Influence of Water Injection Pressure and Method on Oil Recovery of Water Injection Huff and Puff in Tight Volcanic Oil Reservoirs

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ABSTRACT: The water injection huff and puff (WIHP) technology is regarded as one of the important means to improve the recovery factor (RF) of tight volcanic oil reservoirs (TVORs), but the influence of water injection pressure (WIP) and water injection method (WIM) on the oil recovery effect of WIHP has been rarely reported. In this paper, we first collected the real full-diameter cores from a TVOR and then simulated the distribution characteristics of fractures and matrix pores after hydraulic fracturing of the reservoir through the combination and cutting of the cores. Finally, we used the large-sized physical simulation device for tight oil WIHP that can bear high temperature and high pressure and a nuclear magnetic resonance instrument to conduct experiments of five cycles of constant pressure WIHP (CWHP) with WIPs of 25, 32.5, and 40 MPa and step-by-step pressure rising WIHP (SWIHP) (the WIP was 25, 30, 33, 37, and 40 MPa in order) and obtained the liquid production law and mechanism of tight volcanic rock (TVR) under CWIHP and SWIHP. The result shows that under the CWIHP mode, the RF of TVR has a good power-law-positive correlation with the WIP. However, with the increase of WIHP cycles, the RF of CWIHP always decreases rapidly. In the WIHP of TVR, the injected water mainly collects oil in large pores (the pore radius is greater than 0.1 μm), and the closer the area to the outlet end of oil production and the higher the fracture density, the higher the RF. SWIHP can also effectively improve the RF of TVR, but compared with CWIHP with a WIP of 40 MPa, the amount of recovered oil decreases relatively slowly with the increase of WIHP cycles. In the first two cycles of the five cycles of WIHP, the RF of CWIHP was higher, but from the third cycle, the RF of SWIHP begins to be greater, and the more the number of cycles of WIHP, the more obvious the advantage of SWIHP. When the number of WIHP cycles exceeds 5, the oil recovery effect and the economy of SWIHP are better. This study can provide a solid theoretical basis for the efficient development of WIHP in TVORs.

1. INTRODUCTION

The Santanghu Basin is an important petroleum-bearing basin in Northwest China. According to the current exploration and development results, several oil-bearing formations and various reservoir types have been developed in the basin, tight volcanic oil reservoir (TVOR) is one of them.1−6 In 2006, the Tuha Oilfield discovered the TVOR in the Carboniferous Karagang Formation in the Malang Sag of the Santanghu Basin through drilling.7 Since then, the Tuha Oilfield has adopted various measures to increase the production of TVOR. However, due to the tight pores of the reservoir itself, the difficulty of oil flow, and the lack of natural energy, the single-well production of TVORs has been very low.7−9 In recent years, with the continuous change of development ideas, the combined development technology of horizontal wells, volume fracturing, and water injection huff and puff (WIHP) has been gradually conducted in the TVOR of the Tuha Oilfield.10−12 This combined technology has to some extent alleviated the problem of low and fast declining production from single wells in the TVOR, and some old wells have even experienced a sudden increase in production, which has provided important insights for achieving high and stable production from the TVOR in the Tuha Oilfield. In pilot test area A, the effective rate of WIHP development wells is 88.2%, the average daily oil increase of a single well is 5.3 t, and the cumulative oil increase of a single well cycle is 681.0 t. At present, the WIHP technology for TVORs is still in the testing and development stage as a whole. The technology has an obvious effect on increasing production in some wells but also has poor applicability in some wells. Therefore, it is of great significance to clarify the influencing factors of WIHP oil recovery in the TVOR to improve its oil recovery effect.12

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Scholars have conducted some studies on the influencing factors of WIHP in tight oil reservoirs. Sun et al.\textsuperscript{13} concluded that imbibition is an important oil recovery mechanism in WIHP oil recovery in tight oil reservoirs, and the higher the fracture density in the rock, the more favorable the imbibition and energy enhancement effects. Qin et al.\textsuperscript{14} argued that in the WIHP of tight oil reservoirs, massive liquid volume and high-pressure WIMs should be used, the basic principle of which is to increase the microfractures in the reservoir, thus promoting oil–water replacement. Rao et al.\textsuperscript{15} believed that the WIHP in tight oil reservoirs is based on the reservoir being fractured first and forming a fracturing fluid layer. Therefore, parameters such as the saturation, permeability, and width of the fracturing fluid layer affect the oil recovery effect of WIHP in tight oil reservoirs, and different parameters have different degrees of effect. Han et al.\textsuperscript{16} concluded that at the reservoir scale, the fracture network between wells has a significant impact on the oil recovery effect of WIHP in tight oil reservoirs and that WIHP also has a positive impact on the production of neighboring wells other than injection wells. Du et al.\textsuperscript{17} found that carbonized WIHP was more effective in oil recovery and allowed for carbon burial compared to pure WIHP alone. Cao et al.\textsuperscript{18} believed a surfactant WIHP experiment after analyzing the characteristics of conventional pure WIHP and surfactant and analyzed the effects of injection parameters [water injection pressure (WIP), soaking time] and fracture parameters (primary and secondary fractures). Teklu et al.\textsuperscript{19} concluded that the WIHP should be low mineralized water and the water should have surfactant added. Such an approach can effectively improve the oil recovery effect of the injected water by mechanisms including changes in wettability, interfacial tension, and so forth. Wang et al.\textsuperscript{20} found that the injection volume has little effect on the change of water cut during the WIHP oil recovery process but has a great influence on the WIHP oil recovery effect. The larger the injection volume, the higher the recovery factor (RF), but there is a reasonable injection multiple. Tao et al.\textsuperscript{21} concluded that the effect of WIHP oil recovery is positively correlated with pore volume, permeability, and injection volume. Yang\textsuperscript{22} believed that in fractured low-permeability reservoirs, both start-up pressure gradient and stress sensitivity affect oil production from WIHP. The larger the initiation pressure gradient, the greater the effect on well oil production, while the greater the stress sensitivity, the lower the well oil production. Lin et al.\textsuperscript{23} used numerical simulation methods to obtain optimal ranges for five engineering parameters, namely, injection timing, injection volume, injection rate, soaking time, and huff-n-puff cycles in the WIHP of tight oil reservoirs. Gao et al.\textsuperscript{24} believed that under the same development conditions, the lower the oil recovery rate of WIHP, the higher the RF. The optimum values of soaking time and pressure exist, and the cycle of WIHP is recommended to be carried out three times. It can be seen that a great deal of previous research has been conducted on the influencing factors of WIHP, and many useful insights have been gained.

However, the following problems also exist.\textsuperscript{25–32} (1) Although scholars have carried out physical simulation experiments of WIHP, the experimental cores used are small-sized plunger cores. For relatively homogeneous reservoirs, this is desirable, but for non-homogeneous reservoirs, small-scale cores cannot reflect the physical properties and seepage characteristics of the reservoir, and more representative full-diameter large-sized cores must be used. (2) The research on WIHP in tight oil reservoirs focuses on a single small plunger core, but the actual reservoir is subjected to process volume fracturing; that is, the actual reservoir is composed of matrix and fractures, and the seepage characteristics of fractures are significantly different from those of the reservoir matrix. Therefore, the physical simulation experiments of WIHP in tight oil reservoirs must be further optimized and complicated to more closely match the real situation of the reservoir. (3) When the experimental cores simulate both the matrix and fracture seepage, the pore motility characteristics of the cores are not yet clear. (4) The TVOR is the most difficult to develop among unconventional oil reservoirs, with various pore types and extremely complex seepage laws. At present, there are very few reports on the research and efficient development of TVOR and even fewer studies on the WIHP of TVOR. (5) The research on the WIHP in TVOR mainly focuses on constant-pressure WIHP (CWIHP), and there are few studies on other efficient WIMs. Therefore, it is of great significance to study the WIHP oil recovery characteristics and the optimization of WIMs in TVOR by using the combined full-diameter cores that are closer to the actual reservoir and assisted by the NMR monitoring technology. In this paper, we first collected full-diameter cores from the TVOR of the Carboniferous Karagang Formation in the Santanghu Basin by drilling. Then, to simulate the complex fracture network formed after hydraulic fracturing of the reservoir, three cores were fractured and combined to form a combined core system containing matrix fractures and nearwell and far-well zones. Finally, the WIHP physical simulation experimental device and the NMR instrument of tight full-diameter core were used to analyze the oil production law and pore production characteristics of WIHP in tight volcanic rock (TVR) under different WIPs and WIMs. This study can provide a solid theoretical basis and reference for the efficient development of WIHP in TVOR.

2. METHODOLOGY

2.1. Materials. 2.1.1. Experimental Cores. 2.1.1.1. Basic Parameters. The experimental cores are all real cores from the TVOR of the Carboniferous Karagang Formation in the Malang Sag, Santanghu Basin, with a coring depth of 1996–2059 m. Before the experiment, the cores were made into standard cylinders, and the basic parameters of the cores are shown in Table 1. It should be noted that the full-diameter cores of TVR used in this paper are large in size and have very poor permeability. Therefore, the existing conventional instruments for testing the porosity and permeability of the cores are unable to test their porosity and permeability directly. In order to roughly represent the porosity and permeability of full-diameter cores of TVR, small-sized plunger cores (2.5 cm in diameter and about 5 cm in length) were drilled around the full-diameter cores in this paper, and their tested porosity and permeability were approximated to characterize the porosity and permeability of full-diameter cores. Table 1 shows the

| Cores number | Diameter/cm | Length/cm | Permeability/mD (reference value) | Porosity/% (reference value) |
|-------------|-------------|-----------|----------------------------------|-----------------------------|
| N3          | 10.03       | 5.01      | 0.1100                           | 18.84                       |
| N2          | 10.08       | 16.32     | 0.0043                           | 6.1                          |
| N4          | 10.08       | 16.03     | 0.0079                           | 6.3                          |
porosity and permeability of small-sized plunger cores drilled around the full-diameter cores. Due to the strong heterogeneity of TVR, the porosity and permeability values of the small plunger cores listed in Table 1 are only a rough reflection of the porosity and permeability of the experimental full-diameter cores, and there is some error with the actual porosity and permeability of the full-diameter cores. When calculating the saturated oil volume of the full-diameter cores, this paper mainly calculates it by the mass change of the cores. The seepage characteristics (permeability) of the rock are not only related to the pore size distribution of the rock but also closely related to the connection mode between the pores. Due to the special formation and sedimentary process of TVR, the pore volume occupied by amygdale pores and vesicular pores reaches more than 60%. Through core observation, it is found that the size of these pores is generally in the order of millimeters or centimeters. Unfortunately, the interconnectivity between the amygdale pores and vesicular pores of TVR is extremely poor or not at all. Most of these pores are either connected by matrix micropores or distributed independently of each other. This is the fundamental reason why the overall pore radius of some volcanic cores is large, but the permeability is very low. TVR is highly heterogeneous, and the pore structure between cores often varies greatly. This is also an important reason for the difficulty in developing TVOR.33

2.1.1.2. Advantages of Full-Diameter Cores. The advantages of using full-diameter cores to conduct WIHP oil recovery experiments mainly include three aspects.

(1) Compared with the small plunger core (2.5 cm in diameter and 5 cm in length), the full-diameter core can better represent the pore structure characteristics of the actual TVOR due to the larger size of the rock sample. Especially for TVR, the heterogeneity of pore structure is extremely strong, and the advantage of full-diameter cores in representing the real pore structure of the reservoir is more obvious.

(2) The WIHP experiment of full-diameter cores is closer to the actual mechanical state of the reservoir. For the small plunger core, due to the small size of the rock sample, it is greatly affected by the confining pressure and flow pressure, especially on the two end faces and sides of the core, which is greatly affected by the external pressure. For tight cores, they generally have strong stress sensitivity. Therefore, the force characteristics of small plunger cores are different from the actual reservoirs. However, due to the large size of the rock sample of the full-diameter core, the two end faces and sides of the core are less affected by external pressure and are closer to the real stress state of the reservoir. Therefore, the full diameter core is more accurate in simulating the stress characteristics of the reservoir.

(3) The fluid metering accuracy of the full-diameter core is higher. Tight cores have great seepage resistance. For small-scale plunger cores, the fluid volume produced during multiple cycles of WIHP is very small, usually a few tenths of a milliliter. This requires very high experimental measurement accuracy. During the experiment, measurement errors are often caused due to the low oil production. However, the full-diameter core is different. Due to the large size of the rock sample of the full-diameter core, the liquid production in each cycle of the multi-cycle WIHP process is very large. During the experiment, the measurement of the fluid is simple and accurate. In fact, for tight plunger cores, the measurement of the produced fluid volume has always been a difficult problem.

2.1.1.3. Core Arrangement Principle. In the actual development of tight oil reservoirs, staged multi-cluster fracturing is mostly used for volume fracturing, as shown in Figure 1. In laboratory physical simulation experiments, it is very difficult to completely simulate staged multi-cluster fracturing of tight oil reservoirs. Currently, there is also no generally accepted physical modeling method for staged multi-cluster fracturing of horizontal wells of tight oil reservoirs. In addition, the TVOR is a kind of highly heterogeneous reservoir due to its special formation process. The conventional sand filling model and other production methods cannot reproduce the actual pore structure characteristics of the TVOR, and the actual core of the reservoir must be used. However, due to the limitation of the current drilling and coring technology, it is also very difficult to use actual cores to make a physical model of staged multi-cluster fracturing in horizontal wells of TVOR. In fact, for laboratory experiments, the key purpose is to study the mechanism, that is, to analyze the oil production laws and influencing factors of WIHP in TVR in a dual-porosity medium with the coexistence of fractures and matrix. At the same time, in the actual multiple fractures, without considering the mutual interference between the fractures, the WIHP of each hydraulic fracture has a certain similarity. Therefore, it does not make much sense to completely reproduce the staged multi-cluster fracturing of horizontal wells. In this study, from the perspective of exploring the basic laws and mechanisms of WIHP in TVOR, we only studied the WIHP oil recovery process of one hydraulic fracture, as shown in Figure 2. The fabrication process of the physical model during the experi-

Figure 1. Schematic diagram of staged multi-cluster fracturing of horizontal wells in TVOR and the research object of this paper.

Figure 2. Experimental cores and their placement order in the core holder.
First, three full-diameter cores of moderate length were collected, namely, N3, N2, and N4. Because hydraulic fracturing forms fractures, core N4 must be fractured first (cut from the middle of the regular cylinder). At the same time, for TVOR, the heterogeneity of the reservoir is extremely strong, so the distribution of hydraulic fracturing fractures must not be uniform. Therefore, in the research process of this paper, considering the complexity and uncertainty of the actual fracture distribution, the core N2 was added, and it was also cut-fractured, and the two cores were placed vertically according to the direction of the fracture. The role of core N3 is to simulate the unfractured areas of the reservoir. The arrangement of the cores is shown in Figure 2.

2.1.2. Experimental Oil and Water. The experimental oil was prepared by mixing formation oil with kerosene with a density of 0.82 g/cm³ at 25 °C and a viscosity of 2.9 mPa s. The experimental water was prepared according to the reservoir formation water with a water type of CaCl₂ and a mineralization of 9 g/L. In the NMR test, 72 g/L of MnCl₂·4H₂O was added to the water to shield the signal of hydrogen in the water. Thus, the final concentration of the experimental water was 81 g/L.

2.2. Experimental Equipment. The experimental equipment for WIHP oil recovery of TVR mainly includes a thermostat, full-diameter core holder, ISCO high-precision pump, transfer container, pressure gauge, measuring cylinder, and other equipment, and the schematic diagram of the experimental equipment connection is shown in Figure 3. In addition, to test the pore oil recovery characteristics of TVR after multiple cycles of WIHP, the SPEC-PMR-type NMR core analyzer was used in the experiment, which can test the cores of various sample sizes, including full-diameter cores. The main body of the multiple cycles of WIHP experiments in TVR is done in a thermostat. Therefore, the experimental device for multi-cycle WIHP of TVR is divided into three major systems: the temperature control and display system of the thermostat, the multi-cycle WIHP oil recovery system of the full-diameter cores inside the thermostat, and the pressure control system outside the thermostat.

(1) Temperature control and display system of the thermostat: The main function of this system is to control the experimental temperature of multi-cycle WIHP in TVR. In this study, the temperature of the experiments is the same as the actual reservoir temperature of the TVOR to be as close as possible to the real conditions of the reservoir. In addition, the display system of the thermostat can help to read the upstream pressure, downstream pressure, and surrounding pressure of the core directly, which is convenient to observe and analyze the pressure variation characteristics of the core.

(2) Multi-cycle WIHP oil recovery of full-diameter core system inside the thermostat: This system is the most critical component of the multi-cycle WIHP physical simulation experiment of TVR. The basic idea of the equipment connection is to first establish the original pressure state of the core, then conduct the nature energy depletion (NED) of the core to recover oil, and finally conduct multiple cycles of WIHP oil recovery experiments. In the conventional experimental process, the steps of saturating the core mainly include vacuum saturation and displacement saturation. However, the experimental cores in this paper are tight full-diameter TVR cores, which are characterized by the fact that an effective displacement pressure system cannot be established in the cores when conventional displacement saturation equipment is used; that is, although the pressure at the injection end reaches a very high state, there is still no oil at the output end of the cores. Therefore, for the full-diameter cores of TVR used in this paper, the method of saturating oil is vacuum saturation and autoclave high-pressure saturation, and
no original bound water is created. Therefore, for full-diameter cores of TVR, after the cores are placed in the core holder, the pressure at the inlet and outlet ends of the cores is directly increased to the original reservoir pressure value after a trace amount of oil is reserved in the pipeline and then stabilized for a period of time. When the pressure at the inlet end and outlet end of the core is stabilized, it is recognized that the core pressure has returned to the original reservoir state at this time, and thereafter, NED of the core and multiple cycles of WIHP experiments can be performed. In this study, core N3 simulates the distal end of the reservoir, which belongs to the oil supply boundary, while cores N2 and N4 simulate the near-well zone of the fracture, which belongs to the oil recovery boundary; therefore, the left side of core N3 is called the entrance end and the right side of core N4 is called the exit end. The method to restore the original pressure state of the TVR cores is to close the outlet end of the cores and then pressurize the cores from the inlet end of the cores with an ISCO pump. At this time, the fluid in the core will be squeezed due to the increase in external pressure, and then the pressure of the entire core system will gradually increase until the pressure at both ends of the core reaches the preset original reservoir pressure value, and then the four-way valve at the inlet end of the core is closed. When core NED oil recovery is conducted, it is only necessary to preset the oil production speed and cut-off pressure and open the outlet valve to conduct oil production. When the WIHP is to be performed, it is only necessary to close the oil production valve of the cores and open the water injection valve to perform water injection. After the water injection is completed, the oil production valve can be opened again for oil production. According to this method, multiple cycles of WIHP oil production experiments of TVR cores can be completed by performing water injection and oil recovery many times. The container with oil at the inlet end of the core is mainly used to restore the core to its original pressure state. The container with water at the outlet end of the core is mainly used to inject water into the core. The back-pressure valve is used to control the oil production rate and depletion cut-off pressure of the core. The main function of the cylindrical cylinder is to test the volume of oil and water in the produced liquid from the cores.

(3) Pressure control system: The main function of this system is to control the pressure value of the inlet end, outlet end, and surrounding pressure of the core using ISCO pumps, which is the power system of the whole experiment. In this study, the surrounding pressure of the core is always 3 MPa higher than its pore pressure. The combination of the ISCO pump and transfer cylinder can effectively pressurize and depressurize the injection fluid. The first advantage of the ISCO pump is its high accuracy, another advantage is that its two cylinders can work independently, thus greatly saving the number of pumps used in the experiment.

2.3. Experimental Procedures. The specific experimental steps for multi-cycle WIHP of TVR are as follows.

(1) Saturate the cores with oil: First, the three full-diameter cores are vacuumed for 48 h using a vacuum pump. Then, the cores are saturated with oil for 12 h under the pressure difference between atmospheric pressure and vacuum negative pressure. Next, the three full-diameter cores are saturated with oil in an autoclave at a saturation pressure of 45 MPa and a saturation time of 240 h. After all saturation work is completed, the volume of saturated oil in the cores, the degree of saturated oil, and the NMR T2 spectral curve are tested.

(2) Restore the original pressure state of the cores: First, the three full-diameter cores are placed in the core holder in the prescribed order, and the valve at the outlet end of the core is closed. Then, open the four-way valve at the inlet end of the core and use the ISCO pump to displace oil with a displacement pressure of 15 MPa. After the core is saturated under atmospheric pressure and high pressure, the pores already contain a certain volume of oil, so under the action of the ISCO pump, the pressure at the inlet and outlet ends of the full-diameter cores will soon reach 15 MPa. When the pressure at both the inlet and outlet ends of the cores reaches 15 MPa, the cores are considered to have returned to the original pressure state.

(3) NED: First, close the valve at the inlet end of the core. Then, after setting the cut-off pressure of the core back-pressure valve to 5 MPa and the oil production rate to 0.150 mL/min, open the oil production valve at the outlet end of the core. When the pressure at the outlet end of the core reaches 5 MPa, the NED of the core oil recovery process ends. At the same time, close the valve at the outlet end of the core.

(4) The first cycle of WIHP oil recovery: Each complete cycle of WIHP oil production includes three stages: water injection, well soaking, and oil production. The first is the water injection stage. At this time, the water injection valve at the outlet end of the core is opened, and the ISCO pump is used to inject water at the set injection pressure. When the pressure at the inlet and outlet of the cores reaches the set pressure, stabilize for 30 min, and then close the water injection valve. Then, there is the well soaking stage. At this time, the valves at the inlet and outlet ends of the core are kept closed, so that the oil and water can fully play the role of displacement and driving in the core. The well soaking time is 15 h. The last is the oil production stage. At this time, keep the valves at the inlet and outlet ends of the core closed, set the oil production cut-off pressure of the back-pressure pump to 5 MPa, set the oil production rate to 0.150 mL/min, and then open the valve at the outlet end of the core for oil production. When the pressure at the outlet end of the core reaches 5 MPa, the oil production stage is stopped. At this time, one cycle of continuous WIHP oil production is over.

(5) The second cycle to the fifth cycle of WIHP oil recovery. The experimental steps of WIHP from the second cycle to the fifth cycle are the same as the experimental steps of the first cycle of WIHP in step (4). After five cycles of WIHP experiments, the NMR T2 spectrum of the core was tested.

(6) Data processing and law analysis. According to the water injection volume, liquid recovery volume, oil recovery volume, and water recovery volume of the cores recorded by the measuring cylinder and the NMR curve tested by the NMR instrument, the liquid production law and influencing factors of the WIHP of the TVR were analyzed.

This paper focuses on the effects of different WIPs and WIMs on multiple cycles of WIHP in TVR. Therefore, the water injection parameters are variables during different experiments, while the remaining parameters and the experimental steps are kept constant.

3. RESULTS AND DISCUSSION

3.1. Influence of WIP on CWIHP Oil Recovery. The biggest feature of CWIHP oil production is that the WIP in each cycle of WIHP is the same. The advantages of this mode are that the WIM is simple, the operability is strong, and it has a certain oil recovery effect. In CWIHP oil recovery, WIP is the
most important factor affecting the multi-cycle WIHP oil recovery effect of TVR. Different WIPs have different effects on multiple cycles of WIHP oil recovery in TVR.

3.1.1. Liquid Production Law. In this study, we conducted complete five cycles of CWIHP oil recovery experiments with WIPs of 25, 30, and 40 MPa, respectively, and the experimental results are shown in Figure 4 as WIP does not affect the NED oil recovery of the cores but only on the injection and oil recovery in the WIHP stage. Therefore, Figure 4 only shows the liquid production law of the core during CWIHP under different WIPs. However, in the actual experiments, NED of the cores was conducted first in each experiment.

From Figure 4a–c, it can be seen that when constant WIP was used for WIHP, the liquid production from the cores remained relatively stable during the complete five cycles of WIHP, but with the increase of the WIHP cycles, the oil production from the cores decreased significantly while the water production gradually increased. Therefore, one of the most important features of CWIHP oil recovery is that the utilization rate of the injected water becomes lower and lower with the increase of WIHP cycles, and in the late stage of WIHP, the utilization rate of injected water is extremely low and the economic efficiency is extremely poor. As shown in Figure 4d, the WIP has an obvious influence on the liquid recovery law of WIHP in TVR. When the WIP increases, the liquid production, oil production, and water production of CWIHP in TVR increase significantly, but the increase in oil production gradually decreases. This means that when the WIP is small, increasing the WIP can effectively improve the oil production of WIHP in TVR. However, when the WIP is high, it will be more difficult to increase the oil WIP of WIHP in TVR by increasing the WIP alone. The variation of RF and cumulative RF of TVR at each WIHP cycle is shown in Figure 5.

As shown in Figure 5a, for the same WIP, the RF of WIHP in TVR gradually decreases with the increase of the WIHP cycles, and it decreases rapidly in the early stage and slowly in the later stage. For different WIPs, the higher the WIP, the higher the RF in the same WIHP cycle. Figure 5b shows that
the RF of WIHP in TVR increases with increasing WIP, but
the magnitude of the increase gradually becomes slower, and
there is a good power law correlation between the cumulative
RF and the WIP. This also indicates that for TVR, when the
WIP is small, increasing the WIP can effectively improve the
RF of WIHP, but when the WIP is already high, the effect of
increasing the WIP to improve the RF of WIHP will no longer
be obvious.

3.1.2. Pore Production Law. Due to the limitation of the
core holder size of the NMR equipment, the full-diameter
cores cannot be tested online by NMR but can only be tested
ing line. In this study, off-line NMR testing refers to one NMR
T2 spectrum curve scan before the start of the experiment and
one after the end of the experiment, and no NMR T2 spectrum
curve scan is performed during the experiment. Before the
experiment refers to the state where the core is saturated with
oil and has not yet carried out the experiment, and after the
experiment refers to the state of the core after NED and
five cycles of WIHP. In addition, the NMR data of the TVR tested
after oil saturation is the relationship between the core
transverse relaxation time and the NMR signal, not the
relationship between the core pore radius and the NMR signal.
Therefore, the relationship between the NMR transverse
relaxation time and the pore radius of the TVR must be
obtained before testing and analyzing the changing character-
istics of its NMR T2 spectral curve. In a long-term study, the
authors and the Tuha Oilfield have conducted a lot of research
on the relationship between NMR transverse relaxation time
and pore radius of TVR based on the high-pressure mercury
intrusion experiment and NMR test experiment of several
cores. The conversion process is shown in Figure 6.14

According to the conversion result of step ⑤ in Figure 6,
select a set of data with the highest correlation between ln r
and ln T2 and then convert according to the equation in step ④
in Figure 6 to obtain the relationship between the T2 value of
NMR and the pore radius r of TVR. As shown in eq 1

$$r = 0.0212 \times (T_2)^{1.0449}$$ (1)

In eq 1, r represents the pore radius of TVR and T2
represents the transverse relaxation time of NMR of TVR. Using eq 1 and the data of the NMR curves in the completeive cycles of WIHP of TVR under different WIPs, the
variation characteristics of the NMR signal in each type of pore
radius in the complete five cycles of WIHP at different WIPs
can be obtained, and the results are shown in Figure 7.

Comparing Figure 7a–c, it can be seen that, first, WIHP can
effectively reduce the oil content in the full-diameter combined
long core at the same WIP, which indicates that the WIHP

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**Figure 6.** Conversion process between NMR T2 and pore radius r of TVR.
Figure 7. NMR signal variation of full-diameter combined-long core under different WIPs: (a) WIP 25 MPa, (b) WIP 32.5 MPa, and (c) WIP 40 MPa.

Figure 8. RFs of three cores under different WIPs: (a) 25 MPa, (b) 32.5 MPa, and (c) 40 MPa.
technology can effectively improve the RF of TVOR. Meanwhile, the oil recovery effect of WIHP changes significantly when different WIPs are used, and the higher the WIP is, the larger the amount of oil recovered from the core. TVR has a wide range of microscopic pore scales. In the long-term research, Tuha Oilfield has divided the pore types of TVR into three types according to pore size. Among them, the pores with pore radius less than 0.001 μm are divided into small pores, the pores with pore radius between 0.001 and 0.1 μm are divided into middle pores, and the pores with pore radius greater than 0.1 μm are divided into large pores. Under different WIPs, the overall RFs of the three cores are shown in Figure 8, while the RFs of three different types of pores in each core and their contribution rates to the total oil production of each core are shown in Figures 9 and 10.

From Figure 8, it can be seen that when the WIHP is conducted in TVR, the RFs of the three cores increase, indicating that all the three cores participated in the oil production during the WIHP process. The difference is that different cores have different increases in RF. When the WIP is 25, 32.5, and 40 MPa, the RFs of core N4 are higher than those of N2 and N3. However, the RFs of N4 and N2 are relatively close, but both are significantly greater than those of N2. In addition, when the WIP increases, the RF of the three cores will increase, but the increase of N4 and N2 is greater than that of N3. This also fully shows that in the multiple cycles of WIHP in TVR, core N4 and N2 are the main oil-producing areas, and N3 is the secondary oil-producing area. The reason for this can be explained from two aspects. First, the core N4 and N2 are closer to the outlet end of the combined-long core, so the resistance to fluid seepage is relatively smaller. In addition, there are fractures in the core N4 and N2, which make the contact area between the injected water and the oil in the core larger, which not only reduces the seepage resistance of oil but also is very beneficial to the imbibition replacement between oil and water. Therefore, the RF of N4 and N2 is higher than that of N3, and the main reason for the higher RF of N4 than N3 is that N4 is closer to the exit end of the core. In addition, due to the strong heterogeneity of TVR, the differences in pore distribution characteristics between cores will also cause differences in their oil recovery effects. Figure 9 shows that in cores N3, N2, and N4, when different WIPs are used for WIHP oil recovery, the RF of large pores in the core is always the highest, while that of middle pores and small pores is relatively small. This shows that in the multiple cycles of WIHP in TVR, the large pores are the main force of oil production, and the oil in the middle pores and small pores can also be produced to a certain extent, but the degree is relatively low. This is also clearly illustrated by the CRs of different pores in each core to the total oil production in Figure 10; that is, at any WIP, despite the differences in the pore structures of N3, N2, and N4, the large pores and middle pores are always the main pores producing oil in each core, in which large pores dominate, while the CR of small pores to oil production is extremely low and can be negligible.
The main oil recovery mechanism of WIHP in TVR is to increase the elastic energy of the core and the imbibition displacement between oil and water in the micro–nanopores relying on the capillary force. Generally speaking, the smaller the pores, the stronger the imbibition between oil and water. TVR is a core with a very complex pore structure, in which large pores and small pores coexist, but the large pores are the main pore channels and seepage channels. Therefore, injected water will preferentially enter large pores and significantly increase the pressure system of the entire core, while the proportion of small pores is small and the seepage is difficult, so its imbibition oil recovery effect is not obvious. Therefore, in conclusion, elastic displacement is the main oil recovery mechanism of WIHP in TVR, while imbibition between oil and water in the micro–nanopores is very obvious, and when the injected water will squeeze the oil into the deep part of the reservoir, its efficiency of being recovered again will be greatly reduced. This is evident from a large number of high-pressure mercury intrusion experiments and flooding saturation experiments of TVR.

(2) From the engineering point of view and the microscopic oil recovery mechanism of multiple cycles of WIHP in TVOR, in different cycles of WIHP, the oil saturation distribution, water saturation distribution, and pressure distribution of the reservoir and the movability characteristics of oil are different. Therefore, in each cycle of WIHP, when CWIHP is used, it is essentially a rough operation rather than a refined construction. This not only has high energy consumption but also a poor economy. For the WIHP construction in the oilfield, the cost is often increased exponentially when higher WIP is used. Especially for the TVOR in the Tuha Oilfield, the WIHP construction is performed in horizontal wells with staged fracturing. Therefore, the water injection volume per well is high, and the water injection cost is also high. In addition, the operating area of the TVOR in the Tuha Oilfield is large, and there are many horizontal wells. Therefore, an economical and efficient WIM is very important. If the precise WIHP development of each well can be achieved; that is, on the premise of ensuring the RF, the WIP can be reduced, the investment can be reduced, and the energy-saving and emission reduction can be achieved, which is of great significance for the profitable exploitation of the Tuha Oilfield.

3.2. Necessity of CWIHP Optimization. As mentioned above, CWIHP can effectively improve the RF of TVOR, but this WIM has both advantages and disadvantages. The advantage is that in the multi-cycle WIHP construction in the oilfield, due to CWIHP, each water injection parameter remains unchanged in each cycle of WIHP. At this time, the oilfield construction is relatively simple and easy to operate. However, this WIM also has the following shortcomings.

(1) After the end of the NED oil recovery of TVOR, a large amount of residual oil still remains in the reservoir fractures and matrix. In addition, the pore volume of TVOR is not all filled with oil but contains a certain amount of empty pores; that is, the oil saturation of reservoir pores is not 100%. Therefore, in the first few cycles of WIHP, when a higher WIP is used, there are two problems. The first is that the injected water will squeeze the oil from the fractures into the reservoir matrix pores. This is because, before WIHP, the reservoir has undergone NED and produced a certain volume of oil. Therefore, before the first cycle of water injection, the reservoir matrix already contains a part of empty volume and this part of pore volume tends to have better seepage performance. Second, since the reservoir is not 100% saturated with liquid, the injected water will also squeeze the oil in the large and middle pores in the near-fracture zone into the deeper or smaller pores of the reservoir. Since the pores of TVOR are mostly micro-and nanoscale pores, the capillary retention effect of the pores is very obvious, and when the injected water squeezes the oil into the deep part of the reservoir, its efficiency of being recovered again will be greatly reduced.
shown in Figure 11. Compared with the CWIHP, the SWIHP may have greater advantages in reducing oilfield energy consumption and maintaining stable oilfield production.

3.3. Law and Mechanism of SWIHP Oil Recovery.

3.3.1. Oil Recovery Law. Figure 4 shows the complete five cycles of WIHP oil recovery results with WIPs of 25, 32.5, and 40 MPa, respectively. At present, 40 MPa is one of the conventional choices for WIP during CWIHP in the Tuha Oilfield. Therefore, in this study, the five cycles of WIHP with a constant WIP of 40 MPa is used as a control group, and five cycles of SWIHP with pressures of 25, 30, 33, 37, and 40 MPa are conducted. The experimental cores are still the above-mentioned combined-long cores. Except for the WIP, the other injection-production parameters remain unchanged. The experimental results are shown in Figure 12.

![Figure 12. Liquid production law of SWIHP.](image)

It can be seen from Figure 12 that when the SWIHP is adopted for the TVR, with the increase of WIHP cycles, the liquid production of the cores gradually increases, the oil production gradually decreases, and the water production gradually increases. However, it can be clearly seen that compared with five cycles of CWIHP, the rate of decline of oil production from the cores decreases significantly with the increase of WIHP cycles in the SWIHP, and the oil production did not drop sharply to a certain extent. The comparison of RF between CWIHP and SWIHP in five cycles of WIHP is shown in Figure 13.

As can be seen from Figure 13, the RF of CWIHP is significantly higher than that of SWIHP in the first two cycles of five cycles of WIHP in TVR, but from the third cycle onward, the RF of SWIHP increases than that of CWIHP until the end of the fifth cycle. In terms of the RF decline rate, with the increase of WIHP cycles, the RF decline rate of CWIHP is significantly faster than that of SWIHP. From the perspective of ultimate RF, the RF of SWIHP is very close to that of CWIHP after five cycles of WIHP oil recovery. This shows that in the five cycles of WIHP oil recovery in TVR, SWIHP obtained an RF similar to that of SWIHP under the premise of using a relatively small WIP as a whole, indicating that SWIHP is a more economical and effective WIHP oil recovery method. In addition, during the five cycles of WIHP oil recovery, although the oil production of SWIHP gradually decreases with the increase of WIHP cycles, the reduction is relatively small. The oil production remains relatively stable, which is of great significance for the stable production of the oilfield. More importantly, after five cycles of WIHP, the RF of CWIHP is already very low, but the RF of SWIHP remains at a relatively high value, which means that when more cycles of WIHP are performed (more than five cycles), the SWIHP will produce more oil; that is, the more the cycles of WIHP, the more obvious the advantage of SWIHP.

3.3.2. Oil Recovery Mechanism. The biggest difference between SWIHP and CWIHP is that SWIHP takes into account the double-sided nature of the WIP during oil recovery by WIHP. As mentioned earlier, in the process of multiple cycles of WIHP oil recovery in TVR, when a higher WIP is used, such as when the WIP is 40 MPa, at this time, while increasing the elastic energy of the core, the injected water will also push the oil in the large and medium pores in the core, which are easy to flow, to the deeper part of the core and the small pores. Unlike conventional reservoirs, the capillary force in the pores of tight oil reservoirs is extremely obvious, and the seepage resistance is extremely large during fluid flow back. Therefore, when a higher WIP is adopted, although the injected water plays an energy increasing role, the oil in the core needs more energy to flow back after being squeezed into the deep part. The power and resistance of oil seepage will offset each other, which reduces the utilization rate of the injected water. Especially in the third and later cycles of multiple cycles of WIHP, the oil that can be recovered from the core by WIHP is already far away from the outlet end of the core. If the WIP is high, the oil will be further pushed deep into the core, making it difficult to effectively flow back, resulting in extremely low utilization of injected water.

The SWIHP can overcome the negative effects of the CWIHP to a certain extent, which is embodied in the following aspects. First, in the first two cycles of multiple cycles of WIHP in TVR cores, the recoverable oil is mainly located near the core outlet end and fracture surface. At this time, this part of the oil is easy to be recovered from the perspective of seepage resistance and mobility. Although this part of oil can be recovered by using a higher WIP, from the perspective of energy utilization, an excessively high WIP is unnecessary. This can be seen from the SWIHP and CWIHP in the first and second cycles of oil recovery efficiency (the ratio of RF to WIP). In the CWIHP, with the increase of WIHP cycles, especially the third cycle and later, the unproduced oil in the easy-to-recover areas at the outlet end of the core and the fracture surface is basically difficult to be produced. At this time, the injected water mainly collects the oil in the deep part of the core and the deep part of the fracture surface. However, if the SWIHP is adopted, the relatively low pressure can, on the one hand, prevent the oil in the deep part of the core from
being pushed into the deeper part and difficult to flow back. In addition, the SWIHP has a significant effect on the improvement of the core elastic energy. Under the combined effect of the two, relatively low WIP has a better oil recovery effect in the third and subsequent cycles, and the experimental data also favorably support this view. In addition, the SWIHP can also make the oil that cannot be produced by the core in the relatively low WIP cycles to be produced again in the subsequent WIHP cycles, thereby further improving the RF. This can also be seen from the experimental results. Therefore, from the perspective of the economy and RF, the SWIHP may have a better oil recovery effect. For actual oilfield production, the reservoir characteristics and production characteristics are more complex. The reasonable water injection parameters selection must be further confirmed by a large number of production data and numerical simulation technology so as to provide a more solid theoretical basis for the selection of WIP and WIM in TVOR.

3.4. Limitations of This Work. In this paper, we analyzed the effects of WIP and WIM on the oil recovery of TVR by physical simulation experiments and achieved a series of positive understanding, but the following limitations of the research process still exist.

(1) Due to the special formation process of TVR (volcanic eruption, diagenesis, sedimentary characteristics, etc.), its pore structure characteristics are very complex, and the fluid seepage law in each type of pores is difficult to quantitatively characterize. Meanwhile, TVR cores, due to their extremely tight matrix pores, cannot establish an effective pressure gradient to displace saturation under the existing experimental equipment and simulation methods. Therefore, two methods of vacuum saturation and high-pressure saturation were adopted in this study. The result of such a saturation approach is the inevitable presence of unsaturated pores in TVR cores. Although the actual TVOR belongs to the situation that the pores are not fully saturated, in the laboratory physical simulation experiment, such saturation results make the seepage characteristics of the core unable to be finely described and quantitatively characterized.

(2) This paper compares and analyzes the oil recovery differences between CWIHP and SWIHP. However, due to the complexity of pore structure and seepage law of fracture—pore dual medium of TVR, at present, the authors have not been able to explain the fundamental differences and mechanisms of the two types of WIMs in microscopic oil recovery from the perspectives of mathematical models and numerical simulation visualization. In the future, it is expected to further improve equipment such as NMR or CT (such as core holder, high-temperature and high-pressure performance, etc.) and then explain the differences in microscopic oil recovery mechanisms between the two WIMs through online NMR or CT physical simulation imaging experiments of full-diameter cores.

(3) The existence of ferromagnetic minerals in TVR may cause certain errors in the core NMR test results.

4. CONCLUSIONS

(1) In CWIHP under different WIPs of TVR, with the increase of WIHP cycles, the amount of recovered oil and the utilization rate of the injected water all decrease rapidly, and after the fifth cycle, there is all no WIHP value. The RF of the WIHP has a good power-law-positive correlation with the WIP, and the oil produced by WIHP mainly comes from the large pores of TVR. The closer to the oil production end and the higher the fracture density, the higher the RF.

(2) In SWIHP, with the increase of WIHP cycles, the decline rate of the amount of recovered oil is relatively small, and the oil production is relatively stable. The RF of SWIHP is lower than that of CWIHP in the first two cycles, but from the third cycle, the RF of SWIHP starts to increase. After the five cycles of WIHP, the RFs of SWIHP and CWIHP are similar, but the cost of the former is lower. Therefore, when the number of WIHP cycles of TVR exceeds 5, the oil recovery effect and the economy of SWIHP are better. It is suggested that the Tuha Oilfield can further conduct the field applicability and potential of SWIHP in TVOR.

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Notes
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NOMENCLATURE

TVOR, tight volcanic oil reservoir
WIHP, water injection huff and puff
RF, recovery factor
CWIHP, constant pressure WIHP
WIP, water injection pressure
TVR, tight volcanic rock
SWIHP, step-by-step pressure rising WIHP
UR, utilization rate
WIM, water injection method
NMR, nuclear magnetic resonance
NED, nature energy depletion
REFERENCES

(1) Xu, H.; Tang, D.; Zhang, J. Coexistence mechanism of multi-types of reservoir pressure in the Malang depression of the Santanghu basin, China. J. Pet. Sci. Eng. 2013, 108, 279–287.

(2) Wang, W.; Wang, Z.; Chen, X.; Long, F. E. I.; Lu, S.; Liu, G.; Tian, W.; Su, Y. U. E. Fractal Nature of Porosity in Volcanic Tight Reservoirs of the Santanghu Basin and Its Relationship to Pore Formation Processes. Fractals 2018, 26, 1840007.

(3) Tian, W.; Lu, S.; Li, J.; Wang, W.; Li, J.; Wen, Z. Insights into the pore structure and pore development pattern of subaqueous volcanic rocks in the Santanghu Basin, western China. Mar. Petrol. Geol. 2022, 135, 105387.

(4) Hackley, P. C.; Fishman, N.; Wu, T.; Baugher, G. Organic petrology and geochemistry of mudrocks from the lacustrine Lusaogou Formation, Santanghu Basin, northwest China: Application to lake basin evolution. Int. J. Coal Geol. 2016, 168, 20–34.

(5) Li, T.-J.; Huang, Z.-L.; Chen, X.; Li, X.-N.; Liu, J.-T. Paleoenvironment and organic matter enrichment of the Carboniferous volcanic-related source rocks in the Malang Sag, Santanghu Basin, NW China. Pet. Sci. 2020, 18, 29–53.

(6) Song, D.; He, D.; Wang, S. Source rock potential and organic geochemistry of carboniferous source rocks in Santanghu Basin, NW China. J. Earth Sci. 2013, 24, 355–370.

(7) Wang, W.; Li, W.; Fan, T.; Xu, X.; Liu, Y.; Lv, Q. A Comparative Study on Microporous Characteristics of Volcanic Reservoirs in the Carboniferous Kalang and Haerjiawu Formations in the Santanghu Basin, China. Front. Earth Sci. 2021, 9, 735703.

(8) Ma, X.; Zheng, G.; Liang, M.; Xie, D.; Martinelli, G.; Sajjad, W.; Xa, W.; Fan, Q.; Li, L.; Du, L.; Zhao, Y. Occurrence and origin of H2S from volcanic reservoirs in Niudong Area of the Santanghu Basin, NW China. Geofluids 2019, 2019, 1–10.

(9) Mao, Z.-G.; Zhu, R.-K.; Luo, J.-L.; Wang, J.-H.; Du, Z.-H.; Su, L.; Zhang, S.-M. Reservoir characteristics, formation mechanisms and petroleum exploration potential of volcanic rocks in China. Pet. Sci. 2015, 12, 54–66.

(10) Pan, Y.; Huang, Z.; Guo, X.; Liu, B.; Wang, G.; Xu, X. Study on the pore structure, fluid mobility, and oiliness of the lacustrine organic-rich shale affected by volcanic ash from the Permian Lusaogou Formation in the Santanghu Basin, Northwest China. J. Pet. Sci. Eng. 2022, 208, 109351.

(11) Deng, Y.; Zheng, B.; Li, Y.; Yue, H.; Li, B. Refracturing technology for horizontal wells in Niudong volcanic oil reservoir. Well Test. 2021, 30, 32–36.

(12) Wu, M.; Zhang, Z.; Zhang, M.; Pan, Y.; Xie, S.; Chen, C. Stereoscopic Waterflooding Technology and Its Application in Niudong Volcanic Oil Reservoir. Xinjiang Petro. Geol. Pet. Geol. 2020, 41, 109–113.

(13) Sun, K.; Liu, H.; Wang, J.; Wei, X.; Ma, L.; Kang, Z.; Zhang, Y. Three-dimensional physical simulation of water huff-n-puff in a tight oil reservoir with stimulated reservoir volume. J. Pet. Sci. Eng. 2022, 208, 109212.

(14) Qin, G.; Dai, X.; Sui, L.; Geng, M.; Sun, L.; Zheng, Y.; Bai, Y. Study of massive water huff-n-puff technique in tight oil field and its field application. J. Pet. Sci. Eng. 2021, 196, 107514.

(15) Rao, X.; Cheng, L.; Cao, R.; Jia, P.; Wu, Y.; Liu, H.; Zhao, Y.; Chen, Y. A modified embedded discrete fracture model to study the water blockage effect on water huff-n-puff process of tight oil reservoirs. J. Pet. Sci. Eng. 2019, 181, 106232.

(16) Han, B.; Cui, G.; Wang, Y.; Zhang, J.; Zhai, Z.; Shi, Y.; Yan, F.; Li, W. Effect of fracture network on water injection huff-puff for volume stimulation horizontal wells in tight oil reservoir: Field test and numerical simulation study. J. Pet. Sci. Eng. 2021, 207, 109106.

(17) Du, D.; Shen, Y.; Lv, W.; Li, C.; Jia, N.; Song, X.; Wang, X.; Li, Y. Laboratory study on oil recovery characteristics of carbonated water huff-n-puff process in tight cores under reservoir condition. Arabian J. Chem. 2021, 14, 103192.

(18) Cao, B.; Wei, P.; Tian, F.; Yan, Y.; Xie, K.; Cao, W.; Liu, X.; Lu, X.; Li, Y.; Li, H.; Shen, W. Experimental Investigation on Cyclic Huff-n-Puff with Surfactants Based on Complex Fracture Networks in Water-Wet Oil Reservoirs with Extralow Permeability. Geofluids 2021, 2021, 1–10.

(19) Teklu, T. W.; Li, X.; Zhou, Z.; Alharthy, N.; Wang, L.; Abass, H. Low-salinity water and surfactants for hydraulic fracturing and EOR of shales. J. Pet. Sci. Eng. 2018, 162, 367–377.

(20) Wang, X.; Liu, X.; Yang, Z.; Ding, Y.; Liu, G.; Sun, Y. Influence of injection volume on the effect of water injection huff and puff. China Sciencepaper 2017, Vol. 12, pp 2497–2500.

(21) Denghai, T.; Zhan, X.; Gao, J.; Zheng, X.; Ren, L.; Zhou, H. Study and practice of cyclic water injection in Mazhong tight oil reservoir in the Santanghu Basin. Oil Dril. Prod. Technol. 2018, 40, 614–619.

(22) Yang, K. Influencing factors of water flooding development for fractured low-permeability reservoir. Spec. Oil Gas Reservoirs, 2010, Vol. 17, pp 82–84.

(23) Lin, W.; Fan, H.; Yan, L.; Wang, S.; Chen, F. Optimization of engineering parameters for horizontal huff and puff development of tight reservoir. China Sciencepaper 2019, Vol. 14, pp 937–942.

(24) Gao, T.; Zhao, X.; Dang, H.; Zhang, Z.; Wu, X. Mechanism of cyclic water injection and its application in tight oil reservoirs in Yanchang Oilfield. Spec. Oil Gas Reservoirs, 2018; Vol. 25, pp 134–137.

(25) Bai, J.; Liu, H.; Wang, J.; Qian, G.; Peng, Y.; Gao, Y.; Yan, L.; Chen, F. CO2, water and N2 injection for enhanced oil recovery with spatial arrangement of fractures in tight-oil reservoirs using huff-n-puff. Energies 2019, 12, 823.

(26) Chen, T.; Yang, Z.; Ding, Y.; Luo, Y.; Qi, D.; Lin, W.; Zhao, X. Waterflooding huff-n-puff in tight oil cores using online nuclear magnetic resonance. Energies 2018, 11, 1524.

(27) Rao, X.; Zhao, H.; Deng, Q. Artificial-neural-network (ANN) based proxy model for performances forecast and inverse project design of water huff-n-puff technology. J. Pet. Sci. Eng. 2020, 195, 107851.

(28) Wang, D.; Cheng, L.; Cao, R.; Jia, P.; Fang, S.; Rao, X.; Wu, Y.; Dai, D. The effects of the boundary layer and fracture networks on the water huff-n-puff process of tight oil reservoirs. J. Pet. Sci. Eng. 2019, 176, 466–480.

(29) Wang, D.; Sun, J. Oil recovery for fractured-vuggy carbonate reservoirs by cyclic water huff and puff: performance analysis and prediction. Sci. Rep. 2019, 9, 15231.

(30) Wang, J.; Liu, H.-Q.; Qian, G.-B.; Peng, Y.-C. Mechanisms and capacity of high-pressure soaking after hydraulic fracturing in tight/shale oil reservoirs. Pet. Sci. 2020, 18, 546–564.

(31) Wang, X.; Xie, K.; Zhang, J.; Zhang, Y.; Zhang, Y.; Wang, W.; Yan, X.; Zhao, F.; Shen, W. Study on the Key Influential Factors on Water Huff-n-Puff in Ultralow-Permeability Reservoir. Geofluids 2021, 2021, 1–8.

(32) Yu, Y.; Sheng, J. J. A comparative experimental study of IOR potential in fractured shale reservoirs by cyclic water and nitrogen gas injection. J. Pet. Sci. Eng. 2017, 149, 844–850.

(33) Shuai, L.; Shenglai, Y.; Xinyuan, G.; Mengyu, W.; Bin, S.; Jiayi, Y. Characteristics and mechanism of imbibition oil recovery in ultra-low permeability volcanic oil reservoir in Santanghu Basin. Colloids Surf., A 2022, under review.

(34) Li, S.; Shenglai, Y.; Lei, J.; Bin, S.; Kun, Q.; Jiayi, Y. Investigation on Pore Structure, Fluid Mobility and Water Huff-n-Puff Oil Recovery of Tight Volcanic Oil Reservoir. J. Pet. Sci. Eng. 2022, 215, 110651.