

## Research Article

# Effect of Dynamic Imbibition on the Development of Ultralow Permeability Reservoir

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To explore the methodology for improving ultralow permeability reservoir recovery, cores of ultralow permeability reservoirs in China's Ordos Basin were selected to study the dynamic imbibition micromechanism of crude oil in nanopore throat through core-flooding laboratory experiment and nuclear magnetic resonance (NMR) observation. In the meantime, the microimbibition characteristics and dynamic discharge of oil between matrix and fracture in partially closed boundary reservoirs were simulated to utmostly reflect the actual reservoir conditions. Our findings suggest that dynamic imbibition between fracture and matrix serves the core technology for improving the recovery of ultralow permeability reservoirs, while the main factors affecting dynamic imbibition efficiency include wettability, permeability, injection rate, fracture, water huff and puff cycles, and soaking time. Wettability, in particular, weighs the most, and imbibition can take place either on water-wet rocks or transformed oil-wet rocks with an imbibition agent added in during the waterflooding process. Meanwhile, the higher the permeability is in place, the greater the dynamic imbibition recovery might achieve. The experiments indicate that the dynamic imbibition recovery of a fractured core is 16.26% higher than that of a nonfractured core. Additionally, fractures can not only enhance imbibition recovery but also accelerate the occurrence of dynamic imbibition. The optimal water injection rate of dynamic imbibition is 0.1 mL/min; the reasonable huff and puff cycle of the ultralow permeability reservoirs tends to be two to three cycles; the optimal soaking time of ultralow permeability reservoir is speculated to be 30 days. Finally, the field practice shows that after Stimulated Reservoir Volume (SRV) and dynamic imbibition in 5 horizontal wells in An83 oilfield, there is a remarkable drop in water cut and a noticeable rise in oil production. This research underpins the significance of a dynamic imbibition effect in the development of ultralow permeability oilfield.

## 1. Introduction

As an important unconventional reservoir, ultralow permeability reservoir has emerged as a new “sweet spot” in recent years, drawing extensive attention. China has vast reserves of ultralow permeability reservoirs mainly located in Ordos, Songliao, Junger, and Qaidam basins and has huge untapped potential [1, 2]. Ultralow permeability reservoirs, known as reservoirs with permeability ranging from 0.1 to  $1 \times 10^{-3} \mu\text{m}^2$ , are hugely tight and high in irreducible water saturation, which basically mean there is no natural production capacity [3, 4]. Oil exploitation in the matrix is hardly attainable since

injected water tends to flow along the large fractures as a result of small pore throat and fracture development in the reservoir. The resultant multidirection water breakthrough makes water injection ineffective, and the pressure system is difficult to establish. The development effect is, therefore, not desirable with the oil recovery normally below 15% [5–10].

In previous fracturing techniques, the small-scale fracturing operation produces only a limited number of fractures; therefore, the imbibition effect on oil recovery is not obvious [11]. However, in ultralow permeability reservoirs, the complex fracture system increases the contact area between fracture and matrix, and the nanoscale pore throat boasts the

capillary force, which help improve the imbibition volume and imbibition velocity [12–14]. The imbibition between fracture and matrix, therefore, is accepted as an effective method for improving the recovery of ultralow permeability reservoirs [15, 16].

In recent years, some scholars have studied the displacement mechanism [17, 18], mathematical model, and influencing factors of static imbibition through laboratory experiments and numerical simulation [13, 19–22]. The influences of static imbibition on the development of low permeability reservoirs and tight oil reservoirs are elaborated [23–29]. Mattax and KYTE pointed out that imbibition is the main mechanism of oil recovery in fractured waterflooding reservoirs [14]. Li et al. studied hydrophile cores' spontaneous imbibition experiments of low-permeability and showed that chemical injection can reduce the interfacial tension between oil and water and transform the remaining oil into mobile oil, thus improving the ultimate recovery factor [30]. Research findings of Morrow and Xie reveal that the oil displacement efficiency is the highest when the wettability is neutrally and slightly water wet [31]. Zhu et al. calculated and analyzed the mathematical model and concluded that there was an optimal displacement velocity for the water-wet dual media model [32]. Yu et al. pointed out that the imbibition process of tight sandstone is mainly a process of small pores absorbing water and large pores discharging oil, while the oil production degree in small pores is much higher than that in other pores (Yu Fuwei et al., 2015). However, in previous indoor full open boundary core imbibition experiments, the crude oil recovery turns out to be upwards of 50%, a substantial deviation from the actual field situation. There are still limited studies on dynamic imbibition in ultralow permeability reservoirs with fracture development or SRV, and the microscopic mechanism of dynamic imbibition displacement and influencing factors of crude oil in nanopore throat are not yet clearly understood. Therefore, the dynamic drainage and imbibition characteristics of crude oil in matrix and fracture remain to be explored. Ultralow permeability reservoirs have dual-porosity media with matrix and fracture, with boundary conditions affecting the connectivity of porous media and determining the channel of capillary force. In this paper, one flow unit in the dual media: matrix and fracture, was selected to make a partially closed boundary core model to simulate the microimbibition characteristics, dynamic discharge of crude oil in matrix and fracture, and the microinteraction mechanism of imbibition in the dual media. Our experimental results are applicable to field production, lending theoretical support to the establishment of a field production system.

## 2. Dynamic Imbibition Mechanism

Ultralow permeability reservoirs are typical dual-porous media comprised of matrix and fractures, with the matrix serving as the main storage space for oil and the fractures the primary flow channels. As is known, the permeability and flow capacity of high fractures are higher than that of matrix, while the capillary force is positively associated with impermeable media. As can be seen from the equation defini-

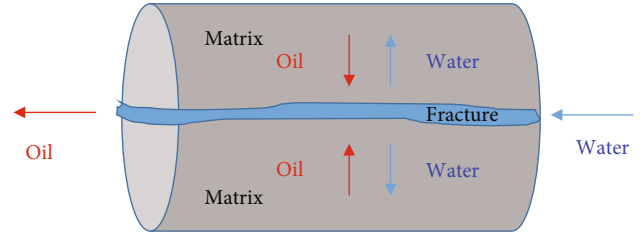


FIGURE 1: Diagram of oil and water exchange between fracture and matrix.

tion of capillary force (Equation (1)), the smaller the pore radius, the larger the capillary force. Ultralow permeability reservoirs feature low porosity and small pore radius, which lead to large capillary force and strong imbibition, and thus, ultralow permeability reservoirs are fit for enhanced oil recovery.

$$p = \frac{2\sigma \cos \theta}{r}, \quad (1)$$

where  $p$  is the capillary force,  $\sigma$  is the interfacial tension,  $\theta$  is the contact angle, and  $r$  is the capillary radius.

Under reservoir conditions, the course of imbibition amid the water injection operation is called dynamic imbibition. Imbibition and displacement coexist in the dynamic imbibition process. The injected water flows along the main fracture by displacement, while water in the fracture displaces oil in the matrix through capillary force. The oil is displaced into the fracture and then further expelled through injected water in fracture channels. The whole process of dynamic imbibition is shown in Figure 1.

## 3. Experimental Methods

In this paper, the imbibition law and characteristics of dynamic imbibition in ultralow permeability reservoirs are studied by the laboratory test and nuclear magnetic resonance method, and the influence of wettability, permeability, injection rate, and other factors on imbibition efficiency is analyzed. Outcrop cores and crude oil are collected from Changqing oilfield in China's Ordos Basin, and the basic sample characteristics and description are summarized in Table 1. To simulate the formation conditions, the testing formation temperature is set to 67°C, the crude oil viscosity is 2.38 mPa·s, and the formation water salinity is 57252 mg/L. The dynamic imbibition is simulated by periodic water injection. The testing formation water is intermittently injected into the core, and this process sustains until the core is entirely water-imbibed. In the meanwhile, the crude oil in the matrix firstly is relocated into large pores and fractures and then exploited through waterflooding displacement. With the application of NMR, the oil-water distribution and residual oil distribution in the dynamic imbibition process have been visualized and analyzed. Most importantly, the main influencing factors of imbibition efficiency are determined, and key parameters affecting production, such as soaking time, injection speed, and water huff and puff cycles, are explored for ultralow permeability reservoirs.

TABLE 1: Basic parameters of testing cores.

Sample	Permeability (mD)	Porosity (%)	Wettability
7042-08	0.61	12.17	Weak water-wet
7042-07	0.69	11.8	Weak water-wet
7042-06	0.7	12.07	Weak water-wet
7042-03 (with fracture)	0.7	12.2	Weak water-wet
5-1	0.32	11.96	Oil-wet
5-2	0.52	12.07	Oil-wet
5-3	0.52	11.08	Oil-wet
2-5-2	0.31	12.31	Weak water-wet
2-12 (with fracture)	0.25	10.01	Weak water-wet
2-2	0.3	11.77	Weak water-wet
2-1	0.21	10.1	Weak water-wet
2-3	1.52	11	Weak water-wet
2-4	8.16	16.1	Weak water-wet

**3.1. Experimental Apparatus.** The experimental apparatus mainly covers apparatus for vacuum saturation, dynamic imbibition (Figure 2), and nuclear magnetic resonance (Figure 3). The dynamic imbibition apparatus shown in Figure 2 consists of (a) Quizix 5000 series high-pressure precise displacement pump produced by Chandler, America, (g) an automatic pressure collection system, and (d) a core gripper. Also applied in this study is an SPEC-023 NMR apparatus developed by Beijing Spike Technology Development Co., Ltd.

NMR is introduced to study the oil-water distribution in rock cores. The NMR technique is usually applied to characterize the pore structure in the core by measuring the transverse relaxation time of H atom in liquid. The larger the pore radius, the smaller the binding degree of H atom, and the longer the relaxation time. Therefore, the relaxation time of H atom is positively correlated to the pore radius, while the strength of the signal value is directly proportional to the amount of liquid containing H atom. Therefore, an interpretation of oil-water distribution in pores of ranging size is attainable based on the aforementioned correlations. To differentiate oil from water via NMR technology, we use heavy water ( $D_2O$ , without H atom) and crude oil (containing H atom) in the experiment.

**3.2. Dynamic Imbibition Recovery Measurements.** To follow the testing regulations of the physical simulation experiment of oil displacement as required by the Chinese industry standard SY/T 6424-2014 and also achieve the experimental objective of optimizing imbibition parameters, we formulate the testing protocols as follows, it is shown in Figure 4:

- (1) Two cores (2-12, 7042-03) were selected to create artificial fractures, and the fracture direction was  $44^\circ$  to the core axial direction. Then, the cores were dried in an oven of  $105^\circ C$  for 4 hours till the mass weight became constant
- (2) The dried cores were mounted into the core holder; then, the simulated formation water was injected

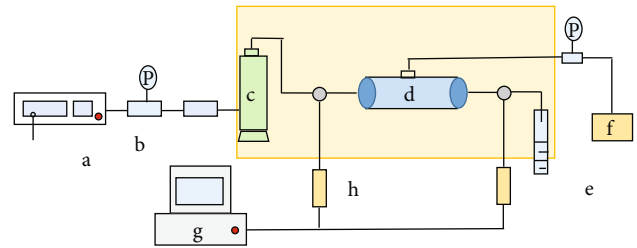


FIGURE 2: Schematic diagram of dynamic imbibition experimental apparatus. (a) High-pressure precise displacement pump, (b) pressure gauge, (c) high-pressure piston container, (d) core gripper, (e) constant temperature system, (f) hand pump, (g) automatic pressure collection system, and (h) pressure transducer.



FIGURE 3: SPEC-023 NMR apparatus.

into the intermediate container. Vacuumize the core holder and intermediate container simultaneously until the vacuum degree reached  $-0.1^\circ C$  and remained at this level for upward of 4 hours. The vacuum pump was then shut down, and the water valve was opened concurrently. The core pore would be fully imbibed with simulated formation

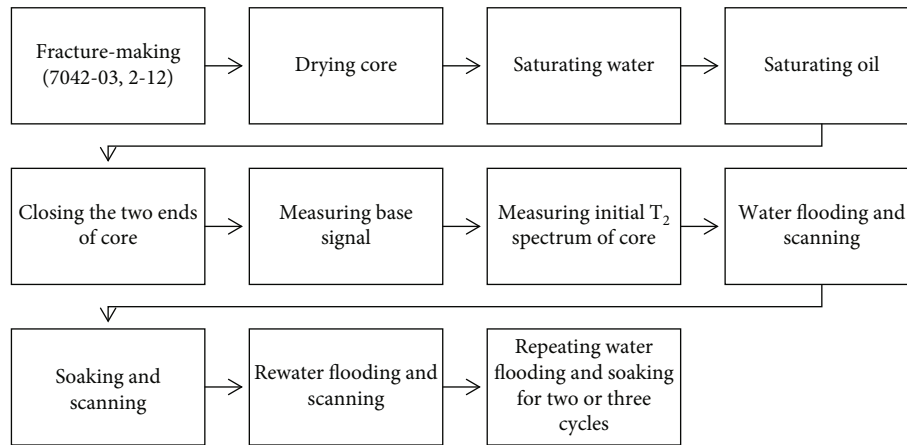


FIGURE 4: A workflow diagram.

water under the action of pressure difference between atmospheric pressure and vacuum negative pressure. Finally, the porosity of testing cores is being calculated by the mass difference method

- (3) The cores were saturated with oil via oil displacement. To create the irreducible water saturation, the displacement of oil quantity is set at about 60-80%, and the displacement oil quantity is controlled according to the displacement water quantity
- (4) The cores were sealed with epoxy resin glue at both ends. During the process, other surfaces of the cores were sealed with plastic wrap to prevent oil phase volatilization, and the strength was reached after the glue was solidified
- (5) Heat the gripper up until the temperature of the target formation stabilizes and measure the  $T_2$  signal as the base signal of the system
- (6) The saturated oil core was placed inside the gripper, which is part of the displacement device and was located in the testing position of the NMR equipment
- (7) Heat the core for five minutes until it stabilizes at the target temperature and measure the oil phase  $T_2$  signal as the initial  $T_2$  spectrum of the core
- (8) Waterflooding at a constant speed of 0.01-0.3 mL/min. In the process of displacement, set the scanning interval as 3 min and the scanning time as 2 min 45 s to obtain  $T_2$  spectra and MRI images at different times. Measure continuously until the oil confidence signal stabilizes, which suggests the waterflooding ceases
- (9) To maximize the imbibition effect, keep the temperature and pressure constant for more than 48 hours and measure continuously through scanning until the oil confidence signal stabilizes, which suggests the end of soaking

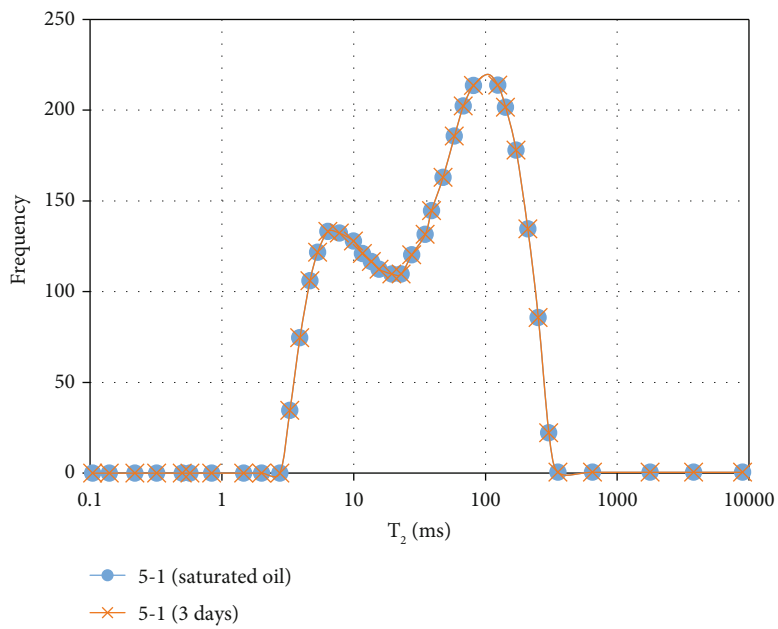
- (10) When imbibition ceases to occur, keep water drive in operation at a constant speed until the oil confidence signal stabilizes

- (11) Repeat steps (8)-(10) for two to three cycles depending on the core conditions

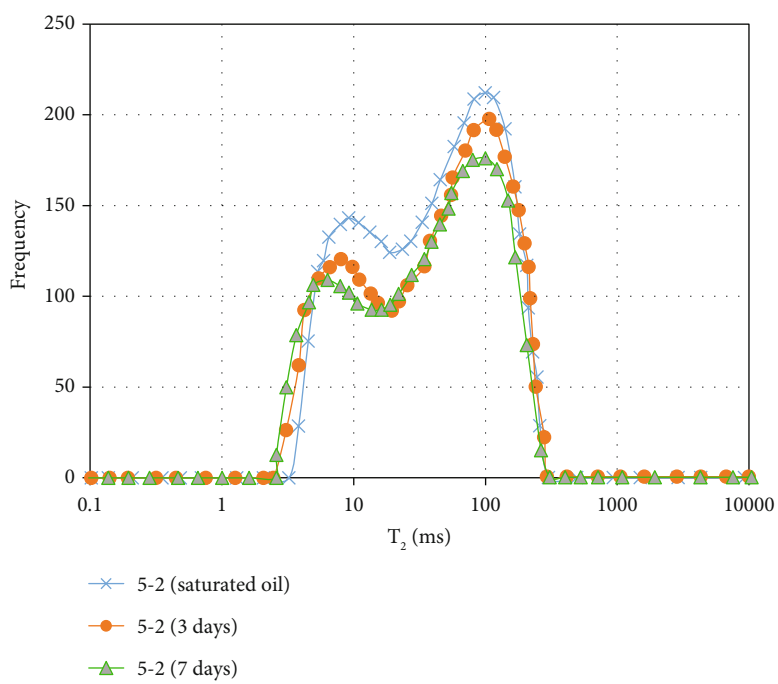
## 4. Results and Discussion

**4.1. Wettability.** Wettability is one of the major factors affecting imbibition. As listed in Table 1, the three testing cores of 5-1, 5-2, and 5-3 are all oil-wet rock samples. As required by the experiment design, the formation water was injected into sample 5-1 as a control group, and results showed that the dynamic imbibition recovery was 0% with formation water only (Figure 5), indicating that oil-wet rocks do not involve any imbibition. In order to compare the influence of wettability on imbibition efficiency, anionic surfactant-CS124 (concentration 0.1%) and nonionic surfactant-JO2 (concentration 0.1%) were added into formation water and injected into samples 5-2 and 5-3, respectively. The core turns out to be water-wet (Figure 6). The experiment results (Figure 6) and NMR (Figure 5) show that the dynamic imbibition phenomenon can take place in the oil-wet core once the rock wettability is switched with the import of the imbibition agent. It is shown in Figure 7 that the imbibition efficiency has been tremendously enhanced with the addition of the imbibition agent, and there is a huge boost in the initial recovery at the preliminary stage of imbibition. After 5 hours, the imbibition recovery is increased by 6%-7%. The imbibition recovery stabilizes after 168 hours with the final recovery reaching up to 7-10%. This shows that imbibition mainly occurs at the initial stage, with 55%-75% of the imbibition process completed in the first 50 hours. The imbibition recovery rate is characterized by an upward trend of fast rising-stable-rising again-stable. Furthermore, both of the imbibition agents proved quite effective in enhancing the oil recovery.

To facilitate the classification of pore size in the paper, the pores with relaxation time of 0.1-10 ms are defined as small pores, 10-80 ms pores medium pores, and 80-100 ms pores macropores. The outcomes of NMR curves in Figure 7 show



(a)



(b)

FIGURE 5: Continued.

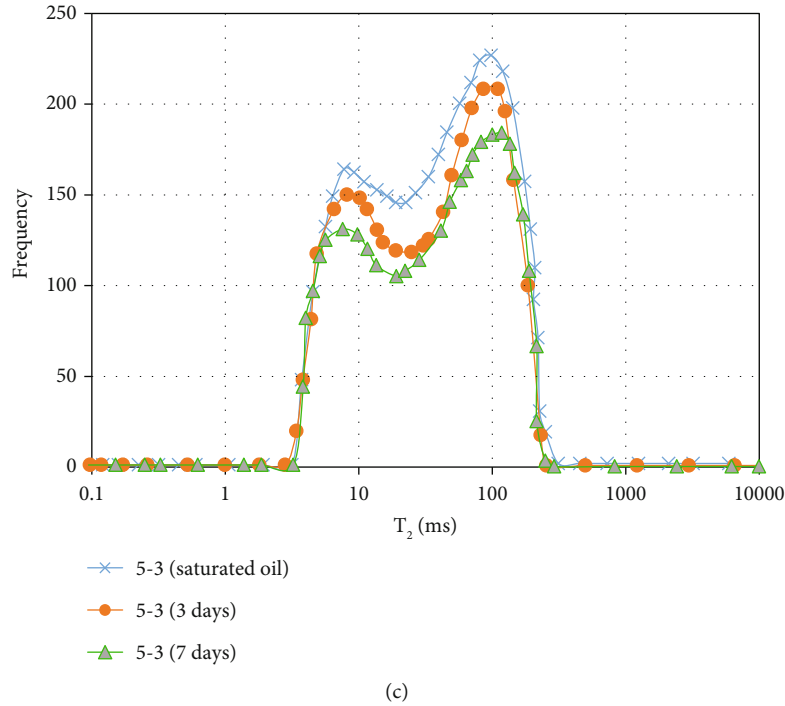


FIGURE 5: NMR scanning results for 5-1 (a), 5-2 (b), and 5-3 (c).

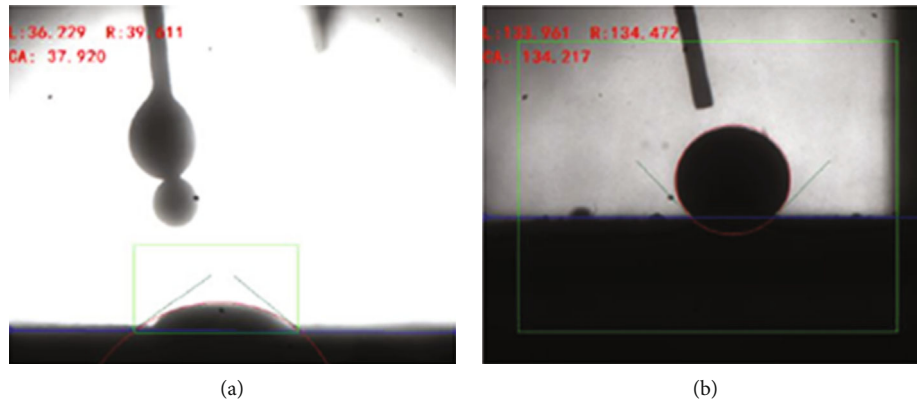


FIGURE 6: The wetting angle (a) predding imbibition agent and (b) postpadding imbibition agent.

that  $T_2$  frequencies of the three samples are typical bimodal types after oil saturation; in particular, the  $T_2$  peak frequency located at a larger pore range shows that more crude oil appears to be saturated in the macropores of testing cores. The NMR scanning curve of the oil-wet core remains constant, which is indicative of the fact that there is no variation in oil-water distribution and no imbibition has occurred. The amplitude of the NMR scanning curve of the water-wet core decreased, and the decline of the small pore curve was even steeper, indicating that there was a drop in oil phase content in both macropores and small pores, but the drop in the latter appeared to be more significant with imbibition occurring mainly in small pores.

For water-wet rock, capillary force is the major driving force for displacement, while the capillary is the resistance force for oil-wet rock. Thus, as far as the water-wet rock is

concerned, the greater the capillary force, the stronger the driving force and the higher the imbibition efficiency. As the capillary force has a strong imbibition effect for ultralow permeability reservoirs in oil recovery, applying the imbibition effect for enhanced oil development is unprecedentedly promising not only for the water-wet ultralow permeability reservoirs but also for oil-wet reservoirs. Thanks to wetting inversion, oil-wet reservoirs can change their wettability type with an importing imbibition agent (Figure 8). With the help of an imbibition agent, the capillary force can be switched from resistance to driving force, which helps realize the imbibition oil recovery in oil-wet reservoirs.

**4.2. Permeability.** Three weak water-wet cores, e.g., samples 2-1, 2-3, and 2-4, were selected to explore the influence of rock permeability on the imbibition effect. Three cores, with a



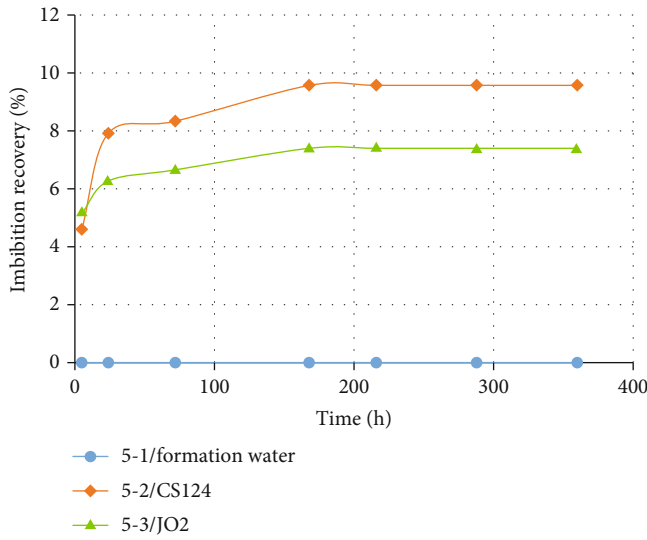


FIGURE 7: Oil-wet core imbibition recovery.

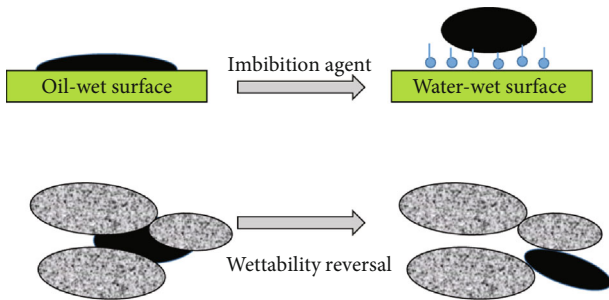


FIGURE 8: Schematic of wettability reversal mechanism for enhanced oil recovery (EOR).

permeability of 0.21 mD, 1.52 mD, and 8.16 mD, respectively, were mounted into the dynamic imbibition experimental apparatus at the testing preparation stage. Then, the drive water was pumped into the core holder continuously for more than 100 h at a constant speed of 0.1 mL/min; meanwhile, the amount of imbibition oil was properly metered. As shown in Figure 9, in terms of the whole dynamic imbibition course, the degree of imbibition and recovery increased with the increment of permeability. The imbibition of 2-1 (0.21 mD) mainly occurred between 20 and 50 h, with 56% of the imbibition completed, and no imbibition occurred after 50 h. The imbibition of 2-3 (8.16 mD) mainly occurred between 0 and 10 h, with 76% of the imbibition completed, and no imbibition occurred after 32 h. Therefore, with the increase of core permeability, the trigger of imbibition and its corresponding time duration of reaching imbibition balance tend to be faster. More importantly, the imbibition recovery improves with enhancement in permeability, as indicated by the imbibition curves in Figure 9. This is because the dynamic imbibition has two main functions: reverse imbibition and displacement, with the former basically involving two processes: water suction and oil discharge. For the testing water-wet cores, the larger the rock permeability is, the lower the starting pressure and seepage resistance of oil are, which is more beneficial for oil drainage. At the same time, the stronger the displacement

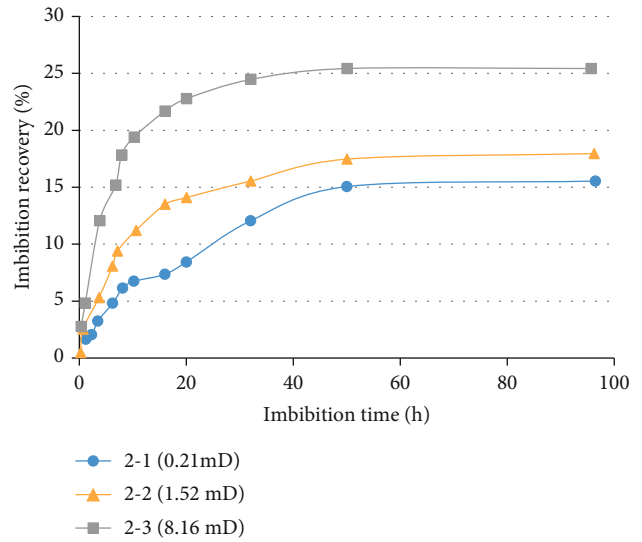


FIGURE 9: Influences of permeability on imbibition recovery.

is, the higher the degree of imbibition will be. Therefore, there is a significantly positive correlation between the permeability of the core and the imbibition recovery, which illustrates the more permeable rock appears to achieve much greater recovery rate and shorter imbibition balance time.

**4.3. Injection Rate.** The impact of injection rate on core imbibition efficiency was studied in this paper by setting variable injection rates. Specifically, the injection rate at 0.01, 0.03, 0.1, and 0.3 mL/min, respectively, has been tested, respectively. The results show that  $T_2$  is positively proportional to the pore size, with  $T_2$  increasing with rising pore size and decreasing with falling pore size [33]. Therefore, the size of  $T_2$  can be used to characterize the pore size. For this block, according to the NMR curve in Figure 9, the pores with  $T_2$  smaller than 10 ms are defined as small pores, and those with  $T_2$  greater than 80 ms are defined as macropores and fractures. Apart from the total recovery rate, by calculating the amplitude changes in a series of  $T_2$  curves, the oil saturation of the core pore is to be calculated, and the imbibition recovery of different pores at different injection rates is carried out at the same time, and the corresponding testing results are shown in Figure 10.

The experimental results show that with the increase in injection rate, the total imbibition recovery first goes up and then drops when an injection rate is at 0.3 mL/min (Figure 10). Of all the four injection rates, the imbibition recovery achieves the highest total recovery rate, namely, 15.5%, when the injection rate is at about 0.1 mL/min. The blue small pore recovery bars illustrate that for small pores with  $T_2$  less than 10 ms, the recovery shows a negative correlation with the injection rate: the larger the injection rate and the lower the small pore recovery rate. For large pores and fractures with  $T_2$  greater than 80 ms, the larger the injection rate, the greater the recovery as shown by the orange bars in Figure 10. The laws of correlation between recovery and injection rate shown above can be explained as that, in the dynamic imbibition, the oil in large pores and fractures is

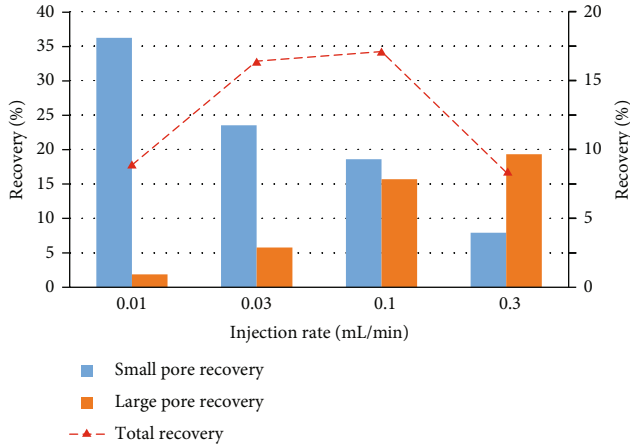


FIGURE 10: Impact of injection rates on recovery.

mainly discharged by displacement, while the oil in small pores is first displaced into the large pores and fractures by capillary force and then discharged by displacement. The high injection rate is able to generate a large pressure difference and a strong displacement in cores; thus, the high injection water phase enters the large pores and fractures, which in turn improves the recovery of large pores. At the same time, the velocity of fluid flowing through large pores and fractures is also increased; however, the chance of water entering small pores through capillary force is reduced. The recovery of small pores is, therefore, reduced. When the injection rate exceeds 0.1 mL/min, accelerating the injection rate will only speed up oil recovery but will not improve the ultimate recovery. Given this, an excessively high injection rate only improves the oil recovery rate and carries water phase rapidly through fractures and large pores, but the benefit to the imbibition in small pores is not obvious. An excessively low injection rate will reduce the oil recovery rate and the production efficiency. In summary, to achieve the best development effect, it is of great significance to find an appropriate injection rate to strengthen the imbibition effect controlled by capillary force and the displacement controlled by pressure difference, and fully taking into consideration of different oil recovery mechanisms is of importance.

**4.4. Fracture.** Fractures have great influence on the matrix recovery, and a fracture-matrix model was made artificially to explore the influence of fractures on imbibition recovery. Other four weak water-wet core samples, labelled as 7042-08, 7042-07, 7042-06, and 7042-03 (fracture), respectively, were prepared for comparative imbibition tests, 7042-03 was artificially fractured by core cutting machine, and the fracture was  $44^\circ$  to the core principal axis. After the cores were saturated with oil by the previous method, 7042-03 was poured with encapsulation glue and put aside for 24 h. Then, the dynamic imbibition experiment was carried out on four cores. The cores were continuously watered at a constant speed of 0.1 mL/min until the water content was more than 98%. As shown in Table 2, the experimental results show that the dynamic imbibition recovery of the fractured core is significantly higher than that of cores without fractures. This mainly

TABLE 2: Contrast of imbibition between fractured core and matrix core.

Sample	Fracture	Increment of oil recovery
7042-08	No	0.59
7042-07	No	14.69
7042-06	No	12.71
7-42-03	Yes	29.96

accounts for the more complex heterogeneity contributed by fractures. The prefractures can not only enhance water absorption in small pore channels but also improve oil discharge in large pore channels and fractures, which work together to reinforce the imbibition effect. Fractures can strengthen reservoir heterogeneities and improve imbibition recovery. In the meantime, the complex fractures are also advantageous for increased contact area of oil and water and the seepage passage of oil, which consequently reduce the oil discharge resistance and improve the imbibition efficiency. Therefore, for ultralow permeability reservoirs, the complexity of the fracture network which is formed near the wellbore after SRV operation is beneficial for enhanced reservoir heterogeneity and further reinforces the imbibition effect. These fracture networks caused would greatly increase the contact area between matrix and fracture, and therefore, the imbibition impact is significantly enhanced. Accordingly, imbibition can help enhance the recovery tremendously.

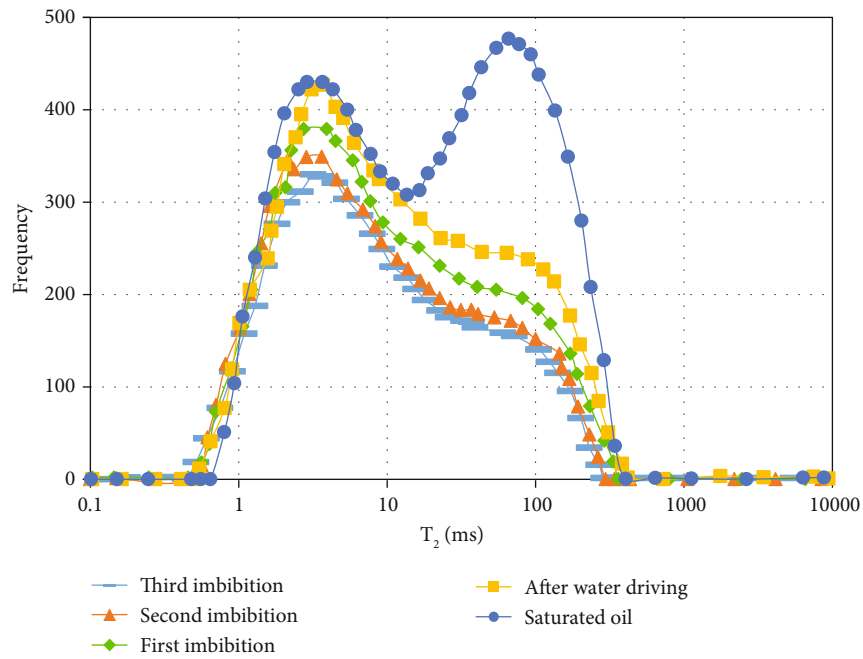
**4.5. Water Huff and Puff Cycles.** In the initial stage of huff and puff, the reservoir oil saturation and oil production are still quite high. With the increase of huff and puff cycles, the oil saturation of reservoir and oil production tend to drop, accompanied by a rise in water saturation. Optimizing huff and puff cycles is expected to maximize the impact of huff and puff and improve economic returns. The water drive recovery of two cores 2-12 (with fracture) and 2-2 is 23.64% and 25.9%, respectively. After three rounds of water huff and puff, the recovery for the same cores has increased by 4.73% and 3.4% due to the dynamic imbibition. However, the increment rate of imbibition recovery gradually slows down with the increase of huff and puff cycles, as shown in Table 3.

The experimental results show that the recovery of fractured core (2-12) does not see an obvious increase after two rounds of imbibition processes, while there is still a small amount of oil extracted after the third time of imbibition for nonfractured core (2-2), e.g., a recordable increase in recovery. However, in regard to the increment of imbibition recovery, the nonfractured core is still not as high as that of the fractured core, which reveals the fact that the fractures in the fractured core can not only increase the recovery of imbibition but also reinforce the efficiency of imbibition. This is because the complex fractures increase specific surface area and seepage channel of oil, which help to reduce the oil discharge resistance and accelerate the occurrence of imbibition. Furthermore, the NMR analyses on the core 2-2 and 2-12 are shown in Figure 11. According to the experimental results, two or three water huff and puff cycles are

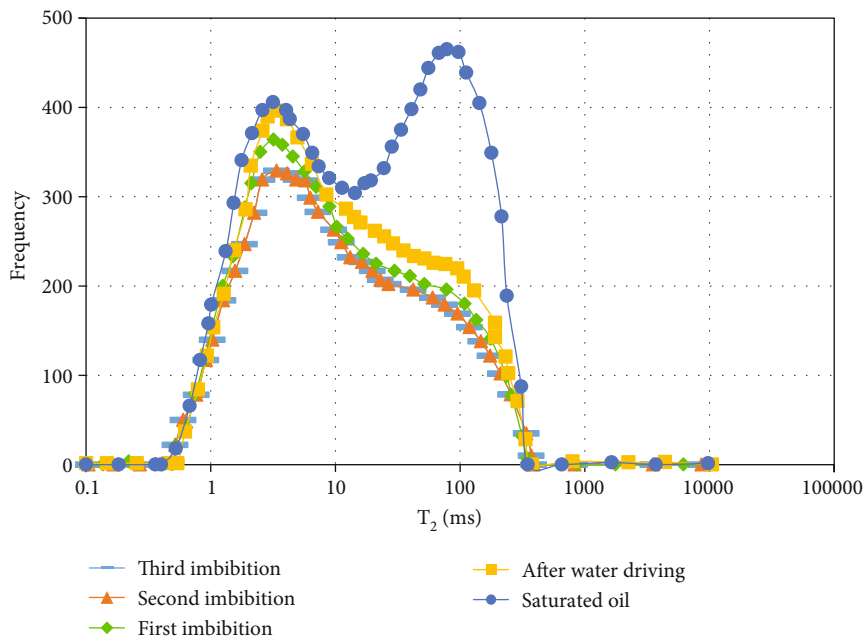


TABLE 3: Core dynamic imbibition data.

Sample	Volume of water drive oil (mL)	Water drive recovery (%)	First imbibition Oil production (mL)	Recovery (%)	Second imbibition Oil production (mL)	Recovery (%)	Third imbibition Oil production (mL)	Recovery (%)	Total recovery (%)	Recovery increment (%)
2-12 (with fracture)	1	23.64	0.15	3.55	0.05	1.18	0	0	28.37	4.73
2-2	1.22	25.9	0.1	2.12	0.05	1.06	0.01	0.21	29.3	3.4



(a)



(b)

FIGURE 11: NMR results of (a) 2-2 (no fracture) and (b) 2-12 (with fracture).

recommended for ultralow permeability oilfields and excessive cycles will result in ineffective water injection and raise the production cost for oilfields.

**4.6. Soaking Time.** Soaking is a process of oil-water saturation rebalancing in formation. Reasonable soaking time plays an important role in enhancing imbibition recovery. The shorter the soaking time, the higher the formation pressure level, the higher the fracture conductivity, the greater the production pressure difference, and the higher the initial production. However, if the soaking time is too short, it is not conducive to taking the advantage of imbibition effect and reducing the recovery of small pores. In this experiment, the recovery does not show any increase after 168 hours, and the corresponding experimental outcomes are shown in Table 4.

Mattax and Kyte [14] proposed to compare the laboratory data with the actual reservoir data through the similarity theory so as to obtain the imbibition characteristics of the whole reservoir that can be obtained on the premise of the same fluid properties and rock characteristics.

$$\left( t \sqrt{\frac{k}{\Phi} \frac{\sigma}{\mu_w L^2}} \right)_{\text{model}} = \left( t \sqrt{\frac{k}{\Phi} \frac{\sigma}{\mu_w L^2}} \right)_{\text{matrix block}}, \quad (2)$$

where  $\sigma$  is the interfacial tension;  $t$  is the time,  $t$ ;  $k$  is the absolute permeability,  $L^2$ ;  $\Phi$  is the porosity;  $\mu_w$  is the viscosity of water,  $m/Lt$ ; and  $L$  is the characteristic size of matrix block or sample,  $L$ .

It can be concluded from the formula that under the same conditions, the imbibition time to reach the specified water saturation is proportional to the square of the characteristic length. The cores used in this laboratory average 4.87 cm in length, and it takes 168 h for the water content to reach 98%. Assume the injected water covers a distance of 0.1 m from the crack to the matrix in the dynamic imbibition, the time taken, according to Mattax's similarity theory, is 708 h, approximately, 30 days. We, therefore, recommend a soaking time of 30 days for ultralow permeability oilfields.

## 5. Field Experiment

An83 oilfield is a typical ultralow permeability reservoir located in China's Ordos Basin. The main oil pay layer is 15-20 m thick, with porosity averaging 7.9% and permeability 0.17 mD. The pore radius distribution mainly ranges from 2 to 7  $\mu\text{m}$ . The throat radius is at a nanometer scale, and the pore throat connectivity is inferior. The rock type is weakly hydrophilic. In 2013, a substantial fracture network was formed as a result of multicluster fracturing for multiple horizontal wells in this development field. In the early exploitation stage, the initial production of these horizontal wells after fracturing is relatively high and the fracturing effect is ideal. When the reservoir energy is depleted after a certain period of production, the production witnesses a fast decline. Therefore, the water injection has been applied to enhanced oil recovery (EOR) but the outcome is not desirable given the development conditions. In the process of water injection, the injected water is prone to water flooding along the

TABLE 4: Core static imbibition data with surfactant.

Time (h) Sample	5	24	72	168	216	288	360
	Dynamic imbibition recovery after the addition of imbibition agent (%)						
5-1	11.5	15	17.1	17.1	17.1	17.1	17.1
5-2	5.17	7.93	8.28	9.31	9.31	9.31	9.31
5-3	5.63	6.56	6.88	7.50	7.50	7.50	7.50

TABLE 5: Comparison of oil production and water cut before and after dynamic imbibition.

Well	Water cut (%)		Daily oil production (t/d)		Cumulative oil production (t)
	Before	After	Before	After	
A53	38.3	18.4	1.72	3.72	58
A120	46	12.2	2.2	3.67	53
A81	44.9	24.7	0.97	0.96	58
A68	38.5	26	3.04	3	62
A241	47	33.5	1.23	1.31	314
Average	42.94	22.96	1.83	2.53	109

large fractures, and the oil production continues to decline, resulting in an unsatisfactory development effect. Since the year of 2014, two rounds of water huff and puff tests have been carried out for five oil wells in this area, with a single soaking time of 30 days. The next round of huff and puff tests was carried out after five months' production. After two cycles of huff and puff operations, the water cut dropped in all the five wells. As shown in Table 5, the average daily oil production of each single well has increased by 1.3 t and the average cumulative oil production of each single well has increased by 2145 t, which suggest the general recovery effect is desirable. As a consequence, the outcomes of the test area have provided some significant guidance for water injection development in other similar ultralow permeability oilfields.

## 6. Conclusion

Imbibition between fracture and matrix has been accepted as an effective method for improving the recovery of ultralow permeability reservoirs. Wettability, permeability, injection rate, fracture, water huff and puff cycles, and soaking time all have significant effects on imbibition recovery of ultralow permeability reservoirs. The experimental results show that the hydrophilic rocks are prone to imbibition. The higher the permeability, the greater the dynamic imbibition recovery. The dynamic imbibition recovery of fractured cores is 16.26% higher than that of nonfractured cores, indicating that the more developed the fractures, the higher the dynamic imbibition recovery. When the injection rate is about 0.1 mL/min, the sum of imbibition and displacement effect reaches their maximum, and imbibition recovery achieves its highest rate accordingly. With the help of imbibition occurrence in reservoirs, the optimum huff and puff cycles for fractured cores and nonfractured cores have been

proven to be two and three cycles, respectively. Therefore, imbibition is recommended to improve the recovery in ultra-low permeability oil fields after large-scale volume fracturing is conducted. Particularly when water huff and puff is adopted to supply artificial energy support for ultra-low permeability reservoirs, the optimal cycle of water injection is deemed to be two or three cycles, with the well's soaking time being 30 days.

### Data Availability

The raw data will be uploaded if required.

### Conflicts of Interest

The authors declare that they have no conflicts of interest.

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