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Imbibition Distance and Influencing Factors of Surfactant in Tight Reservoir : An Experimental Study

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ABSTRACT

The process of imbibition agents entering pore throats under capillary pressure, displacing and extracting crude oil through spontaneous imbibition, is an important mechanism for enhancing oil recovery in tight reservoirs. Current research primarily focuses on the mechanism of imbibition to improve oil recovery in tight reservoirs, with relatively few studies on the distance of imbibition. Utilizing nuclear magnetic resonance techniques, this study has established a quantitative characterization method for the imbibition distance of surfactants in tight cores based on nuclear magnetic resonance T2 spectrum and projection curve. Through one-dimensional core inlet imbibition experiments and multi-cycle two-dimensional imbibition experiments, the study analyzed the effects of imbibition pressure, core permeability, initial oil saturation, and other factors on the imbibition distance. The results showed that for a core with a permeability of 0.1mD, as the imbibition pressure increased, the imbibition distance increased from 42mm to 60mm, and the oil saturation at inlet decreased by 0.09. As permeability increased, the imbibition distance increased significantly. Under experimental conditions, core permeability had the greatest impact on imbibition distance, followed by imbibition pressure, and initial oil saturation had the smallest impact. In the case of multi-cycle two-dimensional imbibition, the ultimate imbibition distance increased from 60mm for one-dimensional cores to 85mm for multi-cycle two-dimensional cores, representing a 16.8% increase in sweep distance compared to single-cycle development. This study provides quantitative insights and experimental methods for understanding the reverse imbibition distance of surfactants in tight reservoirs, laying a theoretical foundation for the development of imbibition in tight reservoirs.

Keywords: imbibition distance, projection curve, large scale physical simulation experiments, nuclear magnetic resonance

NONMENCLATURE

Abbreviations	
SI	Signal intensity
HP	Hodrick-Prescott
NMR	Nuclear magnetic resonance
OOIP	Original oil in place
EOR	Enhancing oil recovery
Symbols	
So	Oil saturation
SI_A	Signal intensity after imbibition
SI_B	Signal intensity before imbibition
λ	Smoothing factor

1. INTRODUCTION

China is rich in tight oil resources, with a OOIP of up to 200×10^8 tons, making it an important area for future oil resource exploitation in China[1]. Unlike tight oil reservoirs in North America, the reservoir environments in China are complex, characterized by "three lows and two highs" (low original formation pressure, low porosity, low permeability, high capillary pressure, and high brittleness index), making it difficult to establish an effective injection-production relationship[2]. The combination of "horizontal wells and volumetric fracturing" has enabled the initial large-scale utilization of tight oil reservoirs[3], but there are still objective issues of "three lows and one difficulty" (low speed, low production, low recovery factor, and difficulty in water injection)[4]. The overall utilization degree is low, and there is significant remaining development potential, requiring further research and breakthroughs[5, 6].

The process of imbibition agents entering pore throats and extracting crude oil through spontaneous imbibition, is important for EOR in tight reservoirs[7]. Scholars have conducted numerous theoretical and

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experimental studies on the imbibition process in tight reservoirs[8], establishing various imbibition models that consider nano-confinement effects[9]. Currently, experimental methods include volumetric methods, mass methods, nuclear magnetic resonance (NMR), and CT scanning[10]. Among them, volumetric and mass methods are often subject to large errors due to measurement accuracy, while NMR and CT are currently the mainstream research tools[11]. Although scholars have conducted numerous studies, most of them focus on the recovery effect, imbibition mechanism, and pore utilization characteristics of different media[12, 13], with relatively few studies on the imbibition distance. However, the imbibition distance is of great significance for studying the range of imbibition effect after hydraulic fracturing in field and predicting production capacity. In addition, there is still a gap in research on the imbibition distance of a specific petroleum sulfonate.

Utilizing nuclear magnetic resonance technology, this study selects petroleum sulfonate as the imbibition medium to conduct one-dimensional core inlet imbibition experiments and multi-cycle two-dimensional imbibition experiments. The study analyzes the impact of different factors on the imbibition distance of surfactants and the changing patterns of the imbibition distance under multiple cycles of imbibition.

2. MATERIALS AND EXPERIMENTAL METHODS

2.1 Equipment and Materials

The cores used in this experiment are natural cores from the D oilfield with a permeability of approximately 1mD. The crude oil is obtained from the field and has a viscosity of 5.96mPa • s at 25℃. The imbibition agent used in the experiment is petroleum sulfonate.

2.2 One-Dimensional Core Imbibition Experiment

This experiment involves a one-dimensional core inlet imbibition test. During the experiment, a 10cm-long core is placed in a core holder, with one end sealed and the other end used to inject the imbibition medium at a set pressure. The experiment lasts for 96 hours to ensure that the imbibition process proceeds sufficiently. Nuclear magnetic resonance (NMR) scanning is performed on the core before and after the experiment to identify differences in signal intensity along the core. The experimental setup is shown in *Fig. 1*.

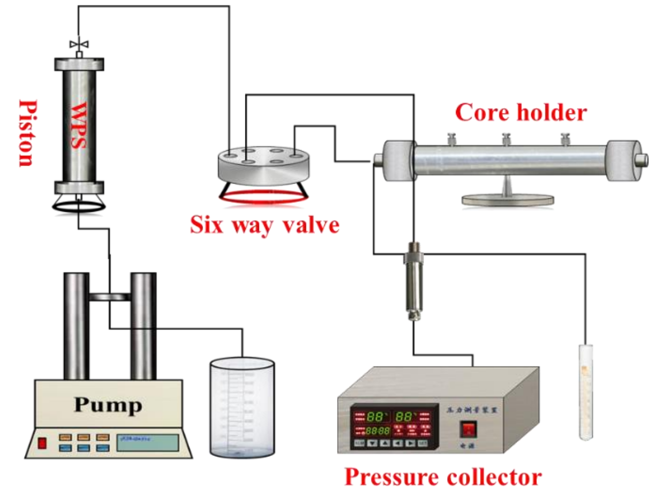

Fig. 1 One-Dimensional Core Imbibition Experiment Setup

This study explores the impact of factors such as permeability, imbibition pressure, and initial oil saturation on imbibition efficiency and imbibition distance. The experimental plan is outlined in Table 1, where different initial oil saturations are established by first saturating the core with water and then with oil, subsequent testing calculations have shown that the oil saturation of the core is 0.65.

Table1 One-Dimensional Core Imbibition Experiment Plan

No	Permeability/mD	Imbibition Pressure/MPa	Initial Oil Saturation
1	0.1	5	1
2	0.1	10	1
3	0.1	15	1
4	0.1	20	1
5	0.5	5	1
6	1.5	5	1
7	0.1	5	0.65

2.3 Two-Dimensional Core Imbibition Experiment

To better simulate the conditions of real reservoirs and address issues such as insufficient elastic energy in small-scale cores and difficulty in measuring the produced fluid volume, this study conducted a series of four-cycle high-pressure imbibition experiments using two-dimensional core samples. As shown in the *Fig. 2*, the core model has dimensions of 15*15*4cm, with a horizontal well located at inlet. The permeability of the model is 0.1mD, and the imbibition pressure is 20MPa. The experiments were conducted in a high-temperature and high-pressure 3D model chamber. After the experiments, core samples were drilled from the plate model, and NMR T2 spectrum were used to analyze the differences in recovery efficiency at different locations.

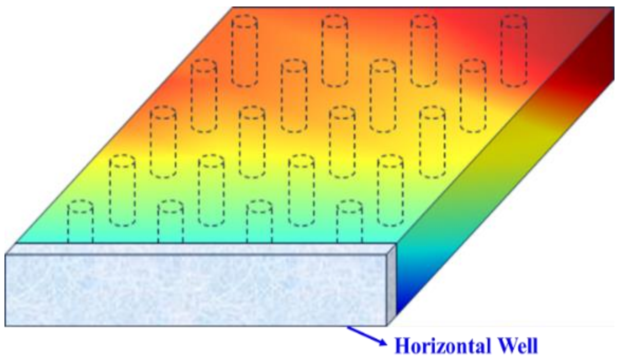

Fig. 2 Position Diagram of the Experimental Plate Core and Drilling Column

2.4 Processing of NMR Projection Data Along the Core

In this study, NMR projection was used to analyze the oil saturation along the core (as shown in *Fig. 3*). By comparing the signal intensity along the core before and after the experiment, changes in oil saturation along the core can be calculated.

$$So = \frac{SI_B - SI_A}{SI_B} \times 100\%$$

Due to the influence of the experimental environment and equipment accuracy, the obtained oil saturation curve along the core often fluctuates. Therefore, the HP filtering method[14] is used to process the curve.

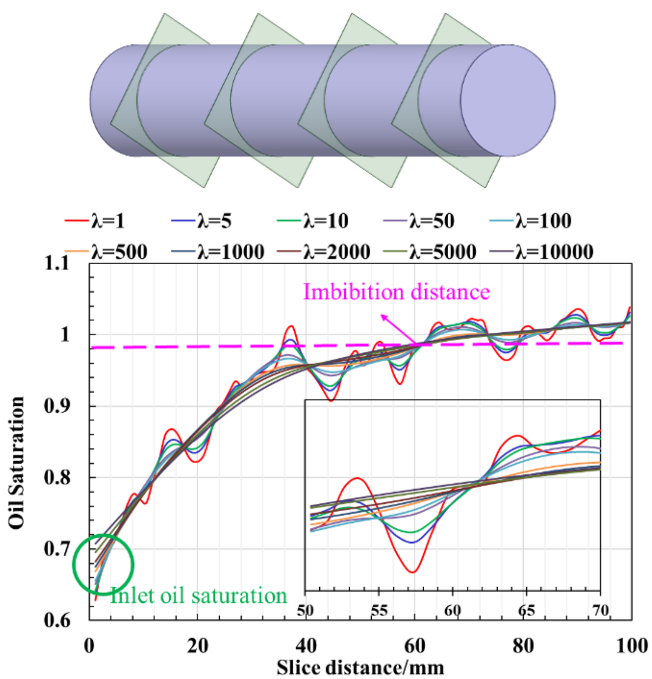

Fig. 3 NMR Projection Curve Processing Method

Based on the noise reduction results, a smoothing factor of λ=2000 is selected as the processing standard, to ensure that the data can be effectively denoised without distortion. In this study, an oil saturation of 0.98 is defined as the imbibition distance.

3. RESULTS

3.1 Testing of Surfactant Properties

The interfacial tension test results showed that the interfacial tension decreased with increasing concentration, and when the concentration of petroleum sulfonate reached 0.5%, the interfacial tension dropped to 0.136mN/m, as shown in *Fig. 4a*. The contact angles before and after soaking the core in petroleum sulfonate were measured to be 89° and 69.5°, respectively, which changed by 19.5°, as shown in *Fig. 4b*. The results showed that the initial state of the core was neutral wetting, and the selected petroleum sulfonate had certain abilities to reduce interfacial tension and change wettability. Therefore, the subsequent experiment selected 0.5%wt petroleum sulfonate.

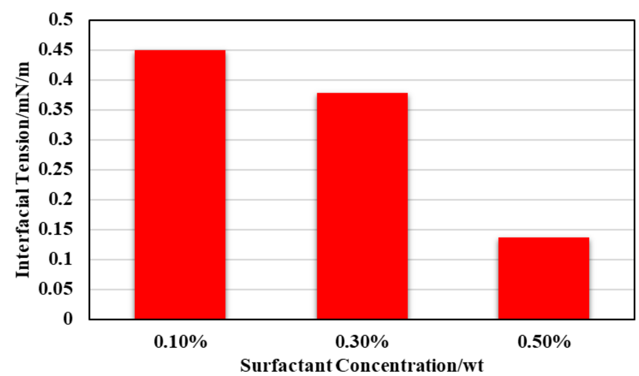

Fig. 4 (a) Interfacial tension of different concentrations of petroleum sulfonate

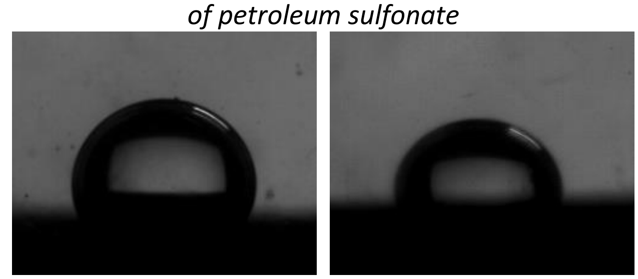

Fig. 4 (b) The ability of 0.5%wt petroleum sulfonate to change wettability

3.2 The Influence of Different Factors on the Imbibition Distance of One-dimensional Cores

A. Imbibition pressure

When comparing the influence of imbibition pressure on the imbibition distance, a core with similar permeability of 0.1mD was selected. Based on the process method of saturation along the way, the variation law of imbibition distance and oil saturation at inlet under different imbibition pressures can be calculated. Within the pressure range selected in the experiment, the imbibition distance shows a linear increase trend with the increase of imbibition pressure. At a imbibition pressure of 20MPa, the imbibition distance can reach 60mm, which is 18mm higher than that at 5MPa. The inlet oil saturation shows a logarithmic decrease trend. When the pressure increases from 5MPa to 20MPa, the inlet oil saturation decreases by about 9%, as shown in *Fig. 5*.

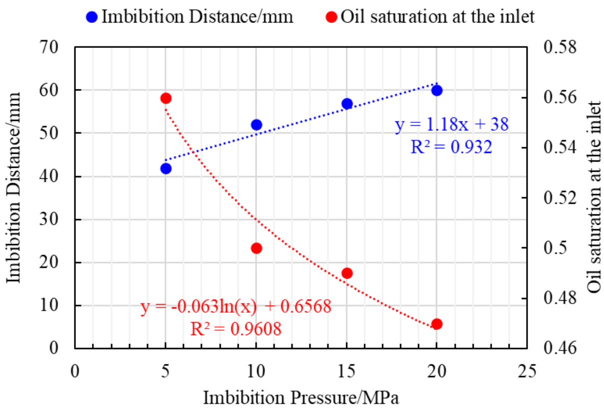

Fig. 5 The variation of imbibition distance and oil saturation at the inlet under different imbibition pressures

With the increase of imbibition pressure, more imbibition agents can enter the core under the effect of pressure, which can make the imbibition leading edge reach farther. In addition, the increase of imbibition pressure may also lead to the thinning of the boundary layer in the core pores, which can increase the proportion of movable fluid and thus imbibition more crude oil.

B. Permeability

The experiment on the influence of permeability on the imbibition distance was conducted using the same method. The influence of permeability on the imbibition distance and the oil saturation at the inlet is shown in the *Fig. 6*. As the permeability of the core increases, the imbibition distance increases significantly according to the logarithmic curve. From 0.1mD to 1.5mD, the imbibition distance of the core increases by about 40mm, and the oil saturation of the end face decreases by 0.05.

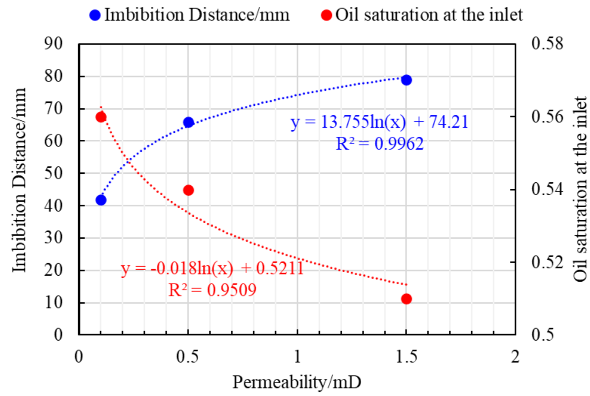

Fig. 6 The variation of imbibition distance and oil saturation at the inlet under different permeability

There are significant differences in the pore structure of cores with different permeability. The larger the permeability, the higher the proportion of large pores, making it easier for the imbibition agent to enter the core interior, and the limit imbibition distance will also increase accordingly, thereby greatly increasing the effective distance of the imbibition agent and improving the corresponding recovery factor.

C. Initial oil saturation

In the real reservoir environment, cores cannot be in a state of only containing water or only containing oil. In most cases, oil and water coexist. To determine the impact of oil saturation on the sweep distance, cores with similar permeability are selected for experiments under the same conditions. The cores are pre-treated with saturated water, then saturated with crude oil. The initial oil saturation is determined to be 65%. As the oil saturation decreases, the imbibition distance decreases to a certain extent, and the initial oil saturation has a small impact on the imbibition distance.

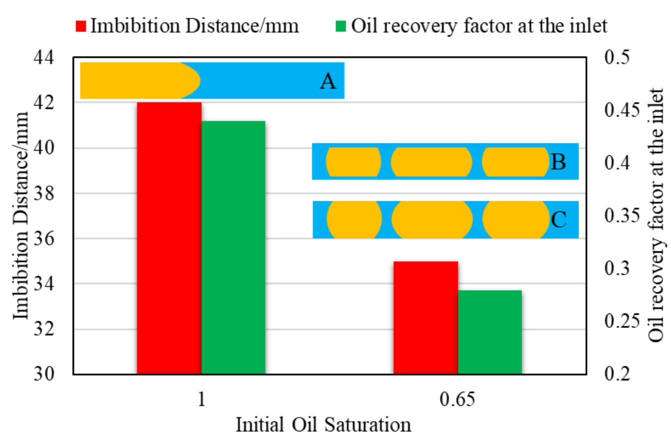

Fig. 7 The variation of imbibition distance and oil saturation at the inlet under different initial oil saturation

When other conditions are similar, the decrease in initial oil saturation leads to a decrease in capillary pressure. As shown in *Fig. 7A*, when the core is initially fully saturated with oil, it often exhibits oil-water piston-like motion, with high capillary pressure and low flow resistance. When the core is initially water-saturated, the oil and water exhibit a discontinuous, dispersed distribution, as shown in *Fig. 7B* and *C*. The resulting superimposed Jamin effect leads to an increase in flow resistance, while the core itself is neutrally wet, which may also result in a water film as shown in *Fig. 7B*. These factors may all contribute to a decrease in imbibition distance.

It is not difficult to find from the experimental results that the permeability of the rock core has the greatest impact on the imbibition distance, followed by the imbibition pressure, and the initial oil saturation of the rock core has the least impact

3.3 Two-Dimensional Core Imbibition

Multiple cycles of imbibition were conducted on the two-dimensional model. The results of the produced fluid volume showed that the total recovery factor of imbibition was 15%. The limitation of imbibition distance led to a rapid decline in the recovery factor of subsequent cycles of imbibition. The recovery factor of the first cycle of imbibition accounted for 54.63% of the total development, and the recovery factor of the first three cycles of imbibition accounted for 94.5% of the overall imbibition recovery factor.

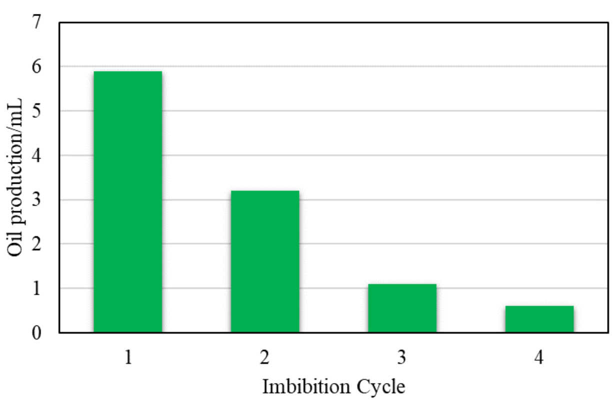

Fig. 8 Oil production from two-dimensional cores with different cycles of infiltration and extraction

Drilling a core at the preset point and performing NMR scanning in sequence to obtain a NMR spectrum arranged longitudinally. The longitudinal NMR spectrum is arranged as shown in the *Fig. 9*. By analyzing the NMR data, it can be seen that the remaining oil content in the core near the horizontal well is less than that in the remote core, and the remaining oil content increases with the increase of distance. In the one-dimensional core experiment, when the pressure increases to 20 MPa, the imbibition distance reaches 60 mm. The imbibition distance of a single cycle imbibition only accounts for 40% of the multi-cycles.

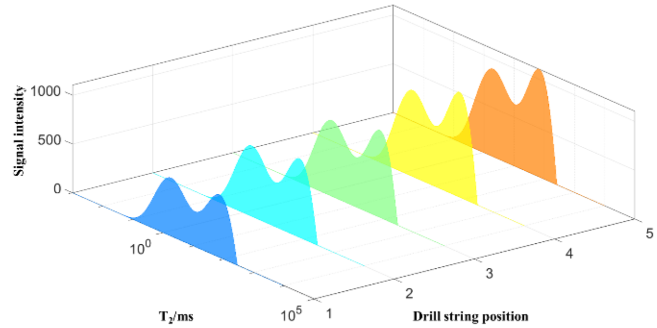

Fig. 9 T2 spectrum of drilling cores from different positions

Combining the T2 spectrum of different locations, this study has drawn a distribution map of oil saturation in the core after multiple cycles imbibition. The results show that under multiple cycles imbibition, the limiting distance increases from 60mm for one-dimensional cores to 85mm for two-dimensional cores, an increase of 25mm, greatly expanding the sweep distance. The proportion of sweep distance increases to 56.8%, an increase of 16.8% compared to single cycle.

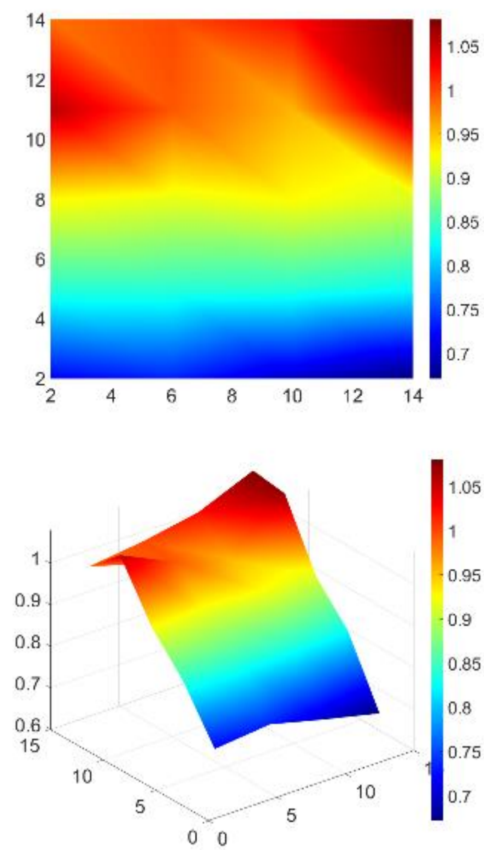

Fig. 10 Saturation distribution diagram of two-dimensional core after multi-cycle imbibition

4. CONCLUSIONS

Utilizing NMR technology, this study conducted one-dimensional core imbibition experiments and two-dimensional core multi-cycle imbibition experiments. An analytical method for NMR projection curves was established, and the imbibition distance and oil saturation at the inlet were defined. The influence of various factors on the imbibition distance of petroleum sulfonate was investigated.

(1) With the increase of imbibition pressure, more imbibition agents entered the core, resulting in a linear increase in the imbibition distance and a logarithmic decrease in oil saturation at the inlet. As the permeability increased, the pore structure improved, large pores proportion in percentage increased, and the imbibition distance significantly increased.

(2) As the initial oil saturation decreased, the oil and water exhibited a discontinuous and dispersed distribution. The resulting superimposed Jamin effect led to an increase in flow resistance. Meanwhile, the core itself had neutral wettability, potentially forming a water film, reducing capillary pressure, and causing a slight decrease in the imbibition distance.

(3) In the multi-cycle imbibition experiment using a two-dimensional core, the recovery factor in the first cycle accounted for 54.63% of the total development. The oil recovery in the first three cycles accounted for 94.5% of the overall imbibition oil recovery. Under the condition of multi-cycle imbibition, the limiting imbibition distance increased from 60mm for the one-dimensional core to 85mm for the two-dimensional core, and the proportion of imbibition distance increased to 56.8%, representing a 16.8% improvement compared to single-cycle development.

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