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Comparison of Micro-Effects of Vacuum Pumping and Displacement Saturation in Tight Sandstone Cores

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Abstract

As global conventional oil and gas resources dwindle, unconventional resources have emerged as a crucial strategy for China's energy transition and reserve augmentation. Tight sandstone reservoirs, a type of unconventional formation, typically feature complex geology, varied and dynamic structures, and limited inter-pore connectivity, often resulting in low extraction efficiency. To enhance recovery rates from tight sandstone reservoirs, detailed studies of the reservoir's micro-pores are essential. Among these, quantitative evaluation of core micro-pores through laboratory experiments stands as an effective and precise technique. The method of saturating the core is critical in these experiments. Several saturation methods are employed both domestically and internationally, with the most common in the lab being the vacuum and displacement saturation methods. However, a microscopic analysis of the differences between these two methods is lacking. Consequently, this study uses cores from the Chang 7 reservoir in the Ordos Basin to experiment with two saturation methods, leveraging nuclear magnetic resonance (NMR) technology to assess the merits of each through NMR T2 spectrum curves. The findings reveal that for tight sandstone, displacement saturation outperforms vacuum saturation when the relaxation time is less than 0.8ms; for 0.8ms<relaxation time<8ms, vacuum saturation is preferable; and for relaxation times exceeding 8ms, displacement saturation again proves more effective.

Keywords

Dense Sandstone; Vacuum Saturation; Drive Saturation; Nuclear Magnetic Resonance.

1. Introduction

With the global traditional oil and gas resources gradually decreasing, the oil and gas exploration field is constantly expanding. Unconventional oil and gas represented by tight oil and gas and shale oil and gas have shown great potential and have become an important direction for China's energy replacement and increased reserves and production. The successful development of the Sulige tight gas reservoir in the Ordos Basin demonstrates that China's tight oil and gas have broad exploration and development prospects. Changes in domestic oil and gas production also indicate that as the old oil fields in the east enter the late stage of development, the increase in oil and gas mainly comes from low-permeability, ultra-low-permeability and tight oil and gas resources in the west. However, due to the complex and variable pore-throat structure and poor connectivity between pores in tight sandstone reservoirs, the recovery efficiency is relatively low. It can be seen that the microscopic pore structure of the reservoir has a significant impact on the recovery efficiency of oil and gas, especially tight reservoir oil and gas. Therefore, in order to improve the recovery rate, it is necessary to study the microscopic pore-throat structure of the reservoir rock samples and understand their microscopic pore-throat structure in detail [1-3]. Currently, the research on microscopic pore structure mainly falls into two categories: physical experiments and numerical simulation-based model construction. Conventional physical experiments directly test the core through various experimental instruments to obtain the basic parameters of the core. Core numerical simulation technology is based on the two-dimensional cross-sectional images of different core positions obtained by CT scanning, and uses various reconstruction algorithms to establish a three-dimensional model of the core, and then simulates various experiments to obtain the basic parameters of the core. This paper starts from physical experiments to study the microscopic pore structure of tight sandstone cores and compare the microscopic effects of the same tight sandstone core under different core saturation methods.

2. Experimental Materials and Methods

2.1. Experimental Materials

This experiment utilized four rock cores: three authentic cores from the Chang7 reservoir in the Ordos Basin, designated as Cores 1, 2, and 3, and one artificial core B fabricated by high-pressure compaction of fine sand. All four cores employed in this experiment exhibited a cylindrical cross-section. Specific parameters of the experimental cores are detailed in Table 1. The saturated fluid used in the experiment consisted of a 30,000 ppm NaCl solution and distilled water.

Table 1. Core Basic Parameters

Core ID	Diameter/cm	Length/cm	Mass/g	Densityg/cm^3	Permeability/$10^{-3}\mu m^2$	Saturated Fluid
1	2.5	5.01	56.73	2.31	0.4084	NaCl
2	2.5	3.77	47.84	2.59	0.0014	NaCl
3	2.5	7.00	83.67	2.44	0.0151	NaCl
Artificial B	2.5	10.10	82.46	1.66	8.213	Distilled water

2.2. Experimental Procedure

1) Under conditions of 5 MPa and 85°C, wash the core with petroleum ether and benzene for 10 days. After washing, dry at 90°C for 12 hours.

2) Place the core in a vacuum apparatus and evacuate continuously for 24 hours to remove air and moisture from the core. Under vacuum conditions, inject a 30,000 ppm NaCl solution as the saturation solution into the real core, and inject distilled water as the saturation solution into the artificial core. Ensure the saturation solution submerges the core. Perform another 24-hour continuous vacuum extraction to facilitate better penetration of the NaCl solution and distilled water into the core pores.

3) After vacuum saturation, weigh the post-experiment core and send it for NMR scanning to assess saturation status.

4) Dry the core in an 80°C oven for 24 hours. Place the dried core into a core holder and confirm all valves along the piping route are open.

5) Saturate the core by injecting the saturated solution at a constant flow rate of 0.5 ml/min. After displacement saturation, weigh the post-experiment core and send it for NMR scanning to assess saturation status.

3. Analysis of Experimental Results

In the vacuum saturation experiment, calculations yielded porosities of 8.6%, 2.38%, 1.98%, and 16.68% for rock cores 1, 2, 3, and artificial rock core B, respectively. Permeability values obtained through gas displacement for the four cores were $0.4084\times10^{-3}\ \mu m^2$, $0.0014\times10^{-3}\ \mu m^2$, $0.0151\times10^{-3}\ \mu m^2$, and $8.213\times10^{-3}\ \mu m^2$. In displacement saturation experiments, calculations yielded porosities of 11.1%, 2.7%, 5.85%, and 23.7% for rock cores 1, 2, and 3, respectively, compared to artificial rock core B. Permeabilities measured by gas displacement were

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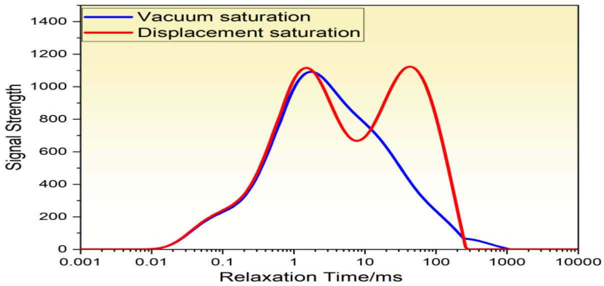
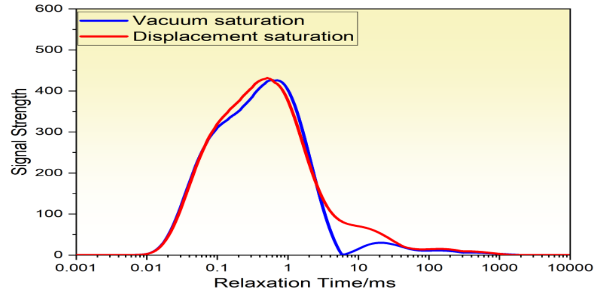
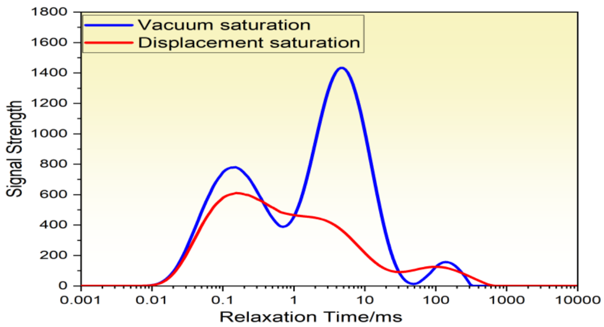
0.4564×10⁻³ μm², 0.0014×10⁻³ μm², 0.0214×10⁻³ μm², and 8.213×10⁻³ μm². In vacuum saturation test results, Core 2 exhibited lower permeability than Core 3 but higher porosity. However, in displacement test results, both permeability and porosity of Core 2 were lower than those of Core 3.



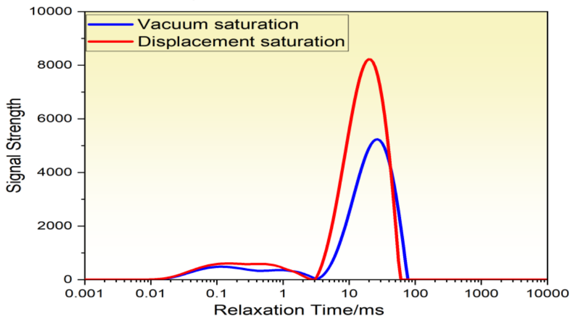
(a)Core 1 nuclear magnetic resonance T_2 spectrum curve



(b)Core 2 nuclear magnetic resonance T_2 spectrum curve



(c)Core 3 nuclear magnetic resonance T_2 spectrum curve



(d)Artificial core nuclear magnetic resonance T_2 spectrum curve

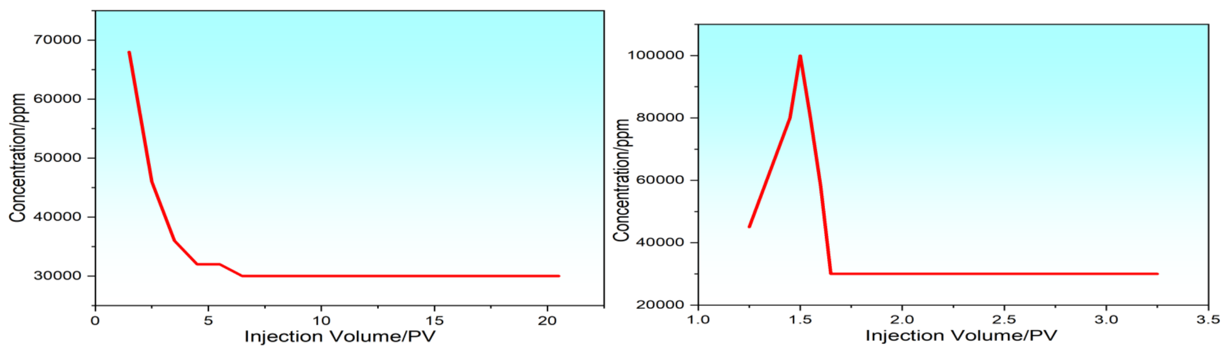
Figure 1. Nuclear magnetic resonance T_2 spectrum curves of four core samples

Based on the NMR T2 curves of the four rock samples: When 0.8 ms < relaxation time < 8 ms, displacement saturation generally outperformed vacuum saturation overall. However, the NMR curves of all three real cores showed a segment where vacuum saturation exhibited higher signal intensity than displacement saturation. When relaxation time > 8 ms, displacement saturation outperformed vacuum saturation. This indicates that for tight sandstones with excessively low permeability, vacuum saturation fails to effectively saturate the medium throughout the core. However, within medium-sized pores, vacuum saturation yields superior saturation compared to displacement saturation.

In summary, after calculating porosity using both saturation methods on four cores and analyzing the NMR T2 spectrum curves of saturated cores, we found that the displacement saturation method is more suitable for saturating tight sandstones than the vacuum saturation method. Vacuum saturation requires extended processing time and yields significantly poorer saturation results in tight cores compared to displacement saturation. Displacement saturation, performed under controlled pressure, enables the saturating fluid to penetrate finer pores, achieving superior saturation levels in the core.

As shown in Figure 2(a), this represents the displacement fluid concentration curve at the outlet end of core 1. The figure clearly shows that during displacement, when the injection volume reached 1.5 PV, the outlet concentration was 68,000 ppm. Subsequent measurements taken every five minutes revealed a continuous decrease in outlet displacement fluid concentration. By the time the injection volume reached 6.5 PV, the outlet concentration had dropped to 30,000 ppm and remained stable thereafter. This indicates that salt crystals within the core continuously dissolved during displacement. Due to the core's high permeability, the displacement fluid concentration peaked during the initial discharge and then steadily decreased until complete dissolution.

Figure 2(b) shows the displacement fluid concentration change curve at the outlet end of Core 3. The figure indicates that during displacement, the outlet displacement fluid concentration reached 45,000 ppm at an injection volume of 1.25 PV. Subsequent measurements showed the outlet concentration steadily increasing, peaking at 100,000 ppm when 1.5 PV was injected. Subsequently, the displacement fluid concentration began to decrease. At an injection volume of 1.65 PV, the measured outlet displacement fluid concentration was 30,000 ppm. The initial increase followed by decrease in outlet displacement fluid concentration for Core 3 may be attributed to its relatively low permeability. At the onset of displacement, the displacement fluid flows along pathways of lower resistance, initially dissolving a small portion of salt crystals along these pathways. As displacement progresses, the fluid begins entering finer pores, dissolving more salt crystals and causing the outlet displacement fluid concentration to rise continuously. Subsequently, with the continued dissolution of salt crystals, the outlet displacement fluid concentration begins to decrease until all salt crystals within the core are completely dissolved. the salt crystals are completely dissolved.



(a)Liquid concentration at the outlet of core 1 (b)Liquid concentration at the outlet of core3

Figure 2. Liquid concentration at the outlet end of the core

4. Conclusion

1) For tight sandstones, displacement saturation cores perform better than vacuum saturation cores in small pores; in a small portion of medium pores, vacuum saturation cores outperform

displacement saturation cores, while displacement saturation remains superior in most medium pores; in large pores, displacement saturation yields better results than vacuum saturation.

2) After the initial vacuum saturation and drying of the core, salt crystals remain inside. During the second displacement saturation, these salt crystals dissolve as the displacement fluid enters. The concentration of the displacement fluid at the outlet initially increases and then decreases, eventually matching the concentration at the inlet. Therefore, the residual salt crystals from the first saturation do not affect the second saturation.

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