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Research Article

Study on the Key Influential Factors on Water Huff-n-Puff in Ultralow-Permeability Reservoir

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Ultralow-permeability reservoirs are difficult to effectively develop using conventional technologies, so it generally produces using horizontal wells' volume fracturing. Besides, oil wells also face the problems of short stable or no production period, rapid decline rate, and extremely low development degree. Water huff-n-puff of oil recovery technology is a quality and efficiency technology to improve the development effect of an ultralow-permeability reservoir. A systematic study on the related key influential factors of water huff-n-puff is done for improving the development effect of ultralow-permeability reservoirs. This manuscript studied the key influential factors of water huff-n-puff and related improving recovery methods using physical simulation experiments to put forward a beneficial condition for water huff-n-puff, combining with the field practice. The results show that imbibition and energy supplement are main mechanisms of water huff-n-puff; imbibition oil recovery is influenced by rock wettability, permeability, boundary condition, fracture length, water injection speed, and imbibition solution type; the stronger the water-wet reservoir rock is, the bigger the core permeability is, the longer the fracture length is, the larger the contacting area between imbibition solution and rock is, the stronger the ability of imbibition solution to change wettability, and to reduce the interfacial tension force between oil and water is, the better effect of water huff-n-puff is. So far, the field practice of water huff-n-puff has been conducted in 38 wells; the success rate can reach 92.1%, cycle oil increment of single well can reach 972 t, and accumulated oil in evaluation period can reach 36936 t, which further proves that water huff-n-puff can achieve a good effect. The effective methods to improve the development effect of an ultralow-permeability reservoir are changing reservoir physical property and supplying reservoir energy. Higher reservoir energy is good for oil flow, and better physical property can improve the displacement effect and imbibition function of injection solution. Artificial fracturing, higher injection-production ratio, and pretreatment of temporary stoppage fracturing are good methods to improve the development effect of water huff-puff.

1. Introduction

With the decrease of conventional oil and gas resources [1–3], unconventional reservoirs [4–6], such as ultralow-permeability and tight oil reservoirs, have gradually become an important field for oil and gas development in the world. China has rich resources in tight oil reservoirs, which is preliminarily estimated to exceed 20 billion tons [7–9]. In recent years, "horizontal well with volumetric fracturing" is an effective technology to develop an ultralow-permeability reservoir [10–12], and oil wells can achieve a higher production in the early stage. However, depletion development is usually adopted after fracturing without energy supplement for reservoir, leading to a short or no stable production period, rapid decline rate, and extremely low-stage development degree; oil recovery generally is less than 5%.

Therefore, it is urgent to explore new technologies to delay decline rate and improve oil recovery in ultralow permeability, so as to improve the total development level and economic benefits of ultralow-permeability reservoirs. Due to the special characteristics, such as low permeability, small pore throat size, and complex heterogeneity, of the ultralow-permeability reservoir [13], water injection or gas injection, which is suitable for conventional low-permeability reservoir, has a poor applicability for ultralow-permeability reservoir. On the one hand, the development of micro-/nanopore throat in ultralow-permeability reservoir makes it difficult to establish an effective displacement pressure system through traditional injection and production well pattern [14]. On the other hand, a complex fracture network system forms after large-scale fracturing; a conventional displacement agent, such as water, is extremely prone to channel along fractures, making it difficult to supply reservoir energy and realize effective displacement [15, 16].

In recent years, the technology of water huff-n-puff in the ultralow-permeability reservoir has developed rapidly, and field practices have been carried out successfully in Changqing, Daqing, Tuha, and other oil fields in China, and obvious effects have been achieved. During the process of water huff-n-puff, the injection water can displace the oil existing in the fracture and matrix and supply reservoir energy; the imbibition function, controlled by the capillary force and gravity, also benefits from the oil-water replacement effect [17–19]. The both functions can effectively enhance oil recovery. Therefore, how to optimize the parameters of water huff-n-puff and improve imbibition oil recovery is important for the ultralow-permeability reservoir. Aimed at the main need of supplying reservoir energy and improving displacement efficiency in the ultralow-permeability reservoir, the spontaneous imbibition experiment was firstly carried out to study the influence of wettability, core permeability, and boundary condition on imbibition effect, and then, the dynamic imbibition in the natural core with facture was conducted to study the influence of crack length and water injection rate on water huff-n-puff effect; the field practices were finally analyzed. The beneficial condition for improving the recovery of water huff-n-puff was put forward; the whole study could provide a theoretical and practical guidance for the popularization of water huff-n-puff.

2. Physical Simulation Experiment of Water Huff-n-Puff

2.1. Experimental Materials

2.1.1. Experimental Water. Experimental water was the simulated water prepared as the ionic composition of the reservoir water of the fact reservoir; the ionic composition is shown in Table 1.

2.1.2. Surfactant. In this study, the nonionic surfactant was selected for use in experiments, in which the content was approximately 40%.

2.1.3. Crude Oil. Dehydrated crude oil, with a viscosity of 2.5 mPa·s at 65°C, was obtained from the reservoir of the Dagang Oilfield. The oil sample was filtered through a core to remove impurities before use.

2.1.4. Core. In this study, we used the natural core, with a length of 5-10 cm, to investigate the influences of individual factors on the effect of water huff-n-puff.

2.2. Static Spontaneous Imbibition Experiment Using Matrix Core

2.2.1. Contact Angle and Wettability Index. The contact angle was measured with an OCA20 optical contact angle measuring instrument using a sessile drop method at 65°C. When exploring the ability of the surfactant to alter the wettability, experimental cores were cut into thin slices and immersed in surfactant samples with different concentrations for 24 h at 65°C before testing. After the surfactant processing, each thin core slice was placed into white oil when measuring the contact angle [20]. The testing of the wettability index was conducted according to the SY/T 5153-2007 standard of petroleum and natural gas industry in China, named Test Method of Reservoir Rock Wettability.

2.2.2. Process of Static Spontaneous Imbibition. Experiments were conducted according to the static spontaneous imbibition experiment process [21, 22] at a temperature of 65°C. The imbibition bottle was handled with a strong hydrophilic treatment to reduce the measurement error. The imbibition oil volume and its corresponding time were recorded to calculate imbibition oil recovery and imbibition rate, so as to evaluate imbibition effect.

2.3. Dynamic Imbibition Experiment Using Fractured Core. The experimental apparatus mainly consists of the displacement system, core holder, and metering system [23–26]. The experimental steps mainly include the following: (1) The core was vacuumed and saturated with simulated water. (2) Oil displaced the water to saturate the core with simulated oil, and oil saturation was calculated. (3) The core was fractured through a triaxial stress testing machine to create cracks with different lengths. (4) Water huff-n-puff experiments were conducted, and oil recovery was calculated; each round of huff-n-puff is 48 h.

2.4. Analysis of Physical Simulation of Water Huff-n-Puff. During the process of water huff-n-puff, imbibition plays an important role to increase oil. So, static spontaneous imbibition and dynamic imbibition were conducted to study related influential factors.

2.4.1. Static Spontaneous Imbibition Experiment Using Matrix Core

(1) The Influence of Wettability on Spontaneous Imbibition Effect. Three different wettability cores were selected to conduct spontaneous imbibition at a reservoir temperature of 65°C. The experimental results are shown in Table 2 and Figure 1.

Table 1: Ionic composition of brine water.

Ion	Na^{+}+K^{+}	Ca^{2+}	Mg^{2+}	HCO_3^{-}	Cl^{-}	SO_4^{2-}	CO_3^{2-}	Total
Concentration (mg/L)	3393	60	49	1831	4077	456	0	9866

Table 2: Experimental results of static spontaneous imbibition under different wettabilities.

Core number	Core basic information						
	Core permeability (10^{-3} μm^2)	Contact angle (°)	Relative wettability index	Core wettability	Core length (cm)	Imbibition solution	Imbibition recovery (%)
1-1	1.2	143	-0.62	Oil-wet	5.3	Simulated water	13.9
1-2	1.1	84	0.10	Intermediate-wet	5.5		22.1
1-3	0.9	48	0.79	Water-wet	5.2		31.3

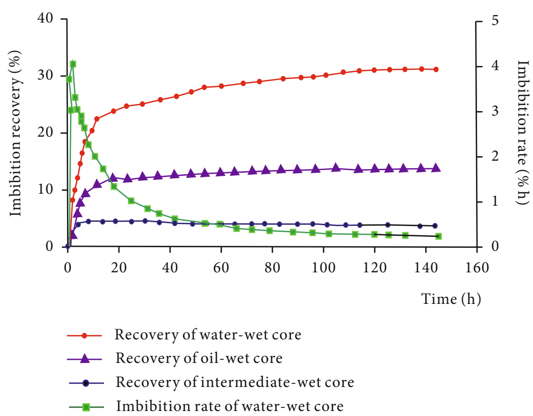

Figure 1: Relationship between static spontaneous imbibition recovery and time.

As can be seen from Figure 1, the wettability has a stronger influence on imbibition recovery. With the water-wet degree of matrix increase, the imbibition rate gets faster, the time to reach an imbibition equilibrium becomes shorter, and imbibition oil recovery increases. The spontaneous imbibition recovery of water-wet core can reach 31.3%, which is 2.3 times as much as that of oil-wet core. Besides, the imbibition rate of the water-wet core can reach a peak of 3.95% about 1 hour after experiment beginning and decreases significantly after 20 hours.

According to the Young-Laplace equation, the capillary driving force P_c causing fluid inhalation in the water-wet capillary with a radius r can be expressed as $P_c = 2\sigma \cos \theta / r$ [27]. When the core is water-wet, the capillary force is the driving force, with capillary force increasing, the imbibition function gets stronger and imbibition oil recovery has more potential. When the core is oil-wet, the capillary force is the resistance force, and the imbibition can not occur in theory, but spontaneous imbibition in oil-wet water also occurs for the gravity difference between oil and water. But, the imbibition recovery is relatively lower for the capillary force and is restricted. Therefore, as for the oil-wet reservoir, changing the core wettability can enhance core water-wet degree, which is good for enhancing the capillary force, thus improving imbibition recovery.

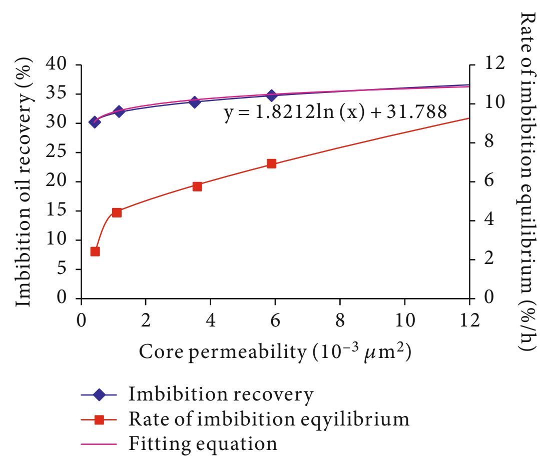

Figure 2: Static spontaneous imbibition recovery of the different permeability cores of water-wet.

(2) The Influence of Core Permeability on Spontaneous Imbibition Effect. Five different permeability cores of water-wet were selected to conduct spontaneous imbibition at a reservoir temperature of 65°C. Figure 2 shows the imbibition equilibrium rate and final imbibition recovery after 140 hours.

As can be seen from Figure 2, there is an exponential relationship between core permeability and imbibition recovery. Within the permeability range in this study, the higher the core permeability is, the higher the spontaneous imbibition recovery is and the higher the imbibition equilibrium rate is. With the permeability increasing, the pore throat size gets bigger and connected degree of pore throats becomes better, the number of effective micropore throat that can contribute to imbibition becomes larger, the seepage resistance of oil drop gets smaller, and mobility of oil becomes stronger, which leads to a faster oil-water cross flowrate, a shorter imbibition equilibrium time, and also a higher imbibition recovery.

(3) The Influence of Boundary Condition on Spontaneous Imbibition Effect. The boundary condition refers to the condition of the core outer surface involved with effective

Table 3: Static spontaneous imbibition effect of the different boundary condition cores.

Core number	Core basic information					Experimental results		
	Core permeability (10^{-3} μm^2)	Relative wettability index	Core length (cm)	Boundary condition	Effective area (cm^2)	Imbibition recovery (%)	Max imbibition rate (%. h^{-1})	Imbibition time (h)
1-3	0.9	0.79	5.2	Full opening	50.63	31.3	4.1	76
3-1	1.2	0.74	5.3	Side opening	41.61	25.9	2.7	89
3-2	1.1	0.82	5.5	End opening	9.81	13.6	1.5	112
3-3	1.1	0.80	5.1	Top ending	4.91	9.5	0.7	143

Table 4: Dynamic imbibition experimental results of cores with different fracture lengths.

Core number	Core basic information				Oil recovery				
	Core permeability (10^{-3} μm^2)	Core length (cm)	Relative wettability index	Fracture length (cm)	First round (%)	Second round (%)	Third round (%)	Fourth round (%)	Final recovery (%)
4-1	1.4	9.9	0.80	3	11.8	10.2	8.7	6.3	37.0
4-2	1.6	9.8	0.75	6	13.3	11.3	10.5	9.2	44.3
4-3	1.4	100	0.75	10	15.6	12.8	10.8	9.4	48.6

imbibition, also named effective imbibition surface. In order to study the influence of an effective imbibition surface on imbibition efficiency, four boundary condition models, including full opening, side opening, end opening, and top opening, were designed to carry out spontaneous imbibition experiment using simulated water. The core was coasted with epoxy resin according to the boundary condition. The experimental results are shown in Table 3.

From the Table 3, we can see that the boundary condition has a great influence on the imbibition recovery. The core with full opening boundary has a highest oil recovery of 31.3%, with a fastest imbibition rate and a shortest imbibition time. However, the core with top opening boundary has a lowest oil recovery of 9.5%, with a slowest imbibition rate and a longest imbibition time of 143 h. Different boundary condition causes different imbibition seepage directions, imbibition areas, and distribution of oil-water, thus leading to a difference of imbibition recovery and imbibition rate. When the core has a full opening condition, imbibition occurs in multidirections, oil produces from side and top surfaces, oil can flow in pore throats through multidirections, cisoid and reverse imbibition occur at the same time, and a more uniform imbibition displacement profile, thus improving significantly the final imbibition recovery. When the core has a side opening condition, seepage occurs as a way of radius flow, the seepage area is smaller than that of full opening condition. Because the decrease of seepage area is not larger, there is still a higher imbibition recovery. When the core has an end opening condition, seepage occurs as a way of liner flow, seepage area decreases obviously, oil drop mainly concentrates on the top ending, cisoid imbibition plays a main role, and slower imbibition causes a lower imbibition recovery. Therefore, conducting a volume fracturing in the initial development stage can form a complex fracture network, which is good for increasing the contact area between the imbibition solution and rock, thus improving the imbibition effect.

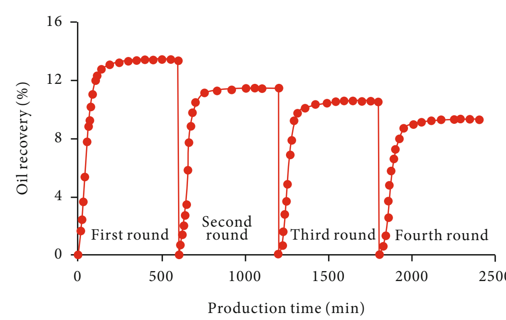

Figure 3: Relationship between water huff-puff recovery and production time (core with a fracture length of 6 cm).

2.4.2. Dynamic Imbibition Experiment Using Fractured Core

(1) The Influence of Fracture Length on Dynamic Imbibition Recovery. Three water-wet natural cores with a length of 10 cm were selected to conduct dynamic imbibition, each core with an artificial fracture of 3 cm, 6 cm, and 10 cm, respectively. Water was injected into the core to conduct water huff-n-puff experiments of four rounds at a speed of 0.1 mL·min^{-1}. The experimental results are shown in Table 4 and Figure 3.

The fracture length and water huff-n-puff rounds have an obviously influence on the final recovery. In general, the ultralow-permeability reservoir is controlled by fracture

Table 5: Dynamic imbibition experimental results of different water injection speeds.

Core number	Core permeability (10^{-3} $\mu m^{2+)}$)	Core length (cm)	Relative wettability index	Imbibition solution	Water injection speed ($mL{\cdot}min^{-1}$)	Final recovery (%)
5-1	1.7	9.9	0.80	Simulated water	0.03	40.6
5-2	1.2	9.8	0.75		0.05	42.8
4-3	1.4	10.0	0.75		0.10	48.6
5-4	1.3	9.6	0.71		0.15	43.1
5-5	1.4	10.0	0.76		0.20	37.4
5-6	1.1	9.7	0.75	Surfactant solution	0.10	52.3

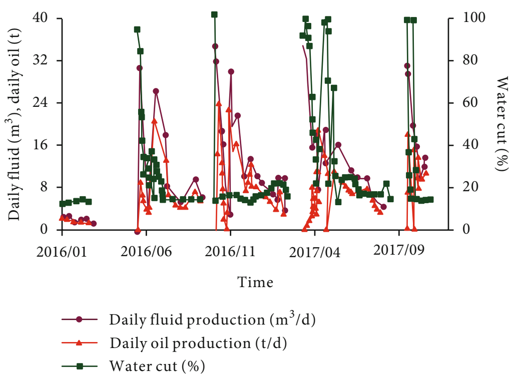

Figure 4: Production curve of water huff-n-puff during the four rounds in typical well.

parameters. The longer the fracture length is, the larger oil-water contacting area is, the higher the imbibition substitution rate is, and the higher the water huff-n-puff recovery is. With the increase of injection rounds, the cycle oil production gradually decreases. Analysis shows that, on the one hand, as the imbibition, driven by capillary force, in water-wet core goes on, water saturation in pore increases, and water film on the pore wall surface becomes thicker and thicker until the throat is entirely occupied by water; thus, water locking occurs. During the above process, imbibition becomes weaker gradually until it disappears. On the other hand, the size scale between the fracture and pore throat of the ultralow-permeability matrix is obviously different; there are two pressure systems. The pressure in matrix increases continuously during the water huff-n-puff; the pressure of fracture is lower in the final production stage. It is difficult to conduct rounds water huff-n-puff in the final production stage; the imbibition effect becomes weaker with the increase of injection round.

Moreover, compared with the static imbibition, dynamic imbibition can acquire a higher oil recovery in a shorter time. The reason of this difference is that the dynamic imbibition has a more displacement function except for the imbibition function, and displacement can promote the imbibition rate.

(2) The Influence of Water Injection Speed and Imbibition Solution Type on Dynamic Imbibition Recovery. Five kinds of the water injection speed were designed to investigate the effect of water huff-n-puff. The imbibition solution included two types of simulated water and surfactant solution (prepared by simulated water) with a interfacial tension force of 0.055 mN/m. The core used in the experiment was a natural core with a fracture length of 10 cm. Table 5 shows the experiment result of the influence of water injection speed on dynamic imbibition.

As can be seen from Table 5, the water injection speed has an obviously influence on the final recovery of water huff-n-puff. With the increase of injection speed, oil recovery presents a trend of "first increase and then decrease." The main reason is that, during the process of water injection and pressure increase, enough big injection pressure is needed to overcome the flow resistance of matrix; a higher oil-water substitution efficiency can be acquired when more water enters into tiny pore throat. When the water injection speed is slower, injection pressure is lower, the number of tiny pore involved with imbibition is less, and imbibition recovery is lower. When the water injection speed is faster, water is trend to flow with fracture, and imbibition recovery decreases. Therefore, during the field practice, reasonable injection speed should be chosen to exploit the substitution function of the capillary force and displacement function which occurred in the fracture to get a higher oil recovery, based on the experimental study and field construction.

Besides, the addition of a surfactant can improve the final recovery of water huff-n-puff to some degree [21–23]. Compared with the simulated water, on the one hand, surfactant solution can strengthen the water wettability of the core, which is good for decreasing the oil thickness on the pore surface and expanding the contacting area of imbibition. On the other hand, the surfactant can decrease the interfacial tension force between oil and water, emulsify crude oil, strengthen the deformation ability of oil drop, and decrease the seepage resistance caused by Jamin effect in the pore throat, thus enhancing oil recovery.

3. Field Practices

The sedimentary facies of the field are sand bar and sand sheet, the sand body distribution is stable, and the connection is good. The reservoir has characteristics of average layer thickness of 25 m, average oil saturation of 64%, average permeability of $1.3 \times 10^{-3}\ \mu m^2$, average pore porosity of 18.1%, average pore throat radius of 78 nm, reservoir

Table 6: Statistical results of water huff-n-puff in the oilfield.

Types	Construction wells	Effective wells	Efficiency (%)	Effective period (t/d)	Initial oil increasing (t/d)	Period oil increasing (t)	Back production efficiency (%)
Water huff-n-puff	26	23	88.5	152	7.5	712	7.5
Water huff-n-puff+ fracturing	12	12	100.0	246	10.3	1231	2.1
Total/average	38	35	92.1	199	8.9	972	4.8

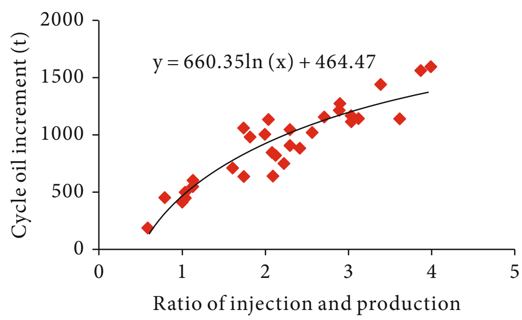

Figure 5: Fitting curve between cycle oil increasing and injection-production ratio in water huff-n-puff.

temperature of 65°C, and oil viscosity of 2.5 mPa·s. Water huff-n-puff in this field has acquired a good effect.

3.1. The Effect of Water Huff-n-Puff in Typical Single Well. The well was fractured into 8 stages and then put into production, with a daily oil production of 15 t at the initial production stage, an accumulated fluid production of 6742 m^3, and an accumulated oil production of 4350 t before water huff-n-puff. The production dynamic of water huff-n-puff during the four rounds in a typical well is shown in Figure 4. A well with an average daily oil production of 2.0 t and an average water cut of 12.8%. After four rounds of construction of water huff-n-puff, cycle highest daily oil production can reach 20 t, and accumulated oil production volume is 2300 t.

3.2. Recognition of Field Practice

3.2.1. Fracturing Can Greatly Improve the Effect of Water Huff-n-Puff. So far, water huff-n-puff had been constructed in 43 wells, 38 wells could be evaluated, 35 wells had a good effect, efficiency reached 92.1%, average single-well cycle oil increasing was 972 t, average back production efficiency was 4.8%, and construction effect was well. Combined operation of water huff-n-puff and fracturing is better than single water huff-n-puff, well efficiency can reach 100%, single-well oil increasing reached 1200 t in a cycle, and back production efficiency could reach 2.1%. The reservoir formed a fracture network after volumetric fracturing, the contacting area between injection water and rock increased, and the sweeping area of huff-n-puff expanded, which was good for releasing the oil reservoir from the matrix under high-pressure state. Thus, substitution efficiency between water and oil gets better, and the development effect is good. The statistical results can be seen in Table 6.

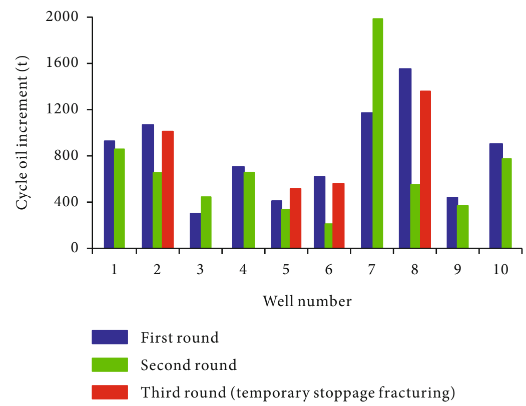

Figure 6: Cycle oil increment of water huff-puff in multirounds of 10 wells.

3.2.2. Higher Injection-Production Ratio and Is Beneficial to Improve the Effect of Water Huff-n-Puff. The fitting relationship between cycle oil increasing and injection-production ratio is shown in Figure 5. The effect of water huff-n-huff is positively correlated to injection-production ratio. Increasing the injection-production ratio can effectively supply reservoir energy, thus extending the period of increasing oil and acquiring a good effect of water huff-n-puff.

3.2.3. Temporary Plugging Fracturing Can Improve Oil Recovery to Some Degree. Figure 6 shows the statistical analysis of the effect of multirounds water huff-n-puff in 10 wells. Compared with the first round of water huff-n-puff, the effect of the second round of water huff-n-puff showed a trend of weakening, and the average cycle oil increment decreased by 14%. 4 wells, with an obvious oil decrease in the second round, were selected to conduct third round water huff-n-puff, but pretreatment of temporary plugging fracturing was conducted. After the pretreatment, the old fracture extended, new fracture emerged, and contacting area between water and rock became larger during the water huff-n-puff. The effect of increasing oil is obvious, which was equal to that of the first round.

4. Conclusions

(1) Water huff-n-puff technology can solve the problems, such as difficulty in establishing effective well pattern, serious channeling when injected with water, and inability to supply reservoir energy, thus achieving a higher oil increasing effect

(2) The stronger the water-wettability reservoir is, the better the physical property is, the longer the fracture length is, the larger the contact surface between water and rock is, the better the effect of water huff-n-puff effect is, and dynamic imbibition can achieve a higher recovery in a shorter time

(3) In a word, the effective methods to improve the development effect of an ultralow-permeability reservoir are changing the reservoir physical property and supplying reservoir energy. Higher reservoir energy is good for oil flow; better physical property can improve the displacement and imbibition function of injection water or surfactant solution

Nomenclature

P_c: Capillary force
σ: Interfacial tension force
r: Radius of capillary
ɵ: The contacting angle.

Data Availability

All data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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