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Mechanism of Pressure Difference Variations on Heavy Oil Start-Up and Percolation Effects

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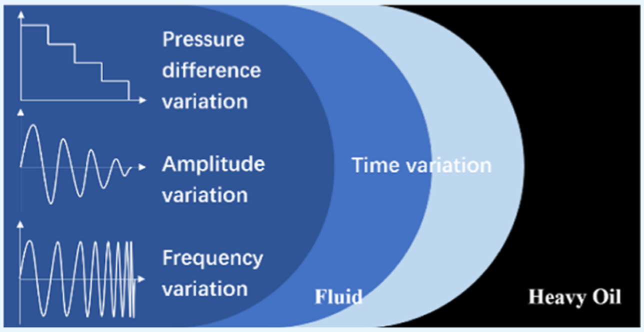

ABSTRACT: To investigate the influence of pressure difference changes on the micro start-up and percolation of heavy oil, a micro visualization displacement device was used to characterize the start-up time and oil—water percolation state of heavy oil. The mechanism of different pressure differences, as well as the frequency and amplitude of pressure difference changes, on the start-up and percolation balance of heavy oil was clarified. The results indicate that high-pressure difference and pressure difference changes can reduce the start-up time of heavy oil. A reasonable frequency of pressure difference changes effectively promotes the balance between positive and negative pressure shear and fluid—solid response. Large pressure difference changes can effectively break the viscous and adsorption resistance during heavy oil start-up; reasonable pressure difference can exert the synergistic effect of pressure difference and infiltration, achieving a balance between the water wave and the initial water film thickening process as well as the continuous percolation process of wire drawing, oil droplets, and oil columns during the medium-to-high water content period; a reasonable frequency of pressure difference variation during the high water content period can promote the superposition of inertia effects at the oil—water interface and break the balance of the oil—water interface. A large amplitude of pressure difference variation is beneficial for the strong deformation of the oil—water interface and the shear dislocation peeling of the oil—solid interface. Therefore, a relatively high amplitude of pressure difference variation and a reasonable frequency of pressure difference variation, as well as the synergistic effect of pressure difference and infiltration, are the keys to effectively start heavy oil and improving oil recovery during the ultrahigh water-cut period.

1. INTRODUCTION

China's heavy oil reservoirs are abundant in reserves, but they are characterized by complex reservoir environments, high crude oil viscosity, and poor fluidity. Conventional oil recovery techniques are increasingly yielding diminished results. While conventional methods like cyclic steam stimulation, steam flooding, and steam-assisted gravity drainage are effective in enhancing production rates and recovery factors, they come with limitations.[1] These include low thermal efficiency in steam injection, gradual depletion of reservoir energy, and reduced cyclic development effectiveness.[2] Furthermore, cold heavy oil production techniques frequently encounter the "three-lows" challenge, characterized by the diminished technical efficacy, sluggish oil recovery rates, and restricted overall extraction yields[3,4] Additionally, whether it is conventional thermal mining or cold mining development technology, variations in production methods across different development wells can impact the stable release of heavy oil production.[5] Hence, in the face of unfavorable conditions, such as low reservoir energy, high crude oil viscosity, and high water saturation, effectively restarting[6] and sustaining high-efficiency production capacity is the key to the development of high water-cut heavy oil reservoirs.

Heavy oil reservoirs, owing to their high viscosity characteristics,[7] exhibit non-Darcy flow behavior within porous media,[8,9] particularly concerning the issue of heavy oil initiation. Research into heavy oil initiation primarily focuses on experimental investigations, the development of initiation pressure gradient models, and subsequent numerical simulations. Utilizing core-scale flow experiments allows for the analysis of the physical initiation processes, investigating the effects of parameters such as temperature, viscosity, and drive velocity on the initiation pressure patterns. Additionally, experimental results are used to validate algorithms and models for predicting initiation pressure in low-viscosity heavy

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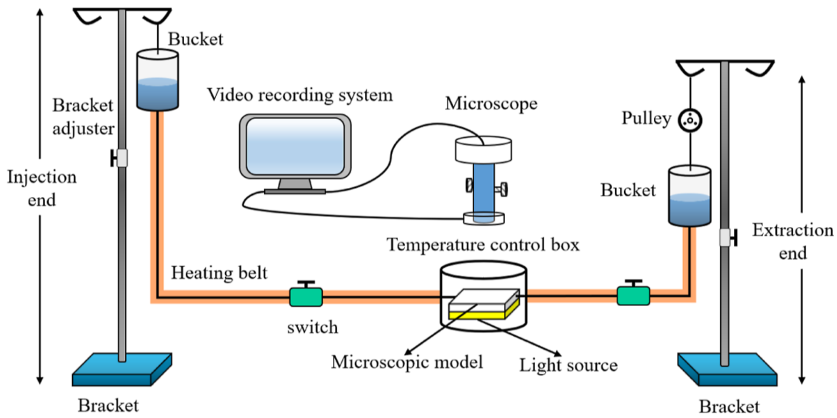

Figure 1. Microscopic visualization displacement experiment apparatus and process.

oil systems.[10] Furthermore, experimental and dynamic data can be employed to deduce methodologies for calculating initiation pressure gradients in heavy oil reservoirs.[11] Some researchers treat initiation pressure gradients as variables related to viscosity and consider their directionality, thus establishing mathematical models for the variation of initiation pressure gradients in heavy oil reservoirs.[12] Furthermore, in model development, considering the impact of the pore structure, boundary layers, and yield, stress in heavy oil porous media can provide a more precise understanding of the mechanisms and influencing factors behind the initiation pressure gradient in heavy oil reservoirs.[13] However, existing reservoir simulation software does not adequately account for the effects of variable initiation pressure gradients and pressure-sensitive behaviors on the field production performance.

The stable and efficient percolation of heavy oil after initiation is the key to maintaining and increasing production during the later stages of heavy oil field development. Regarding development plans, the well network can be enhanced by considering the distribution of remaining oil, which can help adjust the distribution and improve flow efficiency.[14] As for development technology, microbial system oil recovery primarily reduces crude oil viscosity and oil—water interfacial tension by altering the properties of crude oil through metabolic products that lead to efficient percolation.[15] The hot fluid system for oil recovery mainly improves the flow efficiency by heating crude oil, reducing its viscosity, dissolving and expanding it, and also maintaining formation pressure.[16,17] The polymer-based displacement control system enhances sweep efficiency and increases the oil—water contact area by obstructing high permeability channels, leading to efficient oil displacement.[18] However, there are still some challenges that need to be addressed, such as developing high water consumption zones in the later stage of high water content, dealing with severe inefficient water circulation, finding ways to effectively utilize remaining oil in fault block reservoirs, injecting steam into deep and thin layers of ultraheavy oil, managing high heat loss, treating severe scaling in alkaline composite flooding oil systems, addressing stronger dynamic heterogeneity of reservoirs after polymer flooding, and dealing with more dispersed remaining oil.[19]

Physical instabilities in water injection involve the continuous alteration of the pressure difference, creating physical disturbances that disrupt the equilibrium of local oil—water interfaces. By introducing water or chemical agents into the remaining oil-enriched areas during mid-to-high water-cut periods,[20] these instabilities increase the microscopic or macroscopic sweep, thereby aiming to enhance recovery rates.[21] Early successes in this field were initially validated in Canada's cold heavy oil production with sand wells,[22] and subsequent research demonstrated favorable outcomes when combined with chemical agents.[23,24] Mechanistic investigations into pressure difference variations for physical instabilities primarily focus on oil droplet interface deformation,[25] reduced fingering, and enhanced mixing.[26,27] These mechanistic explanations have provided insights into the application effectiveness of unstable pressure difference variations in heavy oil reservoirs during high water-cut stages. However, the processes and mechanisms through which such unstable pressure difference variations affect the initiation and micro-scale influences in mid-to-high water-cut periods in heavy oil reservoirs remain relatively unclear. Building upon the heavy oil samples and reservoir conditions of a certain block, the present study employed a microglass etching model to investigate the influence of pressure difference and pressure difference variations on the coexistence status of oil and water during the microscopic initiation and percolation processes in heavy oil reservoirs. This approach seeks to clarify the impact mechanisms of pressure difference variations on heavy oil initiation and percolation, providing valuable support for effective initiation and enhanced recovery in heavy oil reservoirs.

2. EXPERIMENT

2.1. Experimental Apparatus and Materials. *2.1.1. Experimental Equipment.* A self-made glass etching model with an area of 40 × 40 mm and an average pore diameter of 150 μm was used. A microscope camera (model 928D) was obtained from HanGuang Optical (Wuxi) Co., Ltd. A graduated cylinder was used. A direct-coupled rotary vane vacuum pump (model 2XZ-2) was purchased from Shanghai Lichenbangxi Instrument Technology Co., Ltd. A peristaltic pump (model LSP01-2A) was purchased from Nanjing Xiaoxiao Instrument Equipment Co., Ltd. Suspension bucket, height-adjustable stand, heating band, and thermostatic chamber were also used.

2.1.2. Experimental Materials. Simulated Water. Dehydrated reservoir crude oil (viscosity at 30 °C: 936 mPa·s), methylene blue (AR), and petroleum ether (AR) were used in the experiment.

2.2. Experimental Methods and Procedures. Using a custom glass etching model, a vacuum was created to saturate

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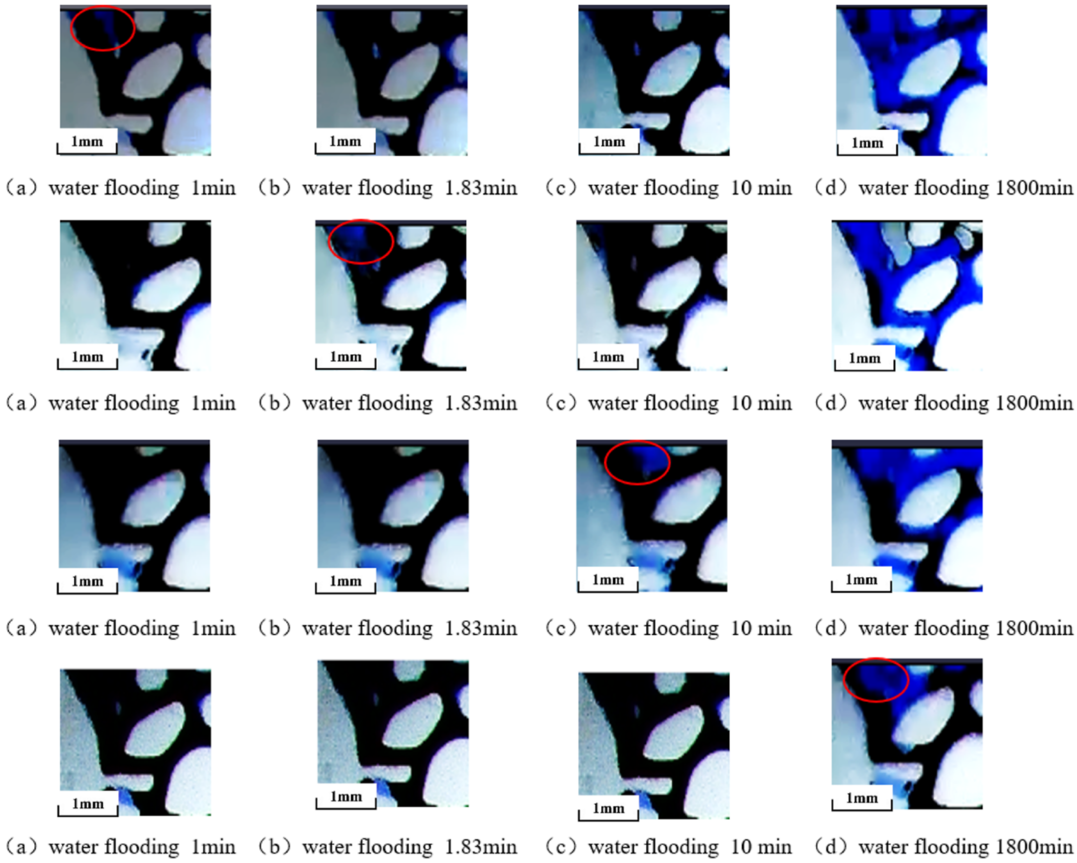

Figure 2. Initiation process of heavy crude oil under different pressure differences (from top to bottom: 20, 10, 5, and 0.5 kPa).

the water phase. Using a peristaltic pump to saturate the dehydrated heavy crude oil, connate water was obtained. Establishing the experimental device as shown in Figure 1, we adjusted the heights of the injection-end support and the hanging bucket (0.5, 5, 10, and 20 kPa) to control various displacement pressures. Pressure amplitude variations (0.5, 2, and 4 kPa) were controlled by moving the pulley at the outlet end. Temperature of the injected water was regulated using a constant-temperature chamber and a heating plate. Water flooding experiments were conducted to study the heavy crude oil behavior. During the experiments, a camera and computer were employed to observe the time it took for the first water droplet to enter the glass slide. This time served as the initiation of heavy oil flow, defined as the duration from the start of displacement to the arrival of injected water at the micromodel's inlet. The distribution of oil and water within the model was examined. The impact of pressure difference changes on the microscale initiation of heavy crude oil and their influence on later-stage enhanced oil recovery mechanisms were investigated. Please refer to Figure 2 for the detailed experimental process. The experimental data were processed by using image processing software (Image-Pro Plus), allowing for the computation and quantitative characterization of various residual oil parameters and recovery levels at different stages.

3. RESULTS AND DISCUSSION

3.1. Impact Mechanism on Microscopic Initiation of Heavy Crude Oil. *3.1.1. Influence of Various Pressure Difference.* To investigate the microinitiation mechanisms of heavy crude oil under different pressure difference, following the experimental methods and procedures described in Section 2.2, the temperature inside the constant temperature chamber was maintained at 30 °C. The high-permeability model was selected for the microglass etching model, and the oil sample (with a viscosity of 936 mPa·s at 30 °C) was saturated. Pressure difference was set at 0.5, 5, 10, and 20 kPa, with the displacement carried out using simulated formation water. The initiation phenomena were observed through a camera and computer recording, and the time for the first water droplet to enter the glass etching model was documented. The experimental results are presented in the following figure.

From Figure 2, it is evident that under different pressure differences, the initiation of heavy crude oil typically begins near the pore edges, gradually spreading to the entire pore space. The physical processes of initiation and the dynamic movement of oil and water are similar. As the pressure difference increases, the continuous phase initiation time of oil and water becomes shorter. Even at extremely low experimental pressure difference (0.5 kPa), initiation can occur after a sufficiently long period (1800 min), indicating the absence of an initiation pressure for heavy crude oil. Based on the relationship between initiation time and pressure difference, as shown in Figure 3, it can be seen that the start-up time changes significantly under different pressure difference. Initiation can be distinctly categorized into three phases based on the initiation performance: the challenging initiation phase (water-drive pressure difference less than 5 kPa, initiation time greater than 10 min; water-drive pressure difference less than 0.5 kPa, initiation time even greater than 1800 min), the equilibrium phase (water-drive pressure difference 5−10 kPa, initiation time between 2 and 10 min),

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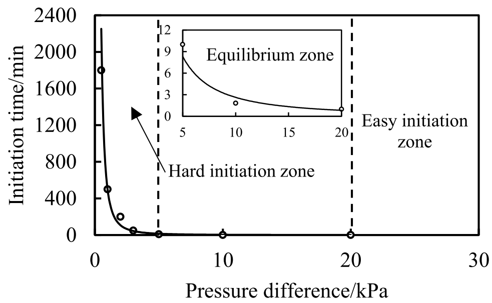

Figure 3. Start-up time under different pressure differences.

and the easy initiation phase (water-drive pressure difference greater than 20 kPa, initiation time less than 1 min). Hence, while heavy crude oil lacks an initiation pressure, an effective initiation threshold exists in engineering applications to ensure the industrial production efficiency.

3.1.2. Impact of Pressure Difference Changes. Building upon Section 3.1.1 and using the experimental setup described in Section 2.2, inlet pressures of 5, 10, and 20 kPa were set. By adjusting the height of the outlet bucket on the top using a rotating pulley, the bottomhole pressure fluctuations were controlled to investigate the impact of different pressure differences on heavy oil start-up. The physical processes of heavy oil start-up and the dynamics of oil−water movement under different pressure fluctuations were similar to those under different pressure difference. Under a pressure fluctuation with an amplitude of 0.5 kPa, the start-up time was observed as shown in Figure 4.

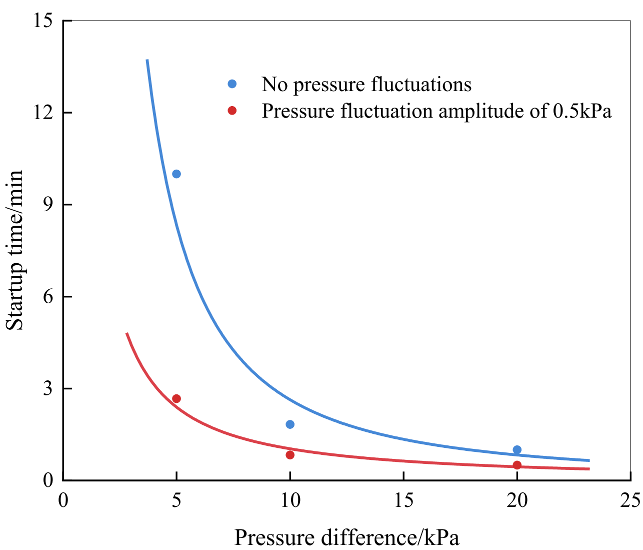

Figure 4. Impact of pressure fluctuations on start-up under different pressure difference (pressure fluctuation 0.5 kPa).

From Figure 4, it can be seen that pressure fluctuations at different pressure differences can all reduce the start-up time. Under the same pressure fluctuation, smaller pressure difference results in greater reductions in start-up time. The reason for this is that the fluid needs to overcome a series of resistance effects, including viscous resistance and adsorption resistance, to initiate flow. Continuous changes in pressure under pressure fluctuations create positive and negative perturbations in the reservoir, reducing the adhesive force and viscous resistance of the fluid on the rock surface. The periodic pressure changes also create pressure waves in the rock matrix and pores, promoting relative movement of the liquid. As a result, fluid movement and start-up are more likely to occur during the alternating changes in external forces. Therefore, different pressure fluctuations can all reduce the start-up time. In addition, a smaller baseline pressure results in more pronounced positive and negative disturbances within the reservoir under the same pressure fluctuation. Conversely, with a larger baseline pressure, the effects of the pressure fluctuation on pressure changes and transmission within the reservoir are weakened. Hence, a smaller baseline pressure leads to a greater reduction in start-up time.

Figures 5 and 6 investigate the start-up times under a pressure difference of 20 kPa with pressure fluctuation periods

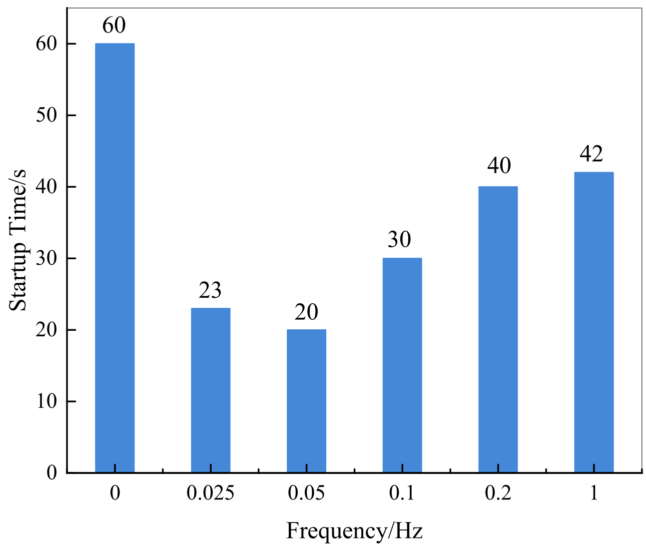

Figure 5. Influence of fluctuation frequency on start-up time.

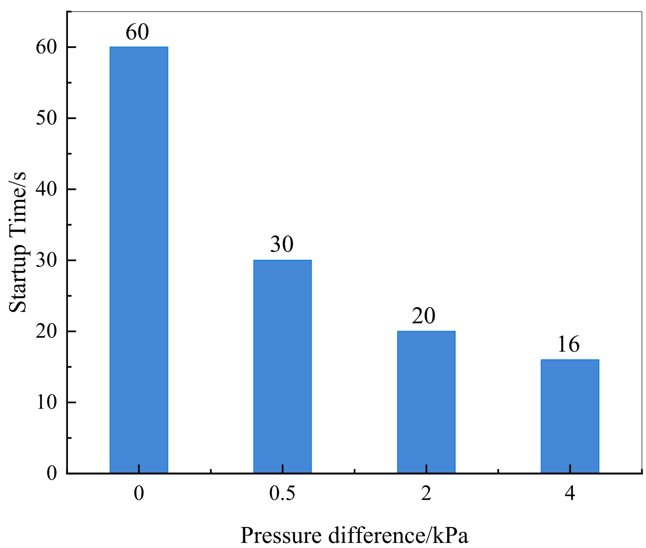

Figure 6. Influence of fluctuation amplitude on start-up time.

of 20 s and pressure fluctuation amplitudes of 0.5, 2, and 4 kPa and pressure fluctuation amplitude of 2 kPa with pressure fluctuation periods of 0 s, 1 s (1 Hz), 5 s (0.2 Hz), 10 s (0.1 Hz), 20 s (0.05 Hz), and 40 s (0.025 Hz).

Figure 5 illustrates that as the fluctuation frequency increases, the start-up time exhibits a decreasing-then-

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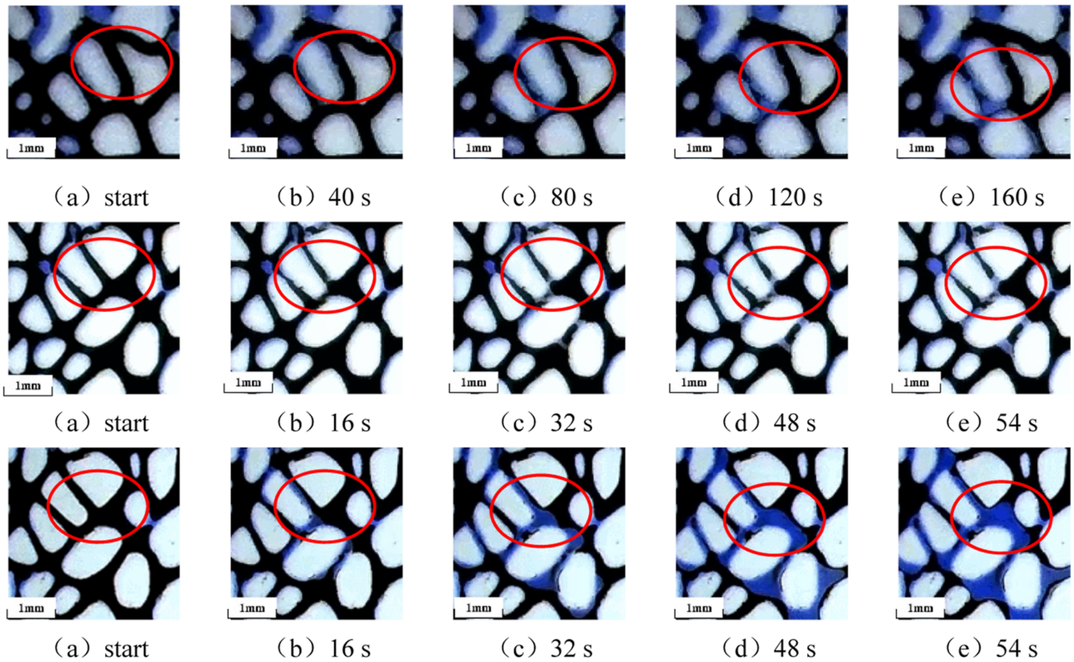

Figure 7. Process of water film thickening under different pressure differences (from top to bottom: 5, 10, and 20 kPa).

increasing trend with respect to the fluctuation frequency. When the frequency of fluctuations is high, pressure changes happen so quickly that there is not enough time for the pressure fluctuations to respond between the fluid and the flow-solid interfaces. As a result, the changes in pressure difference have a relatively small impact on the viscous resistance and adhesion resistance between the fluid and flow-solid interfaces. On the other hand, when the frequency of fluctuations is too low, close to the lack of pressure fluctuations, start-up times tend to be longer.

The results in Figure 6 reveal that start-up times are inversely correlated with fluctuation amplitudes, with the reduction effect diminishing as the amplitude increases. The analysis suggests that under a certain pressure difference, applying specific pressure disturbances results in shearing movements between the viscous fluid and solid surfaces as well as between viscous fluids and fluids. This effectively reduces the adhesion resistance and absorption resistance at the solid−liquid and liquid−liquid interfaces, swiftly breaking the mechanical equilibrium and thus lowering the start-up times. However, under the same physical conditions, as the fluctuation amplitude increases, the decrease in start-up times becomes less pronounced. This is because as the fluctuation amplitude exceeds the critical value required for fluid-flow viscosity in flow-solid interactions, the impact of increasing fluctuation amplitudes on the start-up time becomes less significant.

3.2. Impact Mechanism of Microscopic Percolation in Heavy Crude Oil Percolation.

3.2.1. Impacts of Different Pressure Differences. On the basis of the start-up experiments, microdisplacement experiments with pressure differences of 5, 10, and 20 kPa were conducted to analyze the different pressure difference effects on oil−water percolation and distribution, elucidating the mechanism of pressure difference effects on the microscopic percolation of heavy crude oil. It can be observed from the water flooding process under different pressure differences that, under low-pressure difference conditions (5 kPa), the main process during the displacement is the thickening of the water film. At 10 and 20 kPa, during the early stage of water flooding, there is still a dominant process of water film thickening, even in the water-free production stage. Furthermore, from Figure 7, it can be seen that the process of water film thickening varies under different pressure differences. Due to the hydrophilic nature of the glass slide, the wettability effect is dominant under low-pressure difference, resulting in most of the water film gradually crawling and thickening toward the center along the wall. As the pressure difference increases, this phenomenon gradually weakens. At 20 kPa, the water film starts crawling and thickening from one side of the capillary wall, leading to the predominance of clustered residual oil, water-encased oil columns, and blind-end residual oil under a low-pressure difference. Under high-pressure difference, a large amount of membrane-like residual oil attaches to the rock surface (see Figure 8), which is also a factor leading to the difficulty in improving the recovery in the late stage of high water content.

In the mid-to-high water content period, there is a phenomenon of aggregation and restarting in the regions that have already been swept, showing a dynamic process of "aggregation-dispersion-reaggregation-redispersion". The larger

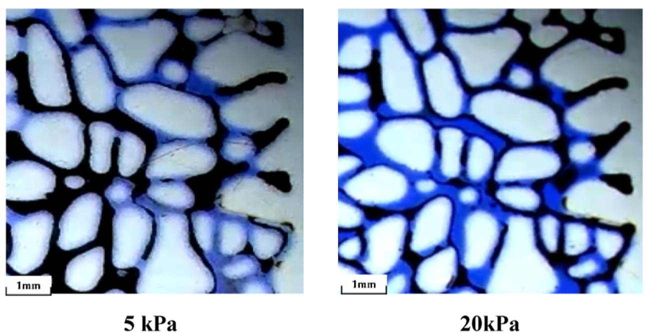

Figure 8. Distribution patterns of remaining oil under different pressure differences.

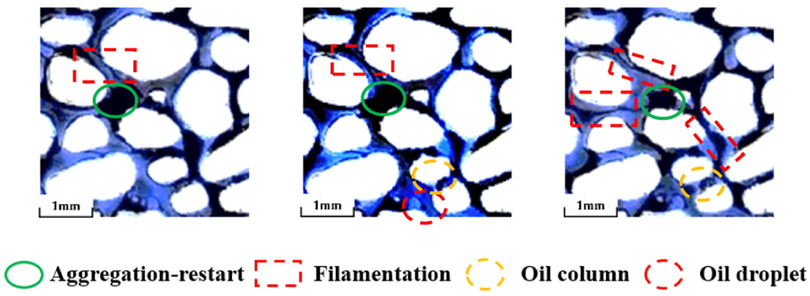

Figure 9. Process of aggregation, initiation, and displacement during the high water-cut period (microscopic elongation, oil droplets, and oil columns).

the pressure difference, the shorter the time for aggregation, restarting, and reaggregation during the dynamic process. Microscopically, it is manifested as thread-like structures, oil droplets, and oil columns, as shown in Figure 9. The thread-like structure represents the movement of oil through water, causing water to be trapped in the formation. This is a key factor for heavy oil reservoirs to increase the recovery in the late high water content stage through intermolecular forces.

The final recovery rate and the occurrence of thread-like phenomena under different pressure differences are obtained through Image software recognition and statistical methods, as seen in Figure 10. From Figure 10, it can be seen that it is not

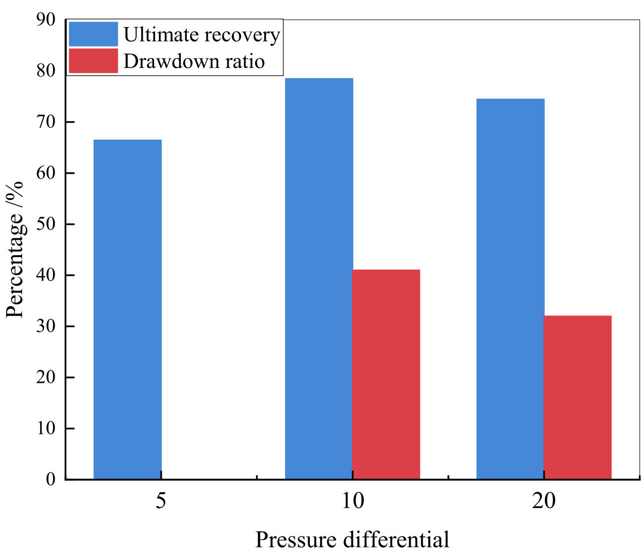

Figure 10. Recovery rates at different pressure difference and the proportion of elongation during high water-cut displacement.

that the larger the pressure difference is, the higher the recovery rate is, but rather that there is a reasonable range of pressure differences. Analysis suggests that the low-pressure difference is mainly due to the infiltration and absorption of water film thickening, and as the pressure difference increases, the driving pressure effect intensifies, while the wicking effect weakens. When the pressure difference increases to 10 kPa, a considerable number of thread-like structures appear. As the pressure difference continues to increase, the driving pressure effect significantly exceeds the wicking effect, reducing the occurrence of thread-like structures and offsetting some of the enhanced recovery due to the higher pressure difference. After a certain point of increasing pressure difference, there is a slight decrease in the recovery rate. Therefore, for heavy oil reservoirs in the mid-to-high water content stage, leveraging the synergistic effects of pressure difference and wicking is crucial for improving recovery.

3.2.2. Impact of Pressure Difference Variation. When dealing with the phenomenon of unextractable residual oil in high water-content heavy oil reservoirs, as discussed in Section 2.2, a control strategy for pressure difference variations was employed. Based on the microscopic experiment of 10 kPa pressure difference at both ends, the influence mechanism of pressure difference change on the microscopic percolation of heavy oil was explored by changing the pressure at the outlet end (the change amplitude was 2 kPa, and the frequency was 0.1 Hz). The results show that under the same pressure difference, any pressure fluctuations could promote both macroscopic and microscopic spreading. The macroscopic manifestation of the displacement process was consistent, presenting as a dynamic process of dispersion, aggregation, redispersion, and reaggregation.

However, in the process of microscopic spreading, localized pressure fluctuations induced local pressure changes in dead-end residual oil regions, directing localized liquid flow (as illustrated in Figure 11a). For contiguous cluster-like and membrane-like residual oil, pressure fluctuations caused the residual oil to deform, elongate, and move through water in the form of fine threads (or thicker threads), oil droplets, or oil columns (as shown in Figure 11b). In the case of columnar residual oil, pressure fluctuations primarily pushed, gradually breaking through the pore throats, and then elongated the oil into threads, oil droplets, ultimately displacing it (as depicted in Figure 11c). As a result, the constant pressure difference was insufficient to reach areas where microscopic residual oil could not be displaced. It did not induce significant pressure fluctuations, which limited the increase in recovery rates. Further investigation was conducted under a pressure difference of 10 kPa, with pressure fluctuation frequencies of 10 s, pressure fluctuation amplitudes of 0.5 and 2 kPa, and pressure fluctuation frequencies of 0 s, 1 s (1 Hz), 5 s (0.2 Hz), 10 s (0.1 Hz), 20 s (0.05 Hz), and 40 s (0.025 Hz). This study aimed to assess the recovery rates under these conditions, as illustrated in Figures 12 and 13.

From Figure 12, it can be observed that as the amplitude of pressure variation increases with changing pressure difference, the incremental recovery factor also increases. However, as the amplitude of the pressure variation continues to increase, the incremental recovery factor tends to stabilize. Analysis suggests that at a certain low frequency of pressure variation and a low amplitude of pressure fluctuation, the energy generated by pressure changes mainly leads to slight and continuous perturbations. This perturbation disrupts the force balance at

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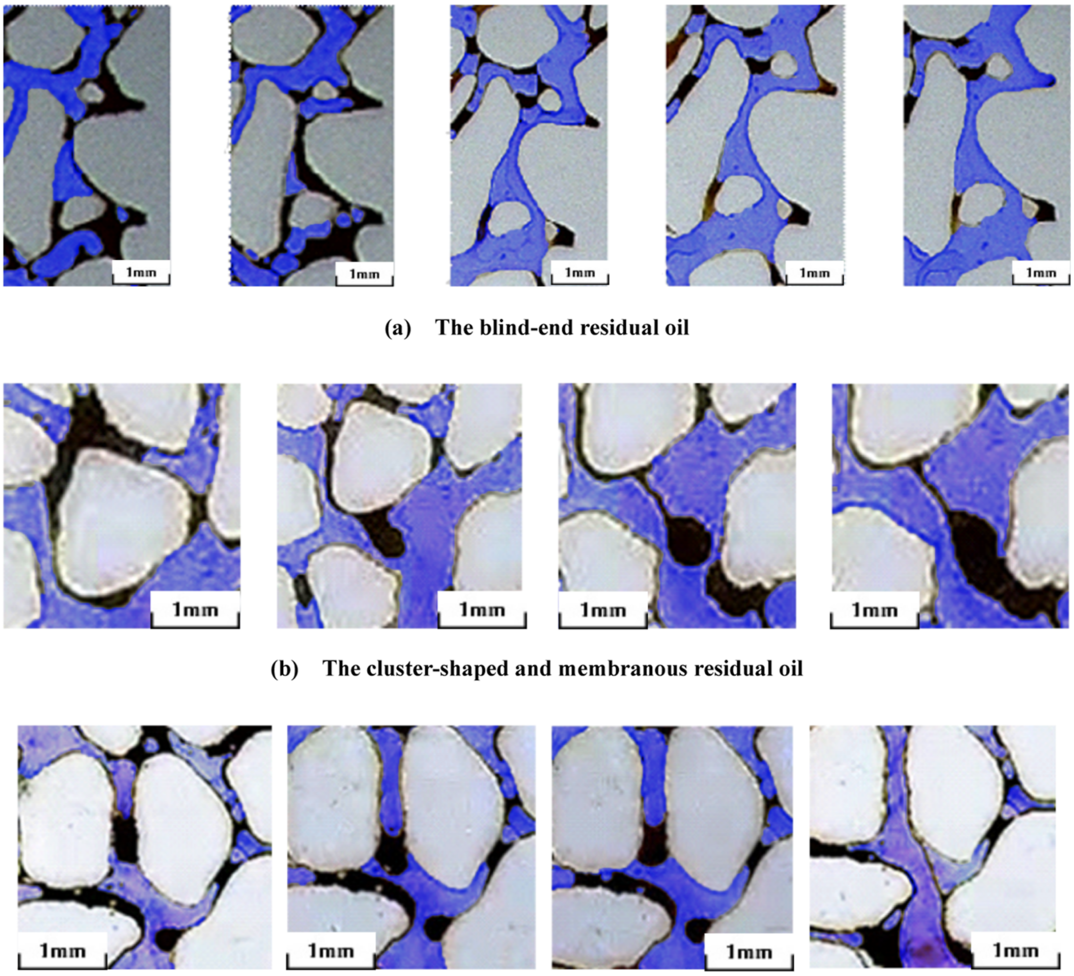

Figure 11. Displacement process of different types of residual oil under pressure fluctuations.

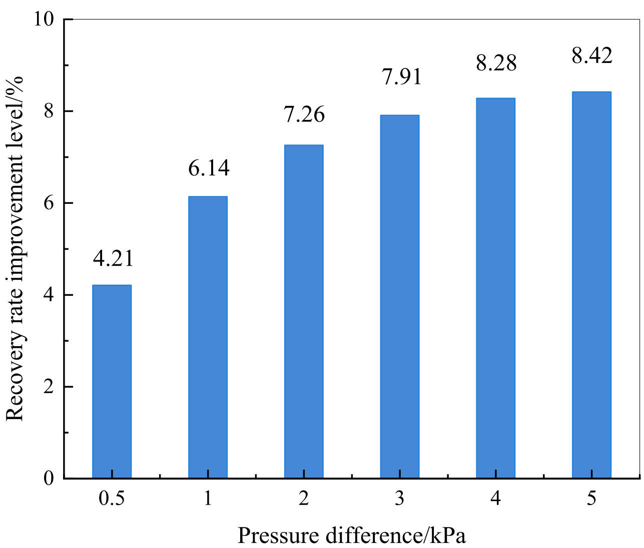

Figure 12. Influence of various pressure fluctuation amplitudes on the recovery rate (10 kPa pressure difference, 0.1 Hz frequency).

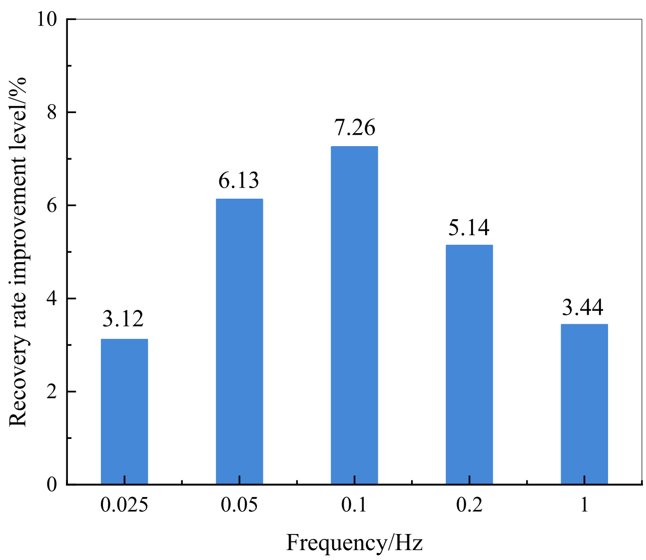

Figure 13. Impact of different pressure fluctuation frequencies on the recovery rate (10 kPa pressure difference, 2 kPa amplitude).

the fluid−solid interfaces, causing crude oil to be expelled in a dispersed form. With a larger amplitude of pressure fluctuation, the substantial perturbations generated by pressure variation not only disrupt the force balance at the fluid−solid interfaces but also produce strong positive and negative shear movements. These movements break up elongated oil columns and

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clustered oils in water into smaller oil droplets or shorter oil columns, facilitating the outflow of residual oil. However, after reaching a certain level, the incremental recovery tends to stabilize.

From Figure 13, it can be observed that when the frequency of pressure fluctuation reaches 0.1 Hz, the maximum incremental recovery factor is 7.26%. Analysis suggests that at relatively low frequencies of pressure fluctuation, the oil−water interface effects do not have sufficient time to accumulate, thereby maintaining the equilibrium of the oil−water interface under the set amplitude of pressure fluctuation. On the other hand, if the frequency of pressure fluctuation is too high, the accumulated pressure cannot propagate effectively. Subsequent pressure fluctuations intensify the main flow channels, and the higher the frequency, the shorter the propagation distance. Therefore, in the late stages of high water cut, a relatively lower frequency and higher pressure amplitude are favorable for further increasing the recovery factor.

4. CONCLUSIONS

1 Any pressure difference can initiate heavy crude oil flow, with shorter initiation times observed at higher pressure difference. The relationship between pressure difference and initiation time follows a power-law function. Based on the initiation results, three regions can be identified: a challenging initiation region, a balanced initiation region, and an easy initiation region. Therefore, although it is observed that heavy crude oil does not exhibit a critical initiation pressure gradient at the microscale (as any pressure difference can eventually initiate flow given sufficient time), operational efficiency considerations lead to the establishment of practical initiation time limits. Depending on the specific requirements, suitable production pressure difference should be chosen from the balanced and easy initiation regions for initiating and managing production processes.

2 Pressure difference changes can reduce initiation times, and under the same oscillation amplitude and frequency, smaller pressure difference leads to greater reductions in initiation times. The frequency of pressure difference changes represents an inertial effect, and higher pressure difference change frequencies result in pressure's positive and negative shear changes that fluid and solid interfaces cannot respond too quickly. Lower pressure difference change frequencies are closer to no pressure difference change, which results in longer initiation times. On the other hand, the amplitude of pressure difference changes mainly disrupts the existing mechanical equilibrium, reducing the adhesion and adsorption resistance at solid−liquid and liquid−liquid interfaces, thereby decreasing the initiation time for heavy crude oil. Larger amplitude pressure difference changes lead to shorter initiation times, but when they reach a critical threshold, further increases in amplitude have a relatively minor impact on initiation times.

3 In the case of low-pressure difference for heavy crude oil, the percolation process primarily involves the thickening of a water film crawling from the wall toward the center, driven by imbibition. As the pressure difference increases, the displacing pressure gradually balances the imbibition effect. The thickening of the water film transitions to crawling and thickening predominantly from one side of the wall, and in the middle to high water saturation phase, there is an increase in the phenomenon of "threading". With further increases in pressure difference, the displacing pressure effect becomes significantly greater than the imbibition effect. However, the "threading" phenomenon decreases and offsets some of the improvements in recovery attributed to higher pressure difference. This results in a situation where, beyond a certain point, the increase in pressure difference has a less pronounced effect on recovery. Therefore, in the middle to high water saturation phase, the synergy between pressure difference and imbibition is crucial for enhancing recovery.

4 Pressure difference variations can disrupt the oil−water distribution in the high water-cut phase, enhancing both micro and macro displacement. When pressure difference variation frequencies are low, oil−water interface deformation and solid−liquid shear effects do not have time to accumulate. However, if the pressure difference variation frequencies are too high, it strengthens the dominant flow channels and reduces the magnitude of the increase in recovery. The pressure difference amplitude primarily breaks the existing mechanical balance, causing deformation at oil−water interfaces and shear-induced disengagement at fluid−solid interfaces. A higher pressure difference amplitude results in more significant oil−water redistribution and shear disengagement. As pressure difference amplitude continues to increase, its impact on improving recovery diminishes. Therefore, in the late high water-cut phase, relatively lower frequencies and higher pressure amplitudes are conducive to further improving recovery.

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Author Contributions

L.J., O.B.M., and Y.H. are mainly responsible for experimental operations and article writing. Z.S.S., D.J., and L.Z.B. are responsible for some experimental operations and image processing. W.F.P. is responsible for experimental guidance and equipment adjustment.

Notes

The authors declare no competing financial interest.

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