Characteristics of imbibition in tight oil reservoirs from the perspective of physical experiments and theory

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Abstract
Imbibition is an important recovery mechanism for tight oil reservoirs, which occurs during hydraulic fracturing and development. Due to the massive distribution of micro-nano scale pore throats and the existence of a boundary layer in tight formation, agreement consensus has not been reached on the imbibition mechanism. Based on the effect of the boundary layer, experiments were conducted to study the imbibition in tight sandstone, and NMR was used to determine the efficiency of imbibition. The results reveal that the imbibition rate is related to the connection area of the matrix-fracture, throat connection, and radius. Then, the effective capillary pressure was modified by describing the thickness of the boundary layer in the micro-nano pore throats. The calculation results show that the existence of a boundary layer in micro-nano throats makes the capillary pressure much larger than those of reservoirs without boundary layer. And the boundary layer reduces the effective flow radius, which dramatically decreases the imbibition quantity. The final result of existence of a boundary layer dramatically weakens the imbibition ability of a tight oil reservoir, and thus, the existence of a boundary layer cannot be ignored. Finally, the effective throat radius limit was analyzed during imbibition in a water-oil-rock system of a tight oil reservoir. Without a boundary layer, the effective radius of the pore throats in the water-oil-rock system during imbibition is greater than 200 nm, which is due to the advantages of the large capillary force and pore throats that are not too small. With a boundary layer, the main radius of the pore throats used for the water-oil-rock imbibition is approximately 400 nm. Thus, the imbibition occurs in the pore throats larger than 200 nm in the water-oil-rock system, and a surfactant could reduce the limit of the throat radius during imbibition in tight oil reservoirs.

KEYWORDS
boundary layer, capillary pressure, imbibition, tight oil reservoirs
1 | INTRODUCTION

Currently, the world's unconventional oil and gas resources can be classified into several types, including shale gas and tight oil. Unconventional oil and gas resources have two key characteristics: the continuous distribution of oil and gas in a large area without obvious boundaries or traps, and lack of a stable natural industrial output, for example, tight oil. The total recoverable tight oil (including shale oil) available in the world is estimated to be $2513 \times 10^8$ tons, constituting approximately 56.8% of the world's unconventional oil resources. The exploration of such unconventional oil resources has significantly improved the production of crude oil in the United States. In many fields, the permeability is as low as 1-10 mD, so traditional recovery methods cannot achieve economic benefits. Hydraulic fracturing has been popularly applied to improve the flow capacity of tight oil reservoirs in recent years. However, problems such as a low recovery factor and high production decline rate have resulted in tremendous amounts of tight oil remaining in the matrix after primary recovery.

Tight oil reservoirs usually require hydraulic fracturing to improve their flow capacity and imbibition. Imbibition is an important recovery mechanism for conventional low permeability reservoirs, which occurs during hydraulic fracturing and development, and has been widely studied. The large surface area open to the imbibition of water in highly fractured reservoirs may result in economic production rates, even in tight oil reservoirs. The spontaneous oil-water imbibition caused by capillary force and gravity during oilfield development was first identified in a study of a bottom water reservoir and a fractured reservoir. Currently, almost all tight oil reservoirs are developed using hydraulic fracturing, during which imbibition occurs between the matrix and the fractures. Zhu et al. analyzed the relationship between the imbibition rate and the matrix-fracture interface location, wettability, and aging time through imbibition experiments and nuclear magnetic resonance (NMR) analyses. Yang et al. studied the factors influencing imbibition, such as mineralogy, pore connectivity, and pore size distribution (PSD). Lai et al. analyzed the effect of the boundary conditions, wettability, temperature, and oil viscosity on water imbibition using NMR. They found that the oil recovery due to water imbibition in an oil-water-rock system is mainly controlled by the capillary force, gravity, and the characteristic length of the core sample. Wang et al. studied the spontaneous and forced imbibition characteristics in tight cores using NMR. Li et al. investigated the dynamic capillary pressure during the displacement process in fractured tight rocks, and the results have shown that the dynamic capillary pressure of the matrix becomes around 5%-20% higher after the fracturing treatment. In tight oil reservoirs, the physical and chemical properties of the pore throats are poor, and the physical and chemical properties of the material on the surface of the pores change due to the small pore-throat size, which makes the fluid interact strongly with the surface of the core channel, and thin layers of fluid are adsorbed on the surface of the pores, thus forming a boundary layer. Cao et al. determined that the boundary layer affects the flow in micro-nano pores, and thus, the boundary layer cannot be ignored during flow research in tight oil reservoirs.

The existence of a boundary layer significantly reduces the seepage space of the fluid in the throat, and thus, it is the main factor restricting fluid seepage. The thickness of the boundary layer is on the nanometer level. Sometimes the boundary layer thickness is almost the same size as that of the effective pore-throat radius of the nanopores. The boundary layer has a significant influence on fluid seepage in tight oil reservoirs. However, previous imbibition research did not consider the effect of a boundary layer in tight oil reservoirs.

In this study, experiments were conducted to study the efficiency of the pores during imbibing through NMR, and the factors affecting imbibition were analyzed, which included the connection area of the matrix-fracture, the throat connection, and the throat radius. Then, the boundary layer was discussed for the imbibition in a water-oil-rock system on the nanoscale. The effective capillary pressure was modified by accurately describing the characteristics of the thickness of the boundary layer in the micro-nano scale throats. It was concluded that the boundary layer decreased the effective flow radius, which dramatically decreased the imbibition rate, and thus, the boundary layer cannot be ignored in the imbibition of tight oil reservoirs. The main effective radius of the throats in a water-oil-rock system during imbibition is greater than 200 nm.

2 | IMBIBITION EXPERIMENTS

2.1 | Experimental setup

The experimental setup includes the following: a Soxhlet apparatus, an NMR instrument (MicroMR12-025V), a precise analytical balance, an incubator, a viscometer, a porosity-permeability measuring instrument, a high-pressure displacement device, a plunger pump, and a glass apparatus.

2.2 | NMR experimental principle

When a tight core sample is placed in a uniform static magnetic field, the hydrogen nuclei in the fluid will interact with the magnetic field to produce a magnetization vector. After applying a Larmor radio frequency field to the tight core in the vertical direction of the magnetic field, a signal with an exponentially decreasing amplitude is produced. The transverse...
relaxation time $T_2$ describes the speed of the signal's attenuation. The core magnetic resonance imaging (MRI) technique can be used to detect the properties of the fluid, the amount of fluid, and the interaction of the fluid with the core wall. This method can be used to directly observe the fluid distribution inside the pores of the tight core without destroying the core's shape. The MRI experiment mainly monitors the hydrogen nuclei within the fluid inside the core's pores. In addition, it uses the strong resonance characteristics between the hydrogen nuclei and the magnetic field to determine the strength of the nuclear magnetic resonance signal of the fluid and the duration of the $T_2$. The fluid in the larger pores is less affected by the core wall's surface, so the relaxation speed is slow and the $T_2$ is long. The fluid in the small pores is relatively strong near the core wall's surface, the relaxation speed is slightly faster, and the $T_2$ is short. MRI can be used to obtain a two-dimensional image of a slice in any direction. The gray signal in the image, or the brightness, reveals the distribution of the fluid in the core. The brighter the gray level, the higher the fluid saturation of the core. Therefore, the total amount of fluid in the core directly affects the strength of the nuclear magnetic resonance signal.

2.3 Experimental materials

The experiment consists of two parts. Part 1 was used to study the influence of rock's permeability, while part 2 was used to investigate the impact of the boundary conditions of the core (single-sided imbibition, double-sided imbibition, and multisided imbibition).

In the first imbibition experiment, two cores with diverse permeability were used. The #1-1 core was a tight sandstone (0.58 mD) with a diameter of 24.96 mm and a length of 52.6 mm. Its porosity and irreducible water saturation were 9.3% and 41.1%, respectively. However, core #1-2 was a conventional low permeability rock (4.98 mD) with a diameter of 25.02 mm and a length of 51.2 mm. Its porosity was 9.6%, and its irreducible water saturation was 34.4%. The parameters are listed in Table 1.

In experiment 2, 6 tight cores were studied. The permeability of each core was measured three times to obtain the average permeability. The average permeability ranged from $0.15 \times 10^{-3} \, \mu m^2$ to $0.21 \times 10^{-3} \, \mu m^2$. Core #2-1 and core #2-2 were used in the single-sided imbibition experiment, core #2-3 and core #2-4 were used in the double-sides experiment, and core #2-5 and core #2-6 were used in the multisided experiment. The basic data for these 6 samples are shown in Table 2. Single-sided imbibition refers to the fact that only one cross section of the core was in contact with the brine, while the other surfaces were wrapped. Double-sided indicates that two cross sections were exposed to the water, and the other surfaces were wrapped. Multisided indicates that all of the surfaces were connected with brine. The schematic of the three modes is shown in Figure 1.

In general, there is a positive correlation between the porosity and permeability of a rock. Low permeability means poor porosity and large seepage resistance. Furthermore, narrow pore throats lead to an increase in the capillary force, which is the kinetic energy of imbibition. The influence of this pair of contradictory factors (higher seepage resistance and higher driving force) caused by low permeability is worth studying.

Based on this analysis, this study was designed to determine the influence of the core's permeability on the seepage efficiency. The parameters are shown in Table 1.

### Table 1: Basic parameters of the imbibition experiment for different permeability

| Core no. | $K$ ($\times 10^{-3} \, \mu m^2$) | $D$ (mm) | $L$ (mm) | $\phi$ (%) | $\mu_o$ (mPa s) | $S_{wi}$ (%) | $\rho_o$ (kg/m$^3$) | $\rho_w$ (kg/m$^3$) |
|----------|-----------------|--------|--------|---------|-------------|---------|-------------|-------------|
| #1-1     | 0.58            | 24.96  | 52.6   | 9.3     | 1.8         | 41.1    | 807         | 1058        |
| #1-2     | 4.98            | 25.02  | 51.2   | 9.6     | 1.8         | 34.4    | 807         | 1058        |

2.4 Experimental procedure

1. Measure the core's geometry, then use the flowmeter to measure the gas permeability of the core under stable conditions.
2. Configure the formation water (heavy water) and the simulated oil, and measure the viscosity, the density of the oil and water, and the oil-water interfacial tension at room temperature.
3. Vacuum the cores, and then, saturate the cores with heavy water under a certain pressure. Then, weigh the cores.
4. Measure the $T_2$ relaxation spectrum at the initial water saturation.
5. Place the core horizontally in the simulated formation water for spontaneous imbibition.
6. Measure the $T_2$ relaxation spectrum every other day and measure the moisture content of the slice every 2 days. Stop the experiment when there is no significant change in the $T_2$ spectrum.
7. Process the experimental data, save the $T_2$ spectrum images, and calculate the imbibition recovery and the imbibition rate.
8. Steps 1, 2, 3, and 5 are required for both experiments (total of 8 cores), while steps 4 and 6 are only used in the second
In experiment (total of 6 cores). In steps 4 and 6, the main parameters of the NMR were set as follows: waiting time of 2.5 seconds, echo spacing of 0.504 ms, and number of echoes 2500.

3 | EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1 | Experimental results

In the first experiment (cores #1-1 and #1-2), the duration of the imbibition was about 7 days. During the experiment, the imbibition data for the two cores were continuously recorded, with the time and relative density collected in the earlier stage. The core imbibition recovery data are compared in Figure 2.

As can be seen in Figure 2A, the imbibition recovery rate of the low permeability core was significantly higher than that of the tight core. The time for the low permeability core to reach the ultimate imbibition recovery was less than that of the tight core.

Figure 2B illustrates the imbibition velocity curves of the two cores at different times. As can be seen in Figure 2, both curves show that the imbibition velocity is high in the earlier stage, and then, it continually decreases to zero. In addition, the initial rate of decline was very rapid because of the oil-water capillary force inside the core in the late stage of imbibition. The imbibition rate of the low permeability core was generally higher than that of the tight core, but the law reverses in the last stage, because the tight core reaches steady-state imbibition first, and the imbibition rate approaches zero.

| Core no. | Weight (g) | Diameter (mm) | Length (mm) | Permeability ($\times10^{-3} \mu m^2$) | Average permeability ($\times10^{-3} \mu m^2$) |
|----------|------------|---------------|-------------|--------------------------------------|--------------------------------------------|
| #2-1     | 66.59      | 25.00         | 52.0        | 0.15                                 | 0.15                                       |
| #2-2     | 59.13      | 25.00         | 50.1        | 0.18                                 | 0.18                                       |
| #2-3     | 65.43      | 25.00         | 53.8        | 0.20                                 | 0.21                                       |
| #2-4     | 80.14      | 25.01         | 62.5        | 0.18                                 | 0.18                                       |
| #2-5     | 67.77      | 24.97         | 58.8        | 0.16                                 | 0.16                                       |
| #2-6     | 59.95      | 25.00         | 51.5        | 0.17                                 | 0.17                                       |

**TABLE 2** Basic rock data for the imbibition experiments with different boundary conditions

**FIGURE 1** Schematic of the three modes
In the second experiment (cores #2-1, #2-2, #2-3, #2-4, #2-5, and #2-6), based on the NMR monitoring of the T2 spectrum, the larger the interval between the T2 lines at different times, the larger the mobilization. The range of the relaxation time corresponds to a certain throat radius, and thus, a certain range of T2 for a change can indicate that the fluid flow occurs in the corresponding pore throats. The pore-throat size grades were classified as follows: 0.001-0.1 ms corresponds to micropores, 0.1-100 ms corresponds to small mesopores, 100-10 000 ms corresponds to mesopores, and 10 000-1 000 000 ms corresponds to macropores.

As can be seen in Figure 3A,B, for single-sided imbibition, there was almost no fluid flow in the small pores and large pores during the imbibition process, only the fluid in the medium pores infiltrated, and the variation between the T2 spectra at different time intervals was small, indicating that the overall fluid utilization was not strong. The final recovery factor was only about 10%-15% (Figure 4).

As can be seen in Figure 3E,F, for multisided imbibition, the imbibition process also occurred in the large pores, while the small pores were hardly used.

Compared with double-sided imbibition, the overall utilization of fluids in multisided imbibition was significantly larger, and the ultimate recovery for multisided imbibition reached about 45% (Figure 4). For single-sided imbibition, the recovery was the lowest, and cores #2-1 and #2-2 were only 13%. As can be seen from the T2 spectrum of the imbibition process, the fluid was mainly stored in the medium pores, small pores, and micropores. For core #2-1, the fluids replaced were mainly from the medium pores. In contrast, the fluids from core #2-2 were more evenly swept within the small and medium pores. The imbibition rate of core #2-1 in the early and middle stages was faster than that of core #2-2 due to the connectivity of the pores. Based on the poor connectivity and the hard seepage in the small and micropores in core #2-1, the imbibition recovery of core #2-1 was mainly contributed by the medium pores. Moreover, the good connectivity of the small pores in core #2-2 resulted in a certain recovery contribution of the small and micropores. However, because the fluid in the small and micropores is difficult to drive, the imbibition rate of core #2-2 was slower than that of core #2-1.

From the imbibition velocity diagram (Figure 5), it can be seen that for single-sided imbibition, the initial imbibition rate was 2%-5%/day. For double-sided imbibition, the rate was 5%-7%/day and decreased rapidly. For multisided imbibition, the imbibition rate was 4.5%-6%/day, and the rate of decline was the slowest of the three cases. During imbibition, core #2-5 exhibited a step-like decrease, while core #2-6 exhibited a fluctuating phenomenon, which was caused by its complex pore structure.

The Figure 6 shows the distribution of the residual oil saturation for the different pore radius ranges of core #2-1, #2-2, #2-3, #2-4, #2-5, and #2-6. As shown in Figure 6, for core #2-5, the imbibition velocity during the first 20-30 days was mainly contributed by the small and medium pores (100-10 000 ms). The decrease in the rate indicates that the small and the medium pore throats had a poor throat structure, which is unfavorable for imbibition. For core #2-6, the imbibition rate increases during days 10-20. During this period, the imbibition was mainly provided by the small and medium pore throats (1000-10 000 ms). The increase in the rate indicates that the 1000-10 000 ms throats are well connected, which is beneficial to imbibition.

### 3.2 Discussions of the effect of the boundary layer

The experimental data show that the imbibition rate is related to the connection area of the matrix-fracture, the throat
connection, and the throat radius. The main effective range of the pores involved in the imbibition is above 200 nm, and it could be determined from the NMR analysis. However, several previous studies have reported that imbibition contributes more recovery when the pores are smaller. We suggest that there is a lower pore-throat radius limit for effective imbibition. The pore-throat radius limit for effective imbibition could be affected by the boundary layer. However, little research has been conducted to determine the effect of the boundary layer on imbibition.

Microscale tube experiments were used to study the characteristics of the boundary layer. The principle of the theory is to obtain the theoretical flow of deionized water in a microcircular tube based on the Poisson equation and to compare

**FIGURE 3** Nuclear magnetic resonance monitoring of the T2 spectrum during the imbibition process
the calculated results with the experimental measurements to prove the existence of the boundary layer. Based on the analysis of the effect factor on the thickness of the boundary layer, the expression of the boundary layer thickness is:

$$h = \begin{cases} r \cdot 0.25763 e^{-0.261r(\nabla P)^{-0.419}} \cdot \mu, & \nabla P < \frac{1 \text{ MPa}}{m} \\ r \cdot 0.25763 e^{-0.261r} \cdot \mu, & \nabla P > \frac{1 \text{ MPa}}{m} \end{cases}$$

(1)

The thickness ratio of the boundary layer in a single tube is exponentially related to the radius of the tube, and it has a linear relationship with the fluid viscosity. The pressure gradient is exponentially correlated with the pressure gradient when the pressure gradient is less than 1 MPa/m; and it is almost invariable when the pressure gradient is greater than 1 MPa/m.

For ordinary spontaneous imbibition, the only driving force of the fluids is capillary pressure because the viscosity barely changes. This study mainly focused on the effect of the tube radius (Figure 7). As shown in Figure 8, a new expression was used to characterize the effect of the boundary layer.

$$h = r_{ori} \cdot 0.6827 e^{-0.2668r_{ori}}$$

(2)

The expression of the effective capillary radius is:

$$r_{eff} = r (1 - 0.6827 e^{-0.2668r})$$

(3)

Capillary pressure acts as the driving force of spontaneous imbibition, and it dominates the imbibition ability in tight oil reservoirs. The existence of a boundary layer significantly decreases the effective radius of the micro- or nanosized throats (Figure 8). The radius in the conventional expression for capillary pressure cannot be used to characterize the actual radius of the capillary tubes. In this study, the traditional original radius of the throats was modified as the effective radius in order to take the boundary layer into consideration.

$$p_c = \frac{2\sigma \cos \theta}{r}$$

(4)

After introducing the effective radius, compared with a conventional low permeability reservoir, the capillary pressure calculated for the effective throats is much larger than the capillary pressure calculated for the original throats. This larger capillary pressure promotes imbibition flow; however, because the effective radius is smaller than that of the original throats, the space for the fluids to flow is also reduced, and the reduced flow space restrains the imbibition flow. Thus, the relationship between the opposite effects of these two factors is clear, which is very crucial to understanding imbibition in tight oil reservoir.

4 | CAPILLARY TUBE MODEL

4.1 | Establishment of the capillary tube model

For tight porous media, the distributions of the distribution of the pores and throats are complex, and the idealized homogeneous capillary tube model cannot accurately describe this complex distribution. The radius of the distributions of the pores and throats obtained from numerous air-mercury experiments is shown in Figure 9.

Based on the analysis of the distribution of the pores and throats, the normal distribution can be used to describe the real radius distribution of the pores and throats of the tight core (Figure 10).

$$f(r_i) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(r_i - \mu)^2}{2\sigma^2}\right)$$

(6)

In this study, we used the normal distribution to build the bunches of the capillary bundle models. These models can be divided into 2 categories. The first category contains

FIGURE 5 Imbibition rate diagram
3 models. Each model has a different standard deviation ($\sigma = 0.05, 0.15, 0.25$), and the models in the first category do not consider the existence of a boundary layer. The second category is based on the first category, but the second category does consider the existence of a boundary layer (Figure 11A,B). When considering the existence of a boundary layer, the median radius of the first category changes from 0.5 μm to 0.239 μm.

4.2 | Capillary imbibition characteristic analysis

4.2.1 | Single tube imbibition characteristic analysis

Equations (3) and (5) were used to calculate the effective capillary tube radius and the capillary pressure,
respectively. Based on the radius, the capillary pressure, and the Poiseuille equation, the relationship between the imbibition rate and the capillary pressure and the effective flow space was analyzed. Assuming that the radius of the capillary tube ranges from 50 nm to 1000 nm, the interfacial tension is 30 mN/m, and the wettability angle is 30°, we compared the capillary tube radii and the capillary pressure with and without a boundary layer (Figures 12 and 13).

During the small radius range, the capillary pressure for the case with a boundary layer is much bigger than that for the case without a boundary layer. This phenomenon demonstrates that the boundary layer has a significant effect for small radii. However, for large radii, the capillary pressure is not as obvious as it is for the small throats.

Further study of the flow rate revealed that the imbibition rate of the capillary bundle model without a boundary layer can be expressed by Equation (7). After replacing the original tube radius with the effective tube radius, the imbibition rate of the capillary tube with a boundary layer can be expressed by Equation (8).

\[ v = \frac{r \sigma \cos \theta}{4\mu l} \]  \hspace{1cm} (7)

\[ v_{\text{eff}} = \frac{r_{\text{eff}} \sigma \cos \theta}{4\mu l} \]  \hspace{1cm} (8)

Values of the viscosity and imbibition distance were set as 1 mPa s and 0.1 m, respectively. In addition, a comparison of the capillary imbibition velocity curves with and without a boundary layer is shown in Figure 14. The imbibition rate of the original capillary tube is always larger than that of the rate of the effective capillary tube radius, and as the radius of the original capillary tube increases, the difference in the imbibition rates increases. At the end of the curve, the imbibition rate of the effective radius is approximately half that of the original radius.

Similarly, the conventional capillary rate in Equation (9) was obtained by combining the Poiseuille equation and the capillary pressure equation and by modifying the effective
radius. The effective imbibition quantity expression is expressed by Equation (10).

\[ q = \frac{\pi r^4 \Delta p c}{8\mu l} = \frac{\pi r^3 \sigma \cos \theta}{8\mu l} \]  

(9)

\[ q_{eff} = \frac{\pi r_{eff}^4 \Delta p'_c}{8\mu l} = \frac{\pi r_{eff}^3 \sigma \cos \theta}{8\mu l} \]  

(10)

A comparison of the imbibition with and without a boundary layer is shown in Figure 15.

Figure 15 illustrates that the difference in the imbibition rates of the effective radius and the original radius increases as the radius increases; and the imbibition rate without a boundary layer is always bigger than the imbibition rate with a boundary layer. At the end of the comparison curve, the imbibition rate with a boundary layer is only 1/8 that of the imbibition rate with a boundary layer.

The comprehensive analysis shows that the imbibition rate and the imbibition flow with a boundary layer are much smaller than the imbibition rate and flow for the case without a boundary layer, which demonstrates that the imbibition effect in an ultralow permeability reservoir is much smaller than that in a conventional reservoir.

4.2.2 Imbibition characteristic analysis of the matrix block

Based on the normal distribution of the pore and throat radii, a bundle capillary model was used to represent the matrix
block, with a flow quantity obtained by summing all of the values for all of the tubes in the capillary bundle model. A comparison of the accumulate flow with and without a boundary layer is shown in Figure 16.

Figure 16 shows that the accumulated flow of the model without a boundary layer is much larger than that of the model with a boundary layer. This demonstrates that the smaller the effective flow space, the weaker the imbibition.

Based on the accumulated quantity curve, we analyzed the main flow (Figure 17). Figure 17 shows that without a boundary layer, the largest contribution is made by the 400-600 nm region. However, with a boundary layer, the largest contribution is made by the 200-350 nm region. Compared with the capillary bundle model without a boundary layer, the main flow region is shifted left. This demonstrates that imbibition mainly occurs in a certain range of the capillary radius of the core, and nearly 90% of the imbibition flow is concentrated in this area. If the effective pore and throat radii are not within this main area, there is no imbibition in these throats.
corresponding radius of the original capillary is 480-780 nm. The modeling analysis and NMR test show consistent results. Thus, the radius of the mainstream pore throats is shifted rightward. Under the conditions of tight formation reservoirs, imbibition mainly occurs in large channels.

5 | CONCLUSIONS

1. Imbibition plays an important role in tight oil sandstone reservoirs. The imbibition rate is related to the connection area of the matrix-fracture, the throat connectivity, and the throat radius.

2. Imbibition is also affected by the boundary layer, and the boundary layer significantly changes the capillary force and the effective flow space in the nano-micro pores. A new equation for the capillary force was derived and the effective radii of the pores were described for the case with a boundary layer. The boundary layer was found to have a significant effect on imbibition, and the presence of a boundary layer was found to weaken imbibition.

3. For the case without a boundary layer, the effective radius of the pore throats in water-oil-rock imbibition is greater than 200 nm due to the advantages of a large capillary force and pore throats that are not too small. For the case with a boundary layer, the main effective radius of the throats in water-oil-rock imbibition is about 400 nm in a tight formation. Thus, imbibition occurs in water-oil-rock systems with throats larger than 200 nm, and a surfactant could reduce the limit of the throat radius for imbibition in tight oil reservoirs.

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NOMENCLATURE

\( h \) \hspace{1cm} \text{thickness of the boundary layer (μm)}
\( r \) \hspace{1cm} \text{radius of tube (μm)}
\( \mu \) \hspace{1cm} \text{viscosity (mPa s)}
\( \nabla P \) \hspace{1cm} \text{pressure gradient (MPa/m)}
\( r_{ori} \) \hspace{1cm} \text{original tube radius}
\( r_{eff} \) \hspace{1cm} \text{effect radius}
\( f(x) \) \hspace{1cm} \text{throat distribution frequency, fraction}
\( \sigma \) \hspace{1cm} \text{standard deviation of the pores and throats}
\( \nu \) \hspace{1cm} \text{radius of median value (μm)}
\( \nu \) \hspace{1cm} \text{imbibition rate of the capillary tube for the original tube radius (m/s)}
\( \nu_{eff} \) \hspace{1cm} \text{imbibition rate of the capillary tube for the effective tube radius (m/s)}
\( r \) \hspace{1cm} \text{original capillary tube radius (nm)}

\( \sigma \) \hspace{1cm} \text{oil-water interfacial tension (mN/m)}
\( \theta \) \hspace{1cm} \text{wettability angle}
\( \mu \) \hspace{1cm} \text{oil phase viscosity (mPa s)}
\( l \) \hspace{1cm} \text{distance of imbibition in a single tube (m)}

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