

Study on Microscopic Pore Structure and Gas-Driven Water Seepage Characteristics of Tight Sandstone Using Nuclear Magnetic Resonance

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Abstract

Tight sandstone gas resources hold significant potential, but their reservoir development is often hindered by low porosity, low permeability, and strong microscopic heterogeneity. The microscopic pore structure is a critical factor influencing gas-driven water seepage behavior; however, the quantitative relationship between pore structure and two-phase (gas-water) flow remains unclear. This study focuses on the Upper Shihezi Formation (He 8 Member) tight sandstone in the Yan'an Gas Field, Ordos Basin. Using nuclear magnetic resonance (NMR) technology, we systematically analyzed the pore structure characteristics of core samples and conducted gas-driven water seepage experiments to investigate the influence of different pore structures on gas displacement efficiency. The results indicate that the NMR T_2 spectra of the He 8 Member tight sandstone generally exhibit a bimodal distribution. Based on the skewness of the spectra, the pore structures can be classified into two types: bimodal fine-skewed and bimodal coarse-skewed. The former is dominated by small pores, with poor connectivity and low movable fluid saturation, leading to severely limited gas displacement efficiency. In contrast, the latter shows a significant increase in medium-sized pores, a coarser pore-throat structure, and superior seepage capacity. Furthermore, compared to the centrifugal method, the gas-driven water experiments demonstrated enhanced fluid mobility signals in larger pores on the T_2 spectrum, confirming the additional mobilization effect of gas fingering and bypassing in medium-to-large pore systems during actual gas reservoir development. This study provides key insights into microscopic seepage mechanisms, offering important theoretical support for the evaluation and development optimization of tight sandstone gas reservoirs.

Keywords

Tight Sandstone, Nuclear Magnetic Resonance (NMR), Microstructure, Gas-Water Displacement, Seepage Characteristics.

1. Introduction

As a significant component of unconventional natural gas resources, tight sandstone gas is playing an increasingly prominent role in the global energy landscape. The Upper Paleozoic strata of the Ordos Basin in China host abundant tight sandstone gas resources, with the He 8 member being one of the main producing zones in the Yan'an Gas Field, characterized by typically ultra-low porosity and ultra-low permeability[1]. The complex microscopic pore structure and strong heterogeneity of such reservoirs lead to an unclear mechanism for gas-water two-phase seepage, consequently hindering efficient development and recovery enhancement of the gas reservoirs. The gas-driven water displacement process is central to gas reservoir development, and its efficiency is directly controlled by the microscopic pore structure of the reservoir and the occurrence state of fluids[2, 3]. Therefore, elucidating the

influence of pore structure on gas-water seepage behavior from a microscopic scale is crucial for uncovering the seepage mechanisms in tight sandstone gas reservoirs and guiding development practices. Nuclear Magnetic Resonance (NMR) technology can non-destructively and rapidly acquire information on the distribution and migration of fluids within core samples, making it particularly suitable for characterizing the microscopic pore structure and fluid mobility in tight reservoirs [4]. Based on seepage theory, this study utilizes core samples from the He 8 member tight sandstone in the Yan'an Gas Field of the Ordos Basin. By employing NMR technology combined with centrifugal and gas displacement experiments, it systematically investigates the characteristics of gas-driven water seepage under different pore structure types. The aim is to establish the intrinsic relationship between pore structure and displacement efficiency, thereby providing scientific support for the refined development of such gas reservoirs.

2. Study Area and Samples

The Upper Paleozoic strata of the Ordos Basin are rich in tight gas resources. The Yan'an Gas Field, located in the south-central part of the basin, contains the Permian Lower Shihezi Formation (He 8 Member) as one of its primary gas-producing layers. This member is characterized by ultra-low porosity and permeability, making it an ideal subject for investigating the seepage characteristics and influencing factors of tight sandstone reservoirs. For this study, four core samples were selected from the He 8 Member tight sandstone reservoir in the Yan'an Gas Field. The fundamental petrophysical parameters of these samples are listed in Table 1. The porosity ranges from 6.56% to 8.12%, with an average of 7.19%. The permeability ranges from 0.017 mD to 0.38 mD, with an average value of 0.0248 mD.

Table 1. Basic petrophysical parameters of the core samples from the study area

Sample ID	Depth (m)	Lithology	Porosity (%)	Permeability (mD)
YH-1	2343.2	Light gray fine sandstone	8.12	0.023
YH-2	2857.3	Grayish-white fine sandstone	6.56	0.017
YH-3	2672.4	Light gray fine sandstone	6.75	0.021
YH-4	2462.3	Light gray fine sandstone	7.83	0.038

3. Experimental Methodology

3.1. Experimental Principle.

Nuclear Magnetic Resonance (NMR) responses in rocks originate from the relaxation behavior of hydrogen nuclei (protons) in pore fluids under the combined influence of a static magnetic field and a radiofrequency (RF) pulse. When a fluid-saturated core sample is placed in a uniform static magnetic field, the hydrogen nuclei align and become polarized, resulting in a net macroscopic magnetization vector. The application of an RF pulse at the Larmor frequency then excites these nuclei, causing NMR. After the RF pulse is terminated, a signal-whose amplitude decays exponentially with time-is detected. This transverse relaxation is commonly characterized by the relaxation time, T_2 , as expressed by the following fundamental relationship.

$$\frac{1}{T_2} = \rho \frac{S}{V} \quad (1)$$

where:

T_2 is the transverse relaxation time of the fluid in the pore (ms),

ρ is the surface relaxivity of the rock ($\mu\text{m/ms}$),

$\frac{S}{V}$ is the surface-to-volume ratio of the pore (μm^{-1}).

For a fluid-saturated rock, the fluid molecules are subjected to interactions with the pore surface. The strength of these interactions is governed by a combination of factors, including pore geometry (size and shape), mineralogy (composition and surface properties), and fluid characteristics (type and viscosity). During an NMR measurement, the observed T_2 relaxation time is directly influenced by the intensity of these surface interactions. Consequently, the T_2 distribution serves as a comprehensive indicator of pore structure, mineralogy, and fluid properties. By analyzing the T_2 spectrum, it is possible to characterize the pore-size distribution and the occurrence state of fluids within the rock sample.

3.2. Experimental Procedure

The experimental workflow consisted of the following steps:

(1) Sample Preparation: Representative core plugs (2.5 cm in diameter) were selected. They were cleaned to remove residual hydrocarbons and salts, followed by drying in an oven at 80 °C for 48 hours. Subsequently, the samples were fully saturated with an 8% KCl solution using a vacuum-pressure saturation apparatus for 24 hours to ensure complete pore-filling.

(2) Initial NMR Measurement: The fully water-saturated samples were analyzed using a MacroMR12-150H-I NMR core analyzer to obtain the baseline T_2 spectrum. The key instrument parameters were set as follows: echo time (TE) = 0.2 ms, wait time (TW) = 6000 ms, number of echoes = 4096, and number of scans = 64. All measurements were conducted under constant temperature.

(3) Gas-Driven Water Displacement: Nitrogen was used as the displacing phase to conduct gas flooding experiments on the saturated cores. The T_2 spectrum was monitored in situ using the low-field NMR spectrometer during the displacement process under constant temperature conditions.

(4) Post-Displacement Reset & Resaturation: Following the displacement experiment, the core samples were cleaned and dried again using the procedure described in step (a) to remove all fluids. They were then resaturated with 8% KCl solution via vacuum-pressure saturation to achieve a fully saturated state for subsequent centrifugal calibration.

(5) Centrifugation and NMR Measurement: The resaturated cores were placed in a dedicated centrifuge tube and subjected to centrifugation at a capillary pressure equivalent to 2.07 MPa. After centrifugation, the T_2 spectrum was measured again to determine the fluid distribution after centrifugal desaturation.

4. Pore Structure Characteristics of the Reservoir

Quantitative characterization of the microscopic pore structure was achieved based on parameters derived from NMR experiments, including the transverse relaxation time (T_2) spectrum, NMR-derived total porosity, and the T_2 cutoff value. After saturating the four core samples with formation water, NMR analysis was performed, and the resulting T_2 distributions were used to investigate the pore structure. The T_2 spectra of the tight sandstone core samples from the He 8 Member of the Upper Paleozoic in the Yan'an Gas Field, Ordos Basin, generally exhibit a bimodal distribution under fully water-saturated conditions, with the left peak being more prominent. This indicates the presence of distinct pore types within the rocks, primarily resulting from variations in reservoir lithology and physical properties. Skewness is a parameter used to describe the symmetry of the T_2 spectrum. A spectrum skewed towards the

smaller pore range is classified as fine-skewed, while one skewed towards the larger pore range is considered coarse-skewed. Accordingly, the core samples from the study area can be categorized into two types: bimodal fine-skewed (e.g., sample YH-2) and bimodal coarse-skewed (e.g., sample YH-4).

The bimodal fine-skewed sample YH-2 is dominated by small pores, which account for up to 82.02% of the total pore volume, while the combined proportion of medium and large pores is less than 18%. Its T_2 spectrum displays a typical bimodal fine-skewed. This suggests that the pore system is predominantly composed of abundant nano-scale micropores and clay-bound pores, accompanied by narrow pore throats, complex connectivity, and a poorly developed microscopic seepage network. Consequently, the NMR-derived movable fluid saturation is inevitably low, manifesting as reservoir characteristics of low permeability and low effective porosity, indicating overall poor reservoir quality. In contrast, the bimodal coarse-skewed sample YH-4, although still dominated by small pores (66.71%), shows a significantly increased proportion of medium pores (32.28%). Its T_2 spectrum exhibits a bimodal coarse-skewed pattern. This indicates that within the pore system of this sample, alongside the micro-pores that form the main storage space, there exists a considerable proportion of larger pores, such as dissolution pores or residual intergranular pores. These medium pores significantly enhance the connectivity between pores, forming effective pathways for fluid flow. Therefore, core YH-4 possesses higher movable fluid potential and superior seepage capacity, with noticeably better reservoir properties than sample YH-2.

In summary, the strong microscopic heterogeneity observed within the He 8 Member reservoirs is primarily controlled by local variations in diagenesis, particularly the intensity of dissolution processes. Weaker dissolution in sample YH-2 allowed stronger compaction and cementation features to be preserved, leading to a finer pore structure. In contrast, relatively intense dissolution likely altered parts of the pore system in sample YH-4, resulting in a coarser pore-size distribution and a more favorable seepage structure.

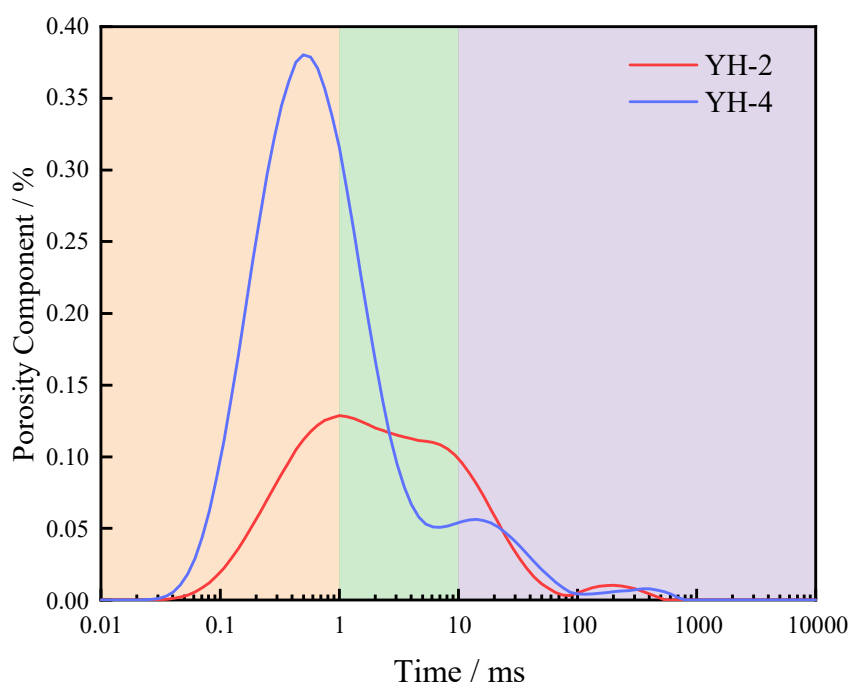


Figure 1. NMR T_2 spectra of representative core samples

Table 2. Pore-size distribution characteristics of typical core samples based on NMR measurements

Sample ID	Pore Size Distribution Pattern	Proportion of Small Pores (%)	Proportion of Medium Pores (%)	Proportion of Large Pores (%)
YH-2	Bimodal	82.02	15.87	2.11
YH-4	Bimodal	66.71	32.28	1.01

5. Microscopic Seepage Characteristics of Gas-Driven Water Displacement

Analysis combining the NMR centrifugation results (Table 3) and the corresponding T_2 spectra before and after centrifugation (Figure 2) for the representative core samples provides deeper insight into the control mechanism of the microscopic pore structure on fluid mobility and seepage capacity in the He 8 Member tight sandstone reservoirs. The fluid occurrence and mobilization characteristics revealed by the experimental data for cores YH-2 and YH-4 are highly consistent with their respective pore structure types. As intuitively shown by the changes in the T_2 spectra before and after centrifugation (Figure 3), the T_2 spectrum of core YH-2 exhibits minimal change after centrifugation. In contrast, for core YH-4 after displacement, the amplitude of the right peak in the T_2 spectrum-representing movable fluid in larger pores-shows a significantly greater reduction compared to YH-2, while the left peak, corresponding to bound fluid, remains relatively intact. This indicates a higher fluid mobilization efficiency within the pores of YH-4.

Core YH-2 demonstrates an extremely high bound fluid saturation (75.63%) and a very low movable fluid saturation (24.37%), with a movable fluid porosity of only 1.60%. Under the same displacement pressure, only about one-quarter of the pore fluid can be mobilized, with the majority remaining trapped in the minute pore throats. This result directly corroborates its "bimodal fine-skewed" pore structure attribute. The reservoir space is predominantly composed of nano-scale micropores and fine throats. Strong capillary forces and surface adsorption effects bind most of the formation water within the pores, resulting in a very limited volume of fluid being effectively mobilized during gas displacement or centrifugal experiments. The poor connectivity hinders the formation of an effective seepage network. Its relatively high T_2 cutoff value (1.46 ms) further indicates that higher centrifugal force or injection pressure is required to overcome the capillary resistance of the small throats and initiate flow in a portion of the trapped fluid.

In comparison, core YH-4 under the same pressure conditions shows a bound fluid saturation of only 33.27%, while the movable fluid saturation is as high as 66.73%. The movable fluid porosity increases to 5.22%, approximately three times that of core YH-2. This result aligns with its "bimodal coarse-skewed" structure, indicating the development of a significant proportion of medium pores and relatively larger throats within its pore system, where capillary forces are weaker, and fluids can move more easily. The lower T_2 cutoff value (0.88 ms) signifies that fluid within the pores can begin to migrate under lower displacement pressures, demonstrating favorable seepage capacity.

Table 3. NMR experimental results for the representative core samples

Sample ID	Bound Fluid Saturation (%)	Movable Fluid Saturation (%)	Movable Fluid Porosity (%)	T_2 Cutoff Value (ms)
YH-2	75.63	24.37	1.60	1.46
YH-4	33.27	66.73	5.22	0.88

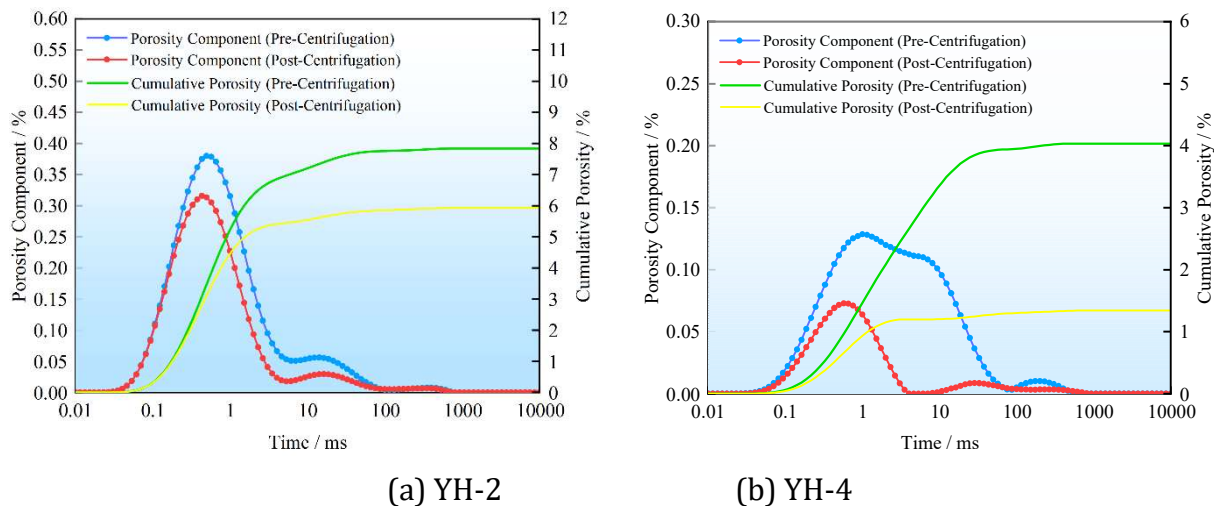


Figure 2. NMR T_2 spectra of the core samples

A further comparison of the responses on the T_2 spectra between the centrifugal method and the gas-driven water displacement experiments (Figure 3) reveals fundamental differences in pore mobilization mechanisms under different displacement processes. The centrifugal method relies on capillary pressure (1.38-2.76 MPa) generated by high-speed rotation to displace movable fluids, whereas gas displacement simulates the process in actual gas reservoir development where the non-wetting gas phase displaces the resident water phase. For cores with favorable pore structures like YH-4, the T_2 spectrum from gas displacement (purple curve) shows significant differences compared to the centrifugation result (red curve) in the movable fluid region ($T_2 > 10$ ms). In the transition zone (10-100 ms), the gas displacement signal is markedly stronger. In the macropore and micro-fracture region ($T_2 > 100$ ms), the signal amplitude from gas displacement can be 2.5 to 3 times higher than that after centrifugation, and the spectral peak extends over a wider range (up to 10,000 ms). This clearly demonstrates that gas, through mechanisms like fingering and bypassing, can mobilize movable water in medium to macropores and even micro-fracture systems more effectively than centrifugation alone. Quantitative analysis reveals that the gas displacement recovery efficiency (55-65%) is 15-25 percentage points higher than the centrifugal recovery efficiency (35-40%), with the primary contribution originating from the additional mobilization of the large-pore system. This mechanism is exemplified by core YH-4, where the amplitude reduction of the right peak (representing movable fluid in large pores) after gas displacement is far greater than in core YH-2, while the left bound-fluid peak remains relatively intact. This discrepancy is attributed to dynamic effects during gas displacement, such as gas invasion potentially inducing the opening of micro-fractures and the resulting non-wetting phase trapping effects, highlighting the dynamic response of the heterogeneously connected pore network under actual displacement conditions. This result also indicates that relying solely on centrifugation experiments may underestimate the potential fluid mobilization efficiency achievable in actual gas reservoir development.

In summary, within the He 8 Member tight sandstone reservoirs of the study area, the pore structure type is the key intrinsic factor controlling displacement efficiency. The "bimodal coarse-skewed" pore structure, characterized by relatively larger throats and better connectivity, not only exhibits high movable fluid saturation but also enables effective mobilization of the large-pore network through more complex seepage mechanisms during gas displacement, resulting in high displacement efficiency. In contrast, the "bimodal fine-skewed" structure, dominated by fine throats and strong capillary forces, contains less movable fluid that is difficult to mobilize effectively, leading to low displacement efficiency. NMR monitoring

can precisely resolve the sequence and contribution of fluid mobilization from pores of different scales. This understanding provides a key microscopic seepage mechanism basis for refined reservoir evaluation and optimization of development strategies in this area.

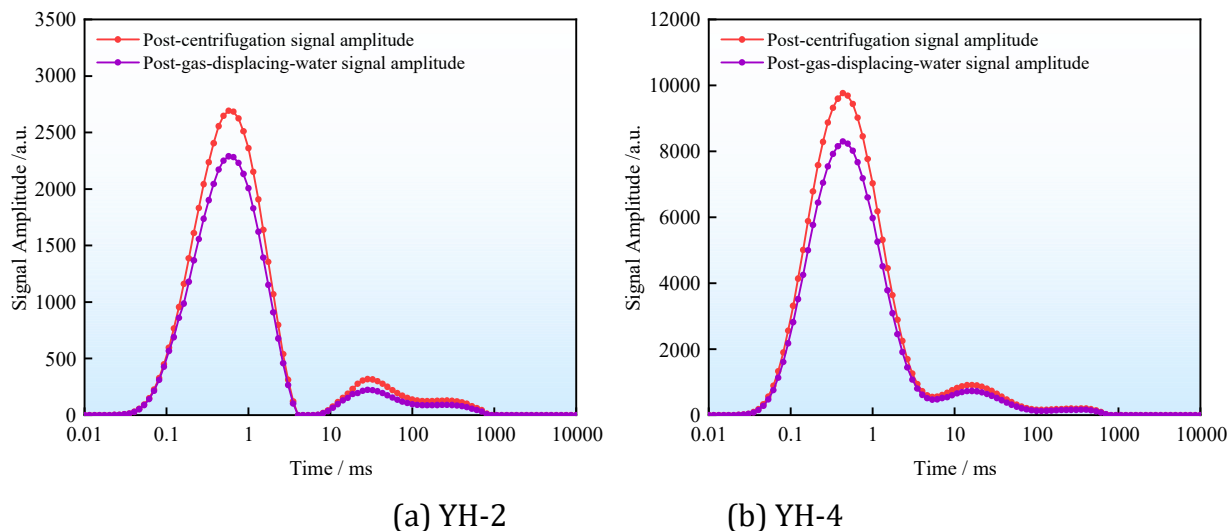


Figure 3. Comparison of NMR T_2 spectra between gas displacement and centrifugation for the core samples

6. Conclusion

(1) The tight sandstone reservoirs in the He 8 Member of the study area exhibit strong heterogeneity in their microscopic pore structure. Based on the morphology of the NMR T_2 spectra, the pore structures can be classified into two types: "bimodal fine-skewed" and "bimodal coarse-skewed". The former is overwhelmingly dominated by small pores ($<0.1 \mu\text{m}$), exceeding 80% of the total volume, resulting in poor pore connectivity. In contrast, the latter shows a significantly increased proportion of medium pores ($0.1\sim 1.0 \mu\text{m}$), over 30%, indicating relatively coarser pore throats and the development of a more effective seepage network.

(2) The pore structure type directly controls the efficiency of gas displacement. Reservoirs with a "bimodal coarse-skewed" structure possess a high movable fluid saturation of up to 66.73%, facilitating effective fluid mobilization and leading to significant gas displacement efficiency. Conversely, reservoirs characterized as "bimodal fine-skewed" have a much lower movable fluid saturation of only 24.37%, where strong capillary forces result in the majority of the fluid being irreversibly trapped, severely limiting gas displacement efficiency. The NMR-derived movable fluid parameters serve as effective indicators for evaluating the seepage capacity of the reservoir.

(3) Differences exist in the pore mobilization mechanisms between the gas displacement process and centrifugal displacement. Compared to centrifugation, which primarily relies on capillary pressure, the gas displacement process involves mechanisms such as gas fingering, bypassing, and potentially induced micro-fracture effects. These mechanisms enable a more effective mobilization of fluids from medium-to-large pores and micro-fracture systems, consequently yielding a higher recovery factor in gas displacement than predicted by centrifugal experiments alone. This indicates that the potential for fluid mobilization in actual gas reservoir development might be underestimated by traditional centrifugal methods. NMR dynamic monitoring provides a crucial means for accurately assessing the mobilization sequence and production efficiency from pores of different scales.

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