Study on Influencing Factors of Water Huff-n-Puff Oil Recovery in Matrix-Fracture Systems of the Tight Sedimentary Tuff Reservoirs

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ABSTRACT: Tight sedimentary tuff reservoirs (TSTRs) are a new type of tight oil reservoirs, which are mainly developed by water huff-n-puff (WHP). However, there is no quantitative study on the effect of water injection pressure (WIP) and fracture density (FD) on the oil recovery effect of WHP, and the reasons for the low flow-back rate (FR) of the injected water are also not fully explained. In this study, the real cores of TSTRs were used to simulate the seepage state of the matrix-fracture systems of the reservoir, the effects of WIP and FD on the WHP were quantitatively studied, and the reasons for the low FR of the injected water were comprehensively analyzed. The result shows that in five cycles of WHP, the recovery factor (RF) of the core only increases from 8.72 to 10.91% with the WIP increasing from 25 to 30 MPa. However, when the WIP is 40 MPa (rock breakdown pressure), the RF of the core reaches 16.47%, indicating that overfracture-pressure water injection has an obvious improvement effect on the oil recovery effect of WHP in TSTRs. Increasing the FD can also significantly improve the RF and oil recovery efficiency (ORE) of WHP in TSTRs. When the FD of the core increases from 0.34 to 0.44 cm⁻¹, the RF of five cycles of WHP increases by 9.26%, the ORE increases by 8.61%, and the FR of the injected water decreases by 0.56%. The reasons for the low FR of the injected water in WHP in tight oil reservoirs are matrix water locking, fracture water locking, and reservoir nonconstant-volume water locking. The study can provide an important reference for the efficient development of the WHP in TSTRs.

1. INTRODUCTION

With the continuous depletion of conventional oil and gas resources and the huge demand for oil and gas resources due to rapid economic development, the exploration and development of unconventional oil and gas resources have become more and more important.1–6 In recent years, the Tuha oilfield has conducted a lot of geological exploration and oil and gas testing in the Santanghu Basin in northeastern Xinjiang, China, and finally discovered a new type of tight oil reservoirs, called tight sedimentary tuff reservoirs (TSTRs).7–11 The formation of TSTRs is closely related to volcanic eruption and lake-basin deposition of volcanic ash. The exploration and development results show that TSTRs are significantly different from conventional tight oil reservoirs in terms of the reservoir-forming model, lithology, physical properties, and fluid properties.12–14

First of all, TSTRs are not self-generating and self-storing. The oil in TSTRs accumulates in the tight sedimentary tuff after a long-distance migration along the fault from other places. Second, the traditional tight oil reservoirs are mostly tight sandstone, while the lithology of the TSTRs is tuff. The TSTRs in the Santanghu Basin are the first tuff-like tight oil reservoirs that have been successfully explored and developed in China and even in the world.15,16 In addition, TSTRs have a low clay mineral content and are weakly to moderately water-sensitive. The hydrophilicity of the rocks is weakly hydrophilic to hydrophilic. The crude oil has a high viscosity under reservoir conditions.

The discovery of the TSTRs is of great significance for enriching the scope of tight oil reservoirs. It not only helps to improve the current tight oil production but also provides storing important enlightenment for the exploration and development of tight oil reservoirs in the future. However, while encouraging, the development of TSTRs is also facing enormous challenges. Because this is a brand new type of tight oil reservoir, there is no successful development case for reference at present, which makes the oilfield often have great blindness and uncertainty when taking various development measures.17,18 Therefore, it is of great practical significance and
urgent to study the efficient development methods of TSTRs.\textsuperscript{19–22} The combined operation of horizontal well and volume fracturing has been widely used in the development of tight oil reservoirs at home and abroad. However, this method can only guarantee high production in the initial stage of reservoir production. With the rapid depletion of reservoir energy, the oil production declines rapidly.\textsuperscript{23–25} To improve the production and recovery factor (RF) of TSTRs, the Tuha Oilfield has conducted a lot of research in the past five years and found that the water huff-n-puff (WHP) technology has great application prospects.\textsuperscript{26–34} In the pilot test area, a total of 52 wells have been conducted with WHP, and the efficiency rate is 92.3\%. The average cumulative water injection volume (CWIV) of a single well is 12,470 m\textsuperscript{3}, the initial daily oil increase is 6.5 t, the periodic oil increase is 540 t, and the validity period is 144 d.\textsuperscript{13} The WHP technology has effectively improved the RF of TSTRs, but the production data in the oilfield shows that WHP can only improve the RF by 1\% on the basis of natural energy depletion. Therefore, it is still of great significance to optimize and improve the oil recovery effect of WHP in TSTRs.

Scholars have conducted research on WHP technology in tight oil reservoirs, including applicable conditions, oil recovery mechanisms, and influencing factors.\textsuperscript{35–45} However, the following problems still exist. (1) There are very few physical simulation experiments for oil recovery by WHP in tight oil reservoirs. In addition, the existing physical experimental samples mostly use small-sized plunger cores, which do not fully consider the seepage characteristics and spatial distribution characteristics of the matrix-fracture systems after reservoir hydraulic fracturing. (2) In the physical simulation experiment of WHP in tight cores, compared with full-diameter cores, small-sized plunger cores are significantly affected by pressure and end-face effects. Also, the full-diameter core can better represent the real pore structure and fluid seepage characteristics of the reservoir rock. However, there are no physical simulation experiments of WHP with full-diameter cores. (3) There is a lack of physical simulation experiments for WHP in tight oil reservoirs at overfracture pressure. Although some oilfields have conducted small-scale mine tests of overfracture-pressure WHP and achieved certain results, there is a lack of relevant theoretical guidance and experimental data. (4) The quantitative relationship between fracture density (FD) and oil recovery by WHP in tight oil reservoirs has not been obtained from the perspective of physical simulation experiments. For example, the quantitative relationship between FD and RF, oil recovery efficiency (ORE), and flow-back rate (FR) of the injected water. (5) The reasons for the low FR of the injected water in WHP have not been comprehensively explained. The above five problems seriously restrict the optimization and improvement of WHP oil recovery in tight oil reservoirs, which must be deeply studied.

In this study, the real full-diameter cores from TSTRs were taken as the research object. First, the seepage state of reservoir matrix-fracture coexistence was simulated by combining and sequencing multiple cores with and without artificial fractures. Then, using the full-diameter core high temperature and ultrahigh-pressure WHP physical simulation experimental device, multiple cycles of WHP experiments were conducted on the tight sedimentary tuff cores including the natural energy depletion oil recovery, and the effects of water injection pressure (WIP) and FD on WHP oil recovery were analyzed. Finally, combined with experimental phenomena and related theories, the main reasons for the low FR of the injected water in multiple cycles of WHP in tight oil reservoirs were analyzed. The research results can provide a solid theoretical basis for optimizing the oil recovery effect of WHP in TSTRs and other types of tight oil reservoirs.

2. EXPERIMENTAL PART

2.1. Experimental Materials

2.1.1. Basic Parameters. The core experiments are real cores from the TSTRs in the Malang sag of the Permian Tiaohu Formation in the Santanghu Basin. The coring depth is 2460–2750 m, and the coring type is full-diameter coring. The basic parameters of the experimental cores are shown in Table 1. It should be noted that the permeability and porosity of the full-diameter cores shown in Table 1 are measured values of permeability and porosity for small plug cores near the full-diameter cores. This is because the size of the full-diameter core sample is too large, and there is less equipment that can test its permeability and porosity. In addition, due to the large seepage resistance of the full-diameter core, the conventional equipment for testing the porosity and permeability of the core is not only difficult to test but also has great errors.

2.1.1.1. Basic Parameters. The experimental cores are all real cores from the TSTRs in the Malang sag of the Permian Tiaohu Formation in the Santanghu Basin. The coring depth is 2460–2750 m, and the coring type is full-diameter coring. The basic parameters of the experimental cores are shown in Table 1. It should be noted that the permeability and porosity of the full-diameter cores shown in Table 1 are measured values of permeability and porosity for small plug cores near the full-diameter cores. This is because the size of the full-diameter core sample is too large, and there is less equipment that can test its permeability and porosity. In addition, due to the large seepage resistance of the full-diameter core, the conventional equipment for testing the porosity and permeability of the core is not only difficult to test but also has great errors.

### Table 1. Basic Physical Parameters of Full-Diameter Cores

| Core | Diameter (cm) | Length (cm) | Permeability (mD) | Porosity (%) |
|------|--------------|-------------|-------------------|--------------|
| M 1  | 10.046       | 7.04        | 0.0710            | 16.10        |
| M 2  | 10.010       | 15.82       | 0.0495            | 18.995       |
| M 3  | 10.054       | 16.00       | 0.120             | 17.135       |

2.1.1.2. Arrangement of Experimental Cores under Different WIPs. Hydraulic fracturing in TSTRs belongs to staged multicluster fracturing, and each fracture belongs to a fracture surface in space. This study belongs to the mechanism research in the laboratory; therefore, only the seepage problem of one fracture is simulated, as shown in Figure 1a. It is known from petroleum engineering rock mechanics that the expansion of hydraulic fracturing fracture surfaces in the reservoir is affected by the combined influence of the in situ stress and heterogeneity of the reservoir. For a single fracture, its expansion in the reservoir is not always in a fixed direction. In this study, for the convenience of research, it is assumed that in the initial stage of fracture propagation, the fracture surface is perpendicular to the wellbore, and then, affected by the in situ stress distribution and reservoir heterogeneity, the fracture surface turns in the deep reservoir. A special case is considered here, that is, the extension direction of the diverted fracture and the original fracture is perpendicular to each other, as shown in Figure 1b.

Figure 1c is the simplified model of Figure 1b at the core scale. From left to right, the three cores simulate the far end of the formation (matrix seepage) and the near-well-bore zone (matrix-fracture system seepage). Meanwhile, considering the complexity of fracture distribution, the fractures of the second core and the third core are perpendicular to each other. Figure 2 shows the arrangement and combination of the actual full-diameter cores. The three cores are named M 1, M 2, and M 3 from left to right.

2.1.1.3. Arrangement of Experimental Cores at Different FDs. To further investigate the effect of FD on the WHP oil recovery in TSTRs, the cores in Figure 2 were further fractured to increase their FD. M 2 and M 3 were continued to be cut perpendicular to the original fracture cut, as shown in Figure 3. The order and orientation of the cores are the
The experimental purpose of this model set in Figure 3 is to investigate the effect of FD on oil recovery by WHP in TSTRs, which is a mechanistic study. There may be differences between this model and the fracture extension pattern of the real formation. The FD of full-diameter cores is defined as the fracture area per unit volume, and the FDs of the core in Figure 2 and Figure 3 are 0.34 and 0.44 cm$^{-1}$, respectively.

2.1.2. Experimental Water and Oil. The experimental water is prepared according to the actual water type of TSTRs; the water type is the NaHCO$_3$ type, and the salinity is 9000 mg/L. The viscosity of crude oil in TSTRs ranges from 97.4 to 351.0 mPa·s at 50 °C. The high viscosity of crude oil makes the core saturation difficult, the experimental process slow, and the fluid metering error large in the WHP experiment, which in turn causes the overall system error of the experiment to be extremely large. Since this study is a mechanism study, the experimental oil in this study is a mixture of formation oil and kerosene, with a density of 0.8 g/cm$^3$ and a viscosity of 3 MPa·s at 25 °C.

2.2. Experimental Equipment. The WHP experimental system of the tight sedimentary tuff core is mainly divided into four subsystems. The first subsystem is the temperature system, which controls the temperature throughout the experiment. The second subsystem is the confining pressure system, whose role is to simulate the stress environment of the actual reservoir rock. The third subsystem is the water injection system, the function of which is to inject water into the core to simulate the water injection process of the actual reservoir. The fourth subsystem is the measurement system, the role of which is to measure the volume of liquid produced from the core, including fine metering of specific volumes of oil and water. Therefore, for the physical simulation experiment of WHP, the experimental device is as follows.
2.2.1. Incubator. The rocks of the reservoir are in a state of high temperature and high pressure, so the WHP in the laboratory must be conducted at high temperatures. The temperature of the TSTRs is 65 °C, so the experimental temperature is 65 °C. Except for the displacement pump, all other experimental devices were placed in an incubator.

2.2.2. Full-Diameter Core Holder. It is used to load experimental cores and can withstand certain confining pressure. During the experiment, the cores were placed in the order in which they were designed.

2.2.3. Transfer Container. During the experiment, there are two transfer containers, A and B. Container A contains oil, and container B contains water. The function of container A is to keep the whole core at the original formation pressure by pressurizing the core before the experiment starts. The role of container B is to inject the load with water, which is used to inject water into the core.

2.2.4. ISCO High-Precision Displacement Pump. It is used to provide the driving force for injected water, to provide confining pressure to the core, etc. The ISCO pump can provide a pressure of 0−7500 psi and a flow rate of 0.001−107 mL/min.

2.2.5. Back-Pressure Valve. The external power of the back-pressure valve is mainly provided by the ISCO high-precision displacement pump. The function of this device is to control the seepage velocity and seepage termination pressure of the core during pressure relief.

2.2.6. Other Auxiliary Equipment. In the experiment, pressure sensors, temperature sensors, oil−water separation cylinders, various conversion valves, and so forth are also needed. Figure 4 shows the physical simulation experimental device of WHP for the full-diameter core of the tight sedimentary tuff.

2.3. Experimental Steps. The WHP in TSTRs generally takes multiple cycles, but the basic process of each cycle is the same. Taking the first cycle of WHP as an example, the process is mainly divided into three stages: water injection, well soaking, and oil production. Details are given below.

2.3.1. Core Saturation. The three full-diameter cores were evacuated for 48 h by a vacuum pump and then saturated with oil under atmospheric pressure and negative vacuum pressure, and the saturation time was 12 h. Then, the three full-diameter cores were put into the autoclave for saturation, the saturation pressure was 35 MPa, and the saturation time was 240 h.

2.3.2. Elastic Energy Oil Production. Place the three full-diameter cores into the full-diameter core holder in the prescribed order. Then, open the inlet valve, close the outlet valve, and use the ISCO pump for displacement until the pressure at both ends of the core reaches the formation pressure of 20 MPa in TSTRs, and then close the core inlet valve after stabilizing for 30 min. After that, set the pumping speed of the back-pressure pump to 0.150 mL/min, and then open the outlet valve of the core. Under the action of elastic energy, the core starts to produce oil. When the core outlet pressure is 5 MPa, close the core outlet valve to stop oil production.

2.3.3. First Cycle of WHP. First, raise the pressure of the water in transfer container B to the predetermined WIP using the ISCO pump. Then, open the outlet valve of the transfer container B, and let the water in container B be injected into the core under the action of WIP. When the inlet pressure and outlet pressure of the core reach the specified pressure, stabilize for 30 min, then close the water injection valve and stop water injection, and record the water injection volume and time. After that, keep the valves at the inlet and outlet ends of the core closed so that the injected fluid can fully function in the core. The soaking time is 15 h. When the soaking process is over, set the liquid recovery speed of the back-pressure pump to 0.150 mL/min, and then open the valve at the core outlet. Under the action of elastic energy, the core starts to produce oil. When the core outlet pressure is 5 MPa, the core outlet valve is closed to stop oil production.

2.3.4. n-th Cycle (n = 2, 3, 4, etc.) of WHP. The experimental operation steps of each subsequent cycle of WHP are the same as those of the first cycle of WHP in step (3).

2.3.5. Data Processing. The characteristics of liquid production, oil production, and water production in each cycle of WHP are analyzed.

Figure 4. Schematic diagram of the full-diameter core WHP physical simulation device.
3. RESULTS AND DISCUSSION

3.1. Oil Recovery Characteristics under Different WIPs.

3.1.1. Liquid Injection and Recovery Characteristics. The reservoir pressure of TSTRs is 20 MPa. According to the rock mechanics test results of the oilfield, the rock breakdown pressure of TSTRs in the Permian Tiaohu Formation in the Santanghu Basin is about 40 MPa. Therefore, according to oilfield construction and reservoir rock breakdown pressure values, three WIPs were selected in the laboratory, namely, 25, 30, and 40 MPa. The liquid production characteristics of the combined full-diameter cores under each WIP are shown in Figure 5. In the abscissa of each figure in Figure 5, 0 represents the natural energy depletion oil recovery, while 1, 2, 3, 4, and 5 represent the cycles of WHP.

Figure 5a–c shows that after the core adopts the same oil saturation method, the natural energy depletion oil production of the combined full-diameter core is relatively close. This is because the natural energy depletion oil production of the tight sedimentary tuff has nothing to do with the WIP of the subsequent WHP. Under the condition of a constant oil production rate, the core elastic depletion oil production is only related to the initial pressure and cutoff pressure. In the five cycles of WHP under different WIPs, with the increase of WHP cycles, the water injection volume and liquid production volume of the core are not constant but change to a certain extent. There are many factors that affect these two parameters in each cycle of WHP in the tight sedimentary tuff, and the influencing methods are complicated, mainly including the following aspects.

1. Natural energy depletion oil production. In the first cycle of WHP, the core water injection volume will be affected by the natural energy depletion of oil production. The more the oil produced by natural energy depletion, the more the space freed up during the first cycle of water injection, and the larger the volume of water injection.

2. Strong fluidity of the injected water. The viscosity of the injected water is lower than that of the oil in the core, so it has stronger fluidity. Although the core oil saturation process was conducted at 35 MPa, the fluidity of the injected water during high-pressure injection was also strong. Therefore, the injected water will replenish some of the core pore volumes that were not fully saturated during the oil-saturated phase, especially at higher pressures and the first few cycles of WHP.

3. The seepage characteristics of the produced fluid in different WHP cycles. The pores of the tight sedimentary tuff are very dense, and the pores have a strong binding effect on foreign fluids. Therefore, the flow of fluids is closely related to the saturation of the oil and water phases. In the first cycle of water injection, the water injection volume of the core is relatively high, but the produced fluid is mainly oil phase at this time. In the second or third cycles, the seepage of the core-produced fluid is dominated by the two oil and water phases, and in the fourth and fifth cycles, the seepage of the core-produced fluid is dominated by the water phase. In different cycles of WHP, the saturation of oil and water in the core-produced fluid is different, so the seepage resistance of the produced fluid in each cycle must be different. The difference in seepage resistance will inevitably lead to differences in the amount of liquid produced. Also, the amount of liquid produced in each cycle will inevitably affect the amount of water injected in the next cycle. Therefore, the fluctuation of the liquid production volume of each cycle brings about the fluctuation of the water injection volume of the next cycle.

From a microscopic point of view, in the multiple cycles of WHP in the tight sedimentary tuff, the change in the liquid production and water injection in each cycle is a very complex process with many influencing factors. When the WIP is different, the influence weights of the above three influencing factors will change correspondingly; especially, when the WIP exceeds the rock breakdown pressure of the tight sedimentary tuff, their influence will become more complicated. When the WIP is different, the difference in the water injection volume of the core is due to the change of elastic energy on the one hand, and on the other hand, the WIP will also affect the opening of each fracture in the core. The higher the WIP of the core, the greater the opening of its internal fractures, and the more the water injection volume required. Also, more water injection will

![Figure 5. Variation characteristics of injection–production parameters in five cycles of WHP under different WIPs.](image-url)
of rock fractures, the saturation of the injected water becomes difficult.

After the water is injected into the core, the oil in the relatively large pores near the fracture wall in the core is first produced due to energy supplementation. However, in the WHP, the pores that are easy to produce oil are precisely the pores that the injected water can easily enter. Therefore, in the next cycle of WHP, the injected water will preferentially enter these pores. This makes the saturation of the injected water in these relatively large pores higher and higher with the increase of WHP cycles, thereby increasing the resistance to oil seepage. The result is that the ORE of the injected water becomes lower and lower, and the water production of the core becomes higher and higher. In addition, in the first few cycles of WHP oil production, the injected water can also produce a part of the oil in the small pores due to the imbibition effect, but with the increase of the WHP cycles, the production of small pores becomes more and more difficult.

Therefore, the reasons for the decrease in oil production and increase in water injection with the increase of WHP cycles can be summarized as the following three aspects. (1) In the vicinity of rock fractures, the saturation of the injected water becomes higher and higher, and the seepage resistance of crude oil becomes greater and greater. (2) The oil in the relatively large pores that are easy to flow is farther and farther away from the fracture wall of the core, the seepage distance increases, and the seepage resistance also increases. (3) Oil production in the small pores in the water-swept area becomes more and more difficult, and the effect of imbibition displacement gradually becomes weaker and weaker due to the previous injection of water.

Figure 6 shows the CWIV, cumulative liquid recovery volume (CLRV), cumulative oil recovery volume (CORV), and cumulative water recovery volume (CWRV) in five cycles of WHP for full-diameter cores under different WIPs.

Figure 6 shows that when the WIPs are 25, 30, and 40 MPa, with the increase of WIP, the CWIV, CLRV, CORV, and CWRV of the core all increase. However, when the WIP increases from 25 to 30 MPa, the increase in the range of these injection—production parameters is not very large. When the WIP increases from 30 to 40 MPa, these injection—production parameters increase significantly.

As mentioned earlier, the rock fracture pressure of the tight sedimentary tuff is close to 40 MPa. Therefore, when the WIP is 25 and 30 MPa, the WHP oil recovery does not change the pore structure of the rock, which can also be seen from the integrity of the core before and after the experiment. The core surface and fracture surface of the experimental cores with WIPs of 25 and 30 MPa were relatively complete after five cycles of WHP, no rock debris was found in the core holder, and the core fracture strength was still high. When the WIP is increased from 25 to 30 MPa, the injection water only increases the elastic energy of the core and its internal fluid.

When the WIP is 40 MPa, the WIP is close to the rock fracture pressure of tight sedimentary tuff. At this time, the injected water forms new microfractures in the areas with weak fracture strength inside the core. The significant increase in all injection and extraction parameters in the core in Figure 6 indicates that new microfractures were indeed created internally during the WHP of the core. The small amount of rock debris found in the core holder after five cycles of WHP also indicates that the local pore structure of the core was disrupted and new fractures were created. The presence of new fractures expands the injection capacity of the injected water and also enhances its oil recovery capacity. The mechanism includes the following aspects. (1) The energy-replenishing effect of the injected water increases. (2) The contact area between oil and water enlarges, and the imbibition capacity is enhanced. (3) The seepage resistance of crude oil is reduced.

3.1.2. Oil Recovery Effect. In the multiple cycles of WHP in the tight sedimentary tuff, the ORE of the injected water refers to the ratio of the volume of produced oil to the volume of the injected water in each cycle. The FR of the injected water refers to the ratio of the volume of produced water to the volume of the injected water. The changes in RF, ORE, and FR in five cycles of WHP in the tight sedimentary tuff under different WIPs are shown in Figure 7.

Figure 7a shows that under three different WIPs, the RF of each cycle of WHP of the core decreases with increasing huff-n-puff cycles. However, the RF of WHP with different WIPs is significantly different under the same WHP cycle. When the WIP is 40 MPa, the RF of each of the first four cycles of the core is significantly higher than that of the WIP of 30 and 25 MPa, demonstrating the great advantage of overfracture-pressure WHP in improving oil recovery. The RF of the core with a WIP of 30 MPa is higher than 25 MPa in all five cycles of WHP, indicating that when the WIP does not exceed the rock fracture pressure, increasing the WIP is beneficial for improving the RF of WHP. However, compared with the superfracture pressure WHP, when the WIP is lower than the rock fracture pressure, the effect of increasing the WIP on the RF is relatively small, and it is mainly concentrated in the first three cycles.

In addition, Figure 7a also shows that, under different WIPs, with increasing WHP cycles, the decline of core RF is different. When the WIP is 40 MPa, the RF of the core WHP decreases the most with increasing huff-n-puff cycles, almost linearly. However, when the WIPs are 30 and 25 MPa, the decline in RF of core WHP with increasing huff-n-puff cycles is mainly concentrated in the first four cycles, and the decline is relatively slow. The reason that the RF of overfracture WHP decreases faster with increasing huff-n-puff cycles is that the increase in the WIP and the generation of new fractures improve the fluidity of the fluid in the core. The flow characteristics of the recoverable fluid in the core tend to the Darcy flow, and there is a better linear correlation between oil production and pressure.
However, when the core pressure is low and no new fractures are created, the flow characteristics of the recoverable fluid in the core are quite different from the Darcy seepage. At this time, the fluid flow belongs to nonlinear seepage, and the flow process is obviously affected by various factors such as oil-water saturation field distribution and starting pressure gradient.

Figure 7b shows that under the WIPs of 25 and 30 MPa, the ORE of the core WHP reaches the maximum in the second cycle. An important reason for this phenomenon is the water-locking effect of the tight core on the injected water. In the multiple cycles of WHP for tight cores, with increasing huff-n-puff cycles, the oil production of the core gradually decreases, but some of the water injected in the previous cycle is retained in the core. Therefore, during the next huff-n-puff cycle, the volume of the injected water required by the core is reduced to reach the same pressure. In the first cycle of WHP, the volume of oil produced by the core and the volume of the injected water are both large, so the ORE of the core is not the highest. In the second cycle of WHP, the volume of oil produced from the core is relatively reduced, but the volume of the injected water is also reduced, and the ratio of the two, that is, the ORE, reaches the maximum. The volume of the injected water in each subsequent cycle is affected by the volume of water retained in previous cycles of the core. After the second cycle of WHP, the main reason for the rapid decline of core ORE is the rapid reduction of core oil production. When the WIP is 40 MPa, the core ORE keeps decreasing with increasing huff-n-puff cycles, which is mainly due to the greater decline in oil production from the core compared to the change in water injection.

Figure 7c shows that the FR of core injected water increases gradually with the number of WHP cycles. Under different WIPs, the FR of core injected water increased relatively small in the first three cycles, and increased rapidly in the fourth cycle. The FR of the injected water in each cycle is related to the volume of the injected water and produced fluid of the core and has a macroscopic negative correlation with the ORE.

Figure 7d is a comprehensive comparison of core RF, ORE, and FR after five complete cycles of WHP under different WIPs. Figure 7d shows that the RF of overfracture-pressure WHP is significantly higher than that of conventional pressure water injection, but the ORE is close (slightly lower) to that of conventional pressure water injection. This is due to two main reasons. First, overfracture-pressure water injection adopts an injection pressure that is greater than or close to the rock fracture pressure and, therefore, requires a larger volume of injection water. Second, the overfracture-pressure water injection creates new fractures. The newly created fractures increase the reach of the injected water and, therefore, also require more injected water. The ORE of the injected water in this study is only from the perspective of the volume of oil recovered versus injected water. From an economic point of view, it is clear that overfracture-pressure WHP is more advantageous. In conclusion, overfracture-pressure WHP is a promising new WHP oil recovery method, which is of great significance for improving the oil recovery effect of WHP in tight oil reservoirs.

3.2. Oil Recovery Characteristics at Different FDs.

3.2.1. Oil Recovery Characteristics. The essence of overfracture-pressure WHP is to generate more microfractures during the water injection process. The previous experimental data have confirmed that the overfracture-pressure WHP of the tight sedimentary tuff has great oil recovery advantages and application prospects. However, the previous WHP experiment with a WIP of 40 MPa only suggested that a certain number of
microfractures are generated inside the core from a macroscopic view, but these microfractures could not be quantitatively described and characterized. To further clarify the effect of FD on the WHP in the tight sedimentary tuff, the WHP experiment on full-diameter cores with FD of 0.44 cm\(^{-1}\) was conducted, and the WIP was still 40 MPa. In five cycles of WHP of cores with a FD of 0.44 cm\(^{-1}\), the variation characteristics of injection—production parameters are shown in Figure 8, and the changes in RF, ORE, and FR are shown in Figure 9.

**Figure 8.** Variation characteristics of injection—production parameters of the core with a FD of 0.44 cm\(^{-1}\) in five cycles of WHP.

**Figure 9.** Oil recovery effect of the core with FD of 0.44 cm\(^{-1}\) in five cycles of WHP.

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\text{Figure 8 shows that when the FD of the tight sedimentary tuff core is expanded, with increasing WHP cycles, the water injection volume and liquid production volume of the core still fluctuate, the oil production volume gradually decreases, and the water production volume gradually increases. Figure 9 shows that with increasing WHP cycles, the RF and ORE of the core with a FD of 0.44 cm\(^{-1}\) gradually decrease, and the FR of the injected water gradually increases. It can be seen that when the WIP is 40 MPa and the FDs are 0.34 and 0.44 cm\(^{-1}\), the overall fluid production characteristics of the core and the variation characteristics of the oil recovery effect are similar, but the difference lies in the specific values.}
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### 3.2.2. Comparison of the Oil Recovery Effect

According to Figures 6—9, the differences in injection—production parameters and oil recovery effects of five cycles of WHP in tight sedimentary tuff cores with FDs of 0.34 and 0.44 cm\(^{-1}\) can be obtained, as shown in Table 2.

Table 2 shows that when the FD of the tight sedimentary tuff core increases from 0.34 to 0.44 cm\(^{-1}\), the CWIV of the core increases by 52.57 mL, the CLRV increases by 59.46 mL, the CORV increases by 39.28 mL, and the CWRV increases by 20.18 mL. This indicates that the increase of FD both increases the injection capacity of the injected water and the volume of produced fluid, including the volume of produced oil and water. Meanwhile, Table 2 also shows that when the core FD increases from 0.34 to 0.44 cm\(^{-1}\), the RF increases by 9.26%, the ORE increases by 8.61%, and the FR of the injected water does not change significantly. This indicates that increasing the FD not only can recover more volume of oil but also increase the utilization rate of the injected water. Therefore, in the multicycle WHP of tight sedimentary tuff, increasing the FD is of great significance to improve the oil recovery effect of WHP.

### 3.2.3. Mechanism

Both the overfracture-pressure WHP experiment and the WHP experiment with different FDs prove that increasing the FD can effectively improve the oil recovery effect of WHP in TSTRs. This can be explained by the oil recovery mechanism of WHP in tight oil reservoirs, which supplement formation energy and promoting oil—water imbibition. The increase of reservoir FD has positive significance for both these two oil recovery mechanisms.

1. **Elastic displacement oil recovery.** When the FD of the reservoir rock increases, the swept range of the injected water expands and more crude oil can be contacted. At this time, the energy supplement effect of the injected water on the crude oil in the reservoir will be more sufficient, and more crude oil will obtain the supplemental energy of the injected water, especially for the crude oil in the deep part of the reservoir before the FD increases. In addition, due to the existence of fractures, the path of crude oil seepage is shortened, the seepage resistance is reduced, and the flow capacity is significantly enhanced. Therefore, the increase of FD effectively increases the elastic displacement oil production of WHP in tight oil reservoirs.

2. **Imbibition displacement oil recovery.** As mentioned earlier, due to the increase in the FD of the reservoir rock, the contact area between the injected water and the matrix pores of the rock increases. Since the imbibition of tight oil reservoirs belongs to surface imbibition, the larger the contact area between oil and water, the higher the imbibition of oil production. Similarly, due to the existence of fractures, the seepage path of crude oil becomes shorter and the seepage resistance decreases. Before the FD increases, the crude oil at a relatively deep position in the rock enters the large pores with stronger flow ability from the original small pores under the action.

### Table 2. Comparison of Injection—Production Parameters and Oil Recovery Effect of Cores with Different FDs

| experiment | FD/cm\(^{-1}\) | CWIV/mL | CLRV/mL | CORV/mL | CWRV/mL | RF/% | ORE/% | FR/% |
|------------|----------------|---------|----------|----------|---------|------|-------|------|
| E3         | 0.34           | 163.04  | 130.47   | 64.22    | 66.25   | 16.47| 39.39 | 40.64|
| E4         | 0.44           | 215.61  | 189.93   | 103.50   | 86.43   | 25.73| 48.00 | 40.08|
| variation  | 0.1            | 52.57   | 59.46    | 39.28    | 20.18   | 9.26 | 8.61  | -0.56|
of imbibition. However, because the seepage path is too long and the resistance is too large, this part of crude oil cannot be recovered. When the FD increases, the crude oil that was not produced due to the long seepage path under the imbibition effect can also be effectively recovered. Therefore, the increase of FD effectively increases the imbibition displacement of oil production of WHP in tight oil reservoirs.

Therefore, it is important to expand the FD to improve the oil recovery effect of WHP in TSSTRs and other tight oil reservoirs. It is suggested that the oilfield should adopt overfracture-pressure injection in the process of WHP oil recovery or expand the scale of reservoir hydraulic fracture as much as possible before WHP oil recovery to increase the reservoir FD.

3.3. Reasons for the Low FR of the Injected Water. The previous WHP experiments of the tight sedimentary tuff with different WIPs and FDs show that the FR of the injected water in each cycle of WHP does not exceed 80%. This means that a considerable volume of water remains in the core after the WHP. For oilfields, the volume of water remaining in the tight oil reservoir is very large, which will inevitably affect the oil recovery effect of the subsequent enhanced oil recovery method. After a large number of investigations and summarization of previous research results, combined with the oil recovery theory of WHP and the results of this study, the main reasons for the low FR of the injected water in WHP in tight oil reservoirs can be summarized into three aspects as a whole. They are matrix pore water locking, fracture water locking, and reservoir nonconstant-volume water locking. The details are as follows.  

3.3.1. Matrix Pore Water Locking. It mainly includes the following eight aspects.

(1) Reservoir wettability. Hydrophilic rocks are not conducive to the flow-back of the injected water.

(2) Reservoir empty volume. When the original fluid saturation of the reservoir is low, the injected water will enter a part of the original empty pores, and then it is difficult for it to flow back under the action of capillary force and additional resistance.

(3) The underbalanced state of irreducible water in the reservoir. The irreducible water on the pore surface of the reservoir with ultralow water saturation has not reached the equilibrium state and has a strong water absorption capacity, which makes the injected water adsorbed on the core surface.

(4) Complex fracture network system. After volume fracturing in tight oil reservoirs, complex artificial and natural fracture networks are formed, which greatly expands the contact area between reservoir matrix pores and injected water. The larger the contact area, the more the volume of injected water bound by the pores.

(5) Large specific surface area of micro−nanopores. Tight oil reservoirs have developed micro−nanopores, and the rock has a large specific surface area and strong water-locking ability.

(6) Strong imbibition effect. The injected water enters into the micro−nano-small pores under the action of imbibition and cannot flow out. The smaller the pore size, the stronger the imbibition effect.

(7) Effect of multiphase seepage. In the WHP, the injected water is injected by high pressure, but it is often oil−water two-phase seepage during flow-back. The seepage resistance of two-phase fluids in micro−nanopores is very large.

(8) The effect of minerals. When the content of clay minerals in the reservoir is high, especially the hydrophilic clay minerals, they often have a super water absorption function and will bring water-sensitive damage to the reservoir.

3.3.2. Fracture Water Locking. It mainly includes the following five aspects.

(1) Effect of fracture closure. After volume fracturing in tight oil reservoirs, part of the fractures is closed due to proppant failure or no proppant added. However, in the process of WHP, the water is often injected at high pressure. Therefore, a portion of the injected water may reopen the closed fractures. Although this part of the opened fractures will be closed again during the WHP oil recovery stage, the injected water cannot fully flow back. This is because this part of fractures locks water in the matrix pores in it when they are opened. Also, after this part of the fractures is closed, some water will be locked in the deep part of the fractures as well because these fractures are not necessarily completely closed.

(2) Effect of complex fracture networks. As mentioned earlier, complex artificial and natural fracture networks are formed after volumetric fracturing in tight oil reservoirs. These fracture networks increase the water locking of matrix pores on the one hand, but meanwhile, these fractures themselves have considerable volume and can also lock a lot of water.

(3) Effect of not adding flow-back aids. In the traditional fracturing fluid flow-back process, flow-back aids such as liquid nitrogen are added to promote the flow-back of fracturing fluid. However, during the flow-back of the injected water in WHP, the oilfield generally does not add flow-back aids. Therefore, the flow-back energy of the injected water during the WHP process is low, and the FR is low.

(4) Effect of not adding the proppant in overfracture-pressure WHP. In overfracture-pressure WHP, the injected water will produce fractures. However, when the water injection stops and the oil recovery starts, the reservoir pressure will decrease, and some fractures will close again, resulting in some water locking in the closed fractures.

(5) New fractures cannot be completely closed during overfracture-pressure WHP. The overfracture-pressure water injection in the oilfield will produce new fractures, and the swept volume of the injected water will expand. However, because the decrease in reservoir pressure will close some fractures, some fractures will not close. The newly added volume of the reservoir can lock water. In addition, the matrix pores on the fracture wall of the newly added volume can also lock part of the water.

3.3.3. Reservoir Nonconstant-Volume Water Locking. For some tight oil reservoirs, their boundaries are not completely fixed. When a large amount of foreign water is injected into the reservoir, the reservoir boundary expands outward. At this time, the volume of the reservoir increases, which can achieve water locking.

In the actual WHP in tight oil reservoirs, the FR of the injected water must be affected by the above three aspects. However, unfortunately, the quantitative characterization and refined description of the influence of these three aspects have not yet
been realized. From the above experimental results and the current oil recovery status in oilfields, it is known that for a single well in TSTRs, there is still a large amount of remaining oil after the WHP oil recovery in addition to the retained water since gas can pass through the water film to some extent. Therefore, gas huff-n-puff is expected to be a process to further improve the RF of tight oil reservoirs after the WHP. However, the oil recovery effect of gas huff-n-puff in tight oil reservoirs is bound to be affected by the distribution of residual water after the WHP. Therefore, it is of great significance to realize the fine description of the residual water distribution and influencing factors after the WHP, and it is also one of the key research directions of WHP in tight oil reservoirs in the future.

4. CONCLUSIONS

(1) In the matrix-fracture dual-medium seepage system of tight sedimentary tuff, the water injection and liquid production fluctuate with increasing WHP cycle under different WIPs and FDs, but the oil production all gradually decreases, and the water production all gradually increases.

(2) When the WIP is less than the rock fracture pressure, increasing WIP will not significantly increase the CWIV, CLRV, CORV, CWRV, and RF of WHP in tight sedimentary tuff. However, when the WIP reaches the rock fracture pressure, these parameters increase significantly. The RFs of five cycles of WHP with WIPs of 25, 30, and 40 MPa (rock fracture pressure) are 8.72, 10.91, and 16.47%, respectively.

(3) Increasing the FD can significantly improve the CWIV, CLRV, CORV, CWRV, RF, and ORE of WHP in tight sedimentary tuff. When the FD of the core increases from 0.34 to 0.44 cm\(^{-1}\), the RF increases from 16.47 to 25.73%, and the ORE increases from 39.39 to 48%.

(4) Overfracture-pressure water injection and increasing FD can effectively improve the RF and oil recovery effect of WHP in TSTRs. Before the WHP, the oilfield should expand the scale of hydraulic fracturing, and during the WHP, overfracture-pressure water injection should be adopted.

(5) The main reasons for the low FR of the injected water in multiple cycles of WHP in tight oil reservoirs are matrix pore water locking, fracture water locking, and reservoir nonconstant-volume water locking, but the quantitative characterization and fine description of the three still need to be further studied.

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Notes
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NOMENCLATURE

TSTR, tight sedimentary tuff reservoir; WHP, water huff-n-puff; WIP, water injection pressure; FD, fracture density; FR, flow-back rate; RF, recovery factor; ORE, oil recovery efficiency; CWIV, cumulative water injection volume; CLRV, cumulative liquid recovery volume; CORV, cumulative oil recovery volume; CWRV, cumulative water recovery volume

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