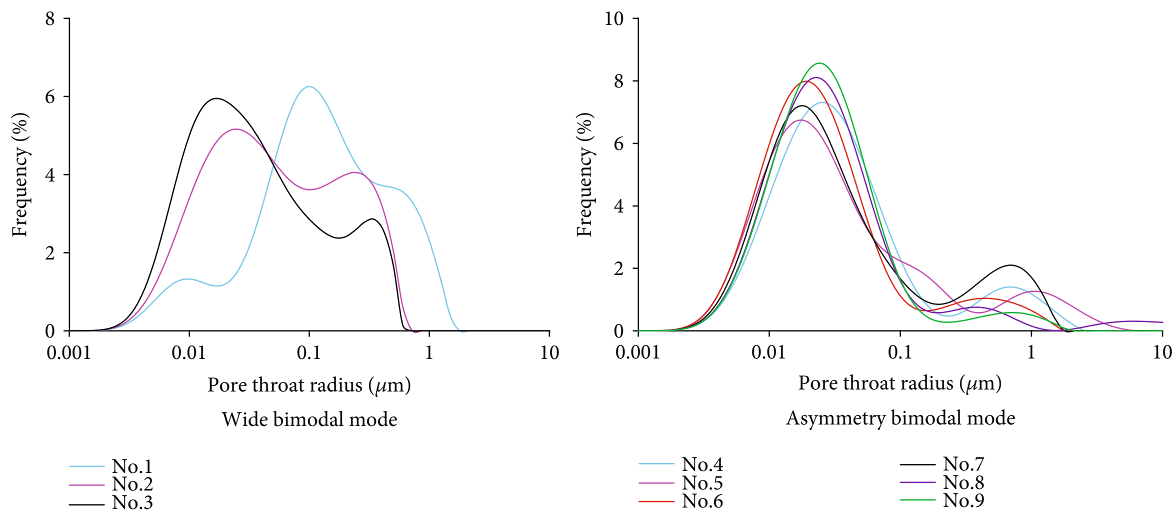

Figure 1: Pore throat distribution characteristics of reservoirs with different pore throat structure types.

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:

$$H = -\sum_{i=1}^{m} z_i \ln z_i. \tag{2}$$

Among them, z_i is the standard value of the occurrence frequency of the ith 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 ($tz_1 = z_2 = \cdots = z_m = 1/M$), 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 pore structure of the reservoir refers to the geometry, size, distribution, and interconnection of pores and throats of the rock, as well as the frequency distribution pattern of the pore throat radius. An in-depth analysis of the frequency distribution of the pore throat radius of the Chang 6 tight sandstone reservoir shows that the distribution of pore throats in different types of reservoir space combinations presents various laws. Based on the characteristics of the pore throat radius frequency distribution curve, the pore throat structure of the Chang 6 tight sandstone reservoir in the study area can be divided into two types by modal analysis: wide bimodal mode and asymmetric bimodal mode.

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 μm. 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 μm, and a weak secondary peak with a very low peak, with a corresponding pore throat radius of approximately 0.7 μm.

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

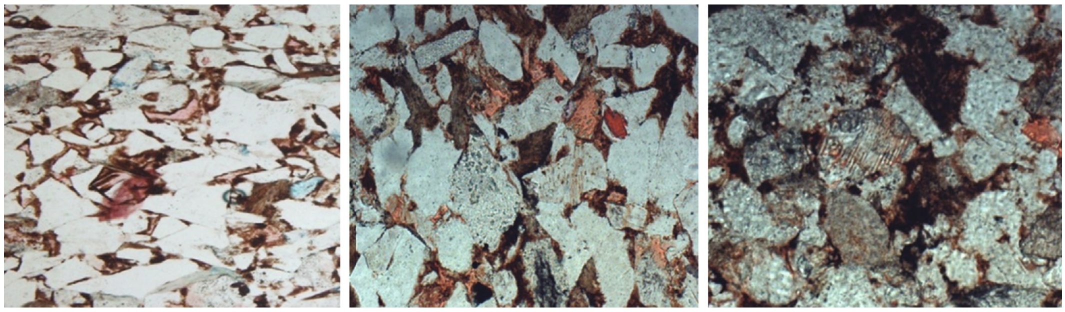

Figure 2: Reservoir space characteristics of different modal pore throat types. No. 1: wide bimodal mode. The main development of intergranular pore, dissolved pores, and a small number of micropores. No. 3: wide bimodal mode. The main development of dissolution pore and a small amount of intergranular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

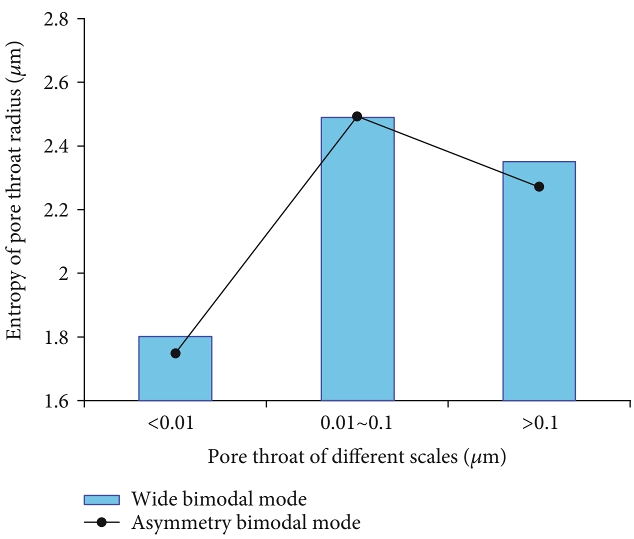

Figure 3: Entropy of microscale pore throat radius of different types of modal pore throat structure reservoirs.

developed parts, configuration relationships, development directions, and development characteristics determine the differences in micropore throat distributions.

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 μm, >0.1 μm, and < 0.01 μm, 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 μm and >0.1 μm, in which the movable fluid saturation corresponding to the radius of 0.01~0.1 μm pore throat is 25.49% and 16.27%; the movable fluid saturation corresponding to the radius of >0.1 μm pore throat is 22.52% and 13.49%, and the movable fluid saturation corresponding to the radius of <0.1 μm 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 μm and 0.01~0.1 μm range, the positive correlation between the entropy of the pore throat radius and the number of the movable fluid

Table 1: Physical properties and dynamic fluid saturation information of the sample.

Sample number	Length (cm)	Diameter (cm)	Porosity (%)	Permeability ($\times 10^{-3}\ \mu m^2$)	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	Asymmetry bimodal mode
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	

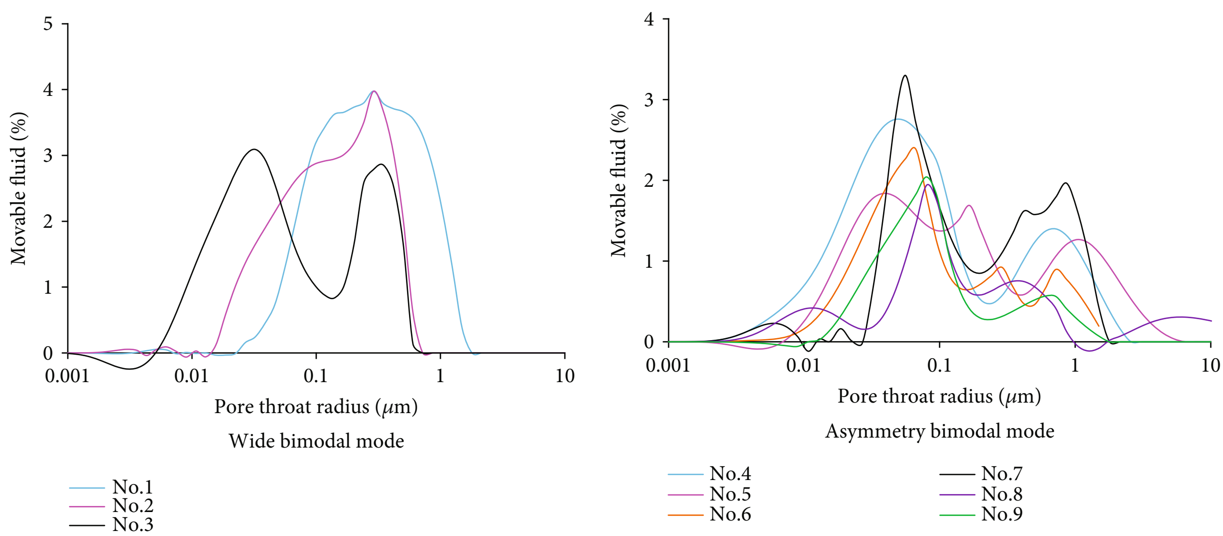

Figure 4: Movable fluid distribution characteristics of reservoirs with different pore throat structure types.

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

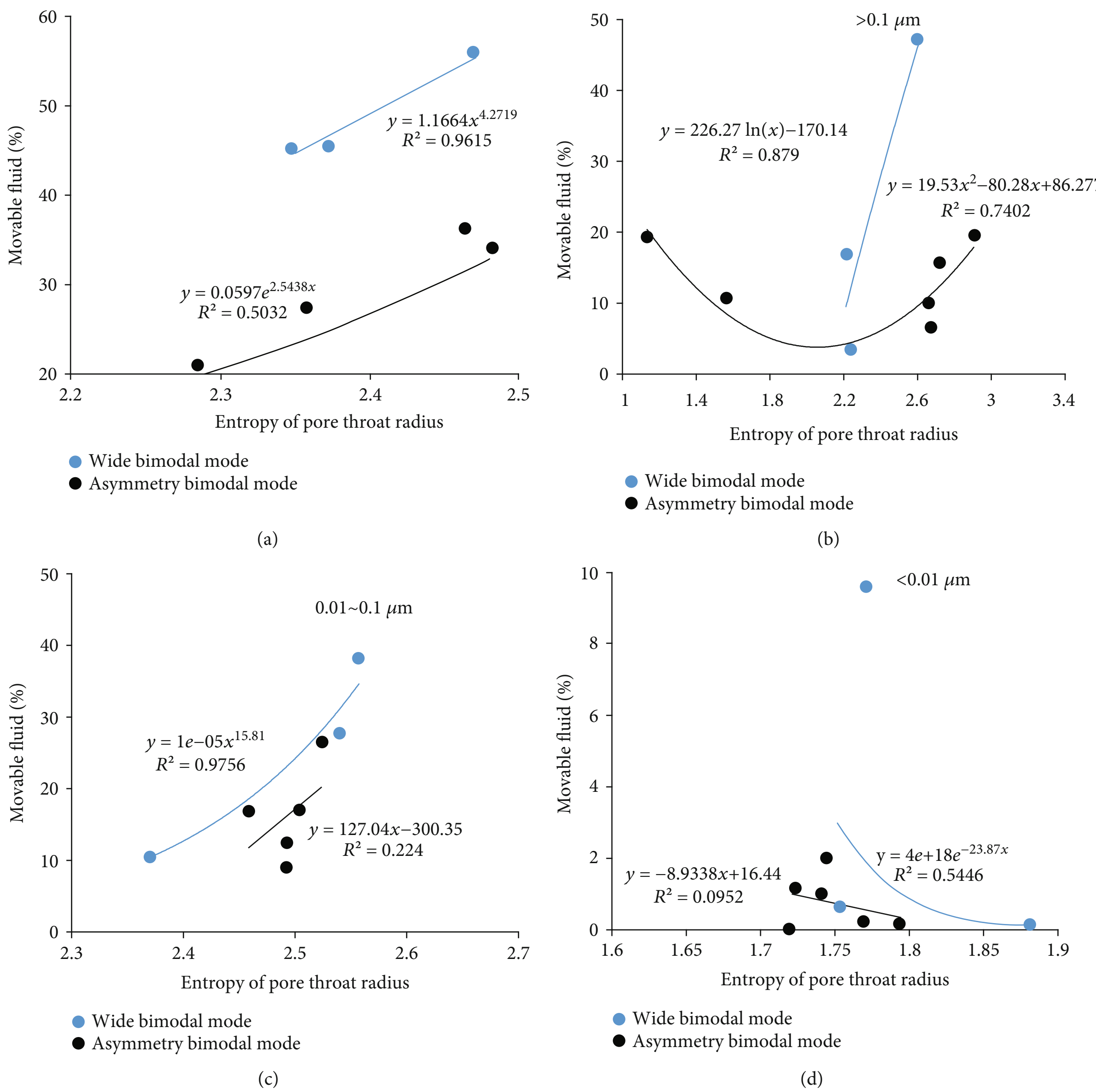

FIGURE 5: The relationship between the entropy of the pore throat radius and the movable fluid saturation.

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.

Acknowledgments

This work was financially supported by the National Natural Science Foundation of China (41802166), Shaanxi Natural Science Foundation Research Project (2017JQ4005), Young Science and Technology Talents Foundation of Shaanxi Province (2019KJXX-054), and Scientific Research Program

Funded by Shaanxi Provincial Education Department (20JS120). We thank the support of these projects.

References

[1] X. Wang, C. Liu, S. Chen, L. Chen, K. Li, and N. Liu, "Impact of coal sector's de-capacity policy on coal price," *Applied Energy*, vol. 265, article 114802, 2020.

[2] C. N. Zou, G. S. Zhang, Z. Yang et al., "Concept, characteristics, potential and technology of unconventional oil and gas — also on unconventional oil and gas geology," *Petroleum Exploration and Development*, vol. 40, no. 4, pp. 385–399, 2013.

[3] C. Z. Jia, C. N. Zou, J. Z. Li, D. H. Li, and M. Zheng, "Evaluation criteria, main types, basic characteristics and resource prospects of tight oil in China," *Acta Petroleum Sinica*, vol. 33, no. 3, pp. 343–349, 2012.

[4] P. Li, W. Sun, B. L. Wu, Y. L. Gao, and K. Du, "Occurrence characteristics and influential factors of movable fluids in pores with different structures of Chang 6_3 reservoir, Huaqing oilfield, Ordos Basin, China," *Marine and Petroleum Geology*, vol. 97, pp. 480–492, 2018.

[5] D. K. Liu, W. Sun, and D. Z. Ren, "Experimental investigation of pore structure and movable fluid traits in tight sandstone," *Processes*, vol. 7, no. 3, p. 149, 2019.

[6] B. Rashid, A. H. Muggeridge, A. Bal, and G. Williams, "Quantifying the impact of permeability heterogeneity on secondary-recovery performance," *SPE Journal*, vol. 17, no. 2, pp. 455–468, 2012.

[7] X. X. Wang, J. G. Hou, S. H. Song et al., "Combining pressure-controlled porosimetry and rate-controlled porosimetry to investigate the fractal characteristics of full-range pores in tight oil reservoirs," *Journal of Petroleum Science and Engineering*, vol. 171, no. 12, pp. 353–361, 2018.

[8] J. Lai, G. W. Wang, Z. Y. Fan, J. Chen, and S. C. Wang, "Insight into the pore structure of tight sandstones using NMR and HPMI measurements," *Energy & Fuels*, vol. 30, no. 12, pp. 10200–10214, 2016.

[9] F. Zhu, W. X. Hu, J. Cao, F. N. Sun, Y. F. Liu, and Z. M. Sun, "Micro/nanoscale pore structure and fractal characteristics of tight gas sandstone: a case study from the Yuanba area, Northeast Sichuan Basin, China," *Marine and Petroleum Geology*, vol. 98, no. 12, pp. 116–132, 2018.

[10] B. Bai, R. K. Zhu, S. T. Wu, W. J. Yang, and L. Su, "Multi-scale method of nano(micro)-CT study on microscopic pore structure of tight sandstone of Yanchang Formation, Ordos Basin," *Petroleum Exploration and Development*, vol. 40, no. 3, pp. 354–358, 2013.

[11] M. G. Luo, "Quantitative models for pore structures of clastic sedimentary rocks," *Acta Petrolei Sinica*, vol. 2, no. 4, pp. 27–38, 1991.

[12] J. K. Liu, "An investigation on structural mode of conglomerate reservoir and its evaluation," *Petroleum Exploration and Development*, no. 2, pp. 45–55, 1983.

[13] Z. Li, H. X. Liu, Z. L. Dun, L. W. Ren, and J. J. Fang, "Grouting effect on rock fracture using shear and seepage assessment," *Construction and Building Materials*, vol. 242, article 118131, 2020.

[14] Z. Li, H. Zhou, D. W. Hu, and C. Q. Zhang, "Yield criterion for rocklike geomaterials based on strain energy and CMP model," *International Journal of Geomechanics*, vol. 20, no. 3, article 04020013, 2020.

[15] Z. Li, S. G. Liu, W. T. Ren, J. J. Fang, Q. H. Zhu, and Z. L. Dun, "Multiscale laboratory study and numerical analysis of water-weakening effect on shale," *Advances in Materials Science and Engineering*, vol. 2020, Article ID 5263431, 14 pages, 2020.

[16] Q. Meng, H. Wang, M. Cai, W. Xu, X. Zhuang, and T. Rabczuk, "Three-dimensional mesoscale computational modeling of soil-rock mixtures with concave particles," *Engineering Geology*, vol. 277, article 105802.

[17] P. Li, C. Z. Jia, Z. J. Jin, Q. Y. Liu, and B. He, "Pore size distribution of a tight sandstone reservoir and its effect on micro pore-throat structure: a case study of the Chang 7 member of the Xin'anbian Block, Ordos Basin, China," *Acta Geologica Sinica - English Edition*, vol. 94, no. 4, pp. 219–232, 2020.

[18] L. H. Zhang, X. Y. Liu, Y. L.. Zhao, Y. Zhou, and B. C. Shan, "Effect of pore throat structure on micro-scale seepage characteristics of tight gas reservoirs," *Gas Industry*, vol. 39, no. 8, pp. 50–57, 2019.

[19] Y. Y. Bai, D. Z. Ren, S. Shi, W. Sun, and D. K. Liu, "Study on flow unit division and production dynamics of tight sandstone reservoir in Huaqing oilfield," *Indian Journal of Marine Sciences*, vol. 48, no. 5, pp. 758–764, 2019.

[20] National development and reform commission, *Rock Thin Section Preparation: SY/T 5913-2004*, Petroleum industry press, Beijing, 2004.

[21] Standardization Administration, *Core Analysis Method: GB/T29172-2012*, Petroleum industry press, Beijing, 2012.

[22] National Energy Administration, *Standard for Laboratory Measurement of NMR parameters of rock samples: SY/T6490-2014*, Petroleum industry press, Beijing, 2015.

[23] H. J. Chen, P. Xie, J. H. Xie, B. B. Li, X. Lei, and B. Zhang, "Variation analysis method of flood process uniformity based on information entropy-a case study of Longchuan station flood process in Dongjiang River Basin," *Journal of Hydraulic Engineering*, vol. 46, no. 10, pp. 1233–1238, 2015.

[24] F. J. Dong, X. F. Lu, H. J. Ju, and W. Sun, "Flow unit division of low permeability sandstone reservoir based on entropy weight TOPSIS method," *Geological Science and Technology Information*, vol. 31, no. 6, pp. 124–128, 2012.

[25] C. E. Shannon, "A mathematical theory of communication," *Bell System Technical Journal*, no. 27, pp. 379–423, 1948.

[26] H. B. Li, J. Y. Zhu, and H. K. Guo, "Methods for calculating pore radius distribution in rock from NMR T_2 spectra," *Chinese Journal of Magnetic Resonance*, vol. 25, no. 2, pp. 273–280, 2008.

[27] S. L. Yin, G. Y. Chen, Y. K. Chen, and X. J. Wu, "Mechanism of complex models of pore structure of sandstone/conglomerate reservoirs," *Journal of Southwest Petroleum University (Science & Technology edition)*, vol. 41, no. 1, pp. 1–17, 2019.

[28] Q. G. Li, Y. L. Kang, and P. Y. Luo, "Multi-scale effect in tight sandstone gas reservoir and production mechanism," *Natural Gas Industry*, vol. 26, no. 2, pp. 111–113, 2006.