Research Article

Experimental Investigation on Cyclic Huff-n-Puff with Surfactants Based on Complex Fracture Networks in Water-Wet Oil Reservoirs with Extralow Permeability

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The injection from a well to other wells can be difficult in extralow-permeability oil reservoirs. In order to address this issue, a method of cyclic huff-n-puff with surfactants based on complex fracture networks for a single horizontal well was proposed and then investigated in terms of the effects of injection and fracture parameters on the oil recovery in water-wet extralow-permeability models. Firstly, the interfacial tension (IFT) and contact angle with different surfactant concentrations were measured to determine the basic properties of the surfactants. Then, the experiments of huff-n-puff with surfactants at different threshold injection pressures and soaking time were carried out to determine the oil increasing effects and analyze the pore-scale (micropores, mesopores, and macropores) mechanisms by combining the technology of nuclear magnetic resonance (NMR), which showed that the recovery increased with threshold injection pressure mostly in mesopores and macropores, while that increased with soaking time mostly in micropores. Eventually, the experiments of cyclic huff-n-puff based on different fracture distributions were conducted in six plate-fractured models to investigate the effects of surfactants, primary fracture, and secondary fracture on each cycle of huff-n-puff. Cyclic huff-n-puff with surfactants assisted by complex fracture networks including both primary and secondary fractures would bring to a higher oil recovery. However, other methods should be taken after several cycles of huff-n-puff due to the rapid reduction of oil recovery of each cycle. The findings for the proposed method should provide a meaningful guide to the development of extralow-permeability oil reservoirs.

1. Introduction

Due to the rapid depletion of the conventional oil production as well as the growing demand for oil consumption, the petroleum industry has drawn much public attention to the exploitation of low-permeability oil reservoirs [1]. The oil production from low-permeability reservoirs has made up larger proportion of the world crude oil production, especially in the U.S. [2]. The low-permeability oil reservoirs can be

classified into three types, namely, ordinary-low (10–50 mD), extralow (1–10 mD), ultralow permeability (0.1–1 mD), and tight oil reservoirs (<0.1 mD) [3]. Among them, the extralow-permeability oil reservoirs have played an important role in the crude oil production. However, the primary recovery with natural reservoir energy for the extralow-permeability oil reservoirs is extremely low, and the oil production declines sharply owing to high flow resistance and no sufficient injection [4–8]. How to effectively improve the oil recovery

for extralow-permeability oil reservoirs has been of great importance to the development of low-permeability reservoirs.

During the secondary stage, an external fluid such as water and gas is injected into the reservoir. However, it can be much difficult to connect an injector to other producers in the extralow-permeability reservoirs without developed natural fractures or hydraulic fractures [9–11]. Through the effective hydraulic fracturing, the fluid can be injected in a larger volume into the reservoir, however, the reservoir heterogeneity will simultaneously be aggravated by the hydraulic fracturing, and the fluid will mostly flow through the fractures to the producers rather than displace the oil in matrix because of extralow matrix permeability [8, 12, 13], especially for the gas injection owing to low-gas viscosity [14–17]. The early water injection with large-scale fracturing in extralow-permeability reservoirs has been implemented in China since the late 1990s, but the average oil recovery can just be 20.5% [4]. The oil far away from the channeling fractures remains unswept in place. Therefore, the technology of huff-n-puff for a single well can be an excellent substitute to recover the oil near the well and the fractures [18–21], particularly during the early production period. Huff-n-puff covers the injection, soaking, and production cycles, which requires substantial water transfer into or out of the oil formation [8]. Both of more injection and effective water exchange for more oil in matrix can perform better and then achieve a higher oil recovery. Based on the fracture networks, the injected fluid can enter into more high oil saturation areas near the fractures [11, 22, 23]. In order to exchange for more oil, the addition of the preferred surfactants will reduce the IFT and result in wettability alteration as well as water-oil emulsification [24–30] and thus achieve more sufficient mixture of oil and water by efficient displacement and imbibition in matrix, which can be a proper way to enhance oil recovery of huff-n-puff for extralow-permeability oil reservoirs. However, the mechanisms and effects of injection and fracture parameters on huff-n-puff with surfactants are still required to be investigated in detail.

In this work, a method of cyclic huff-n-puff with surfactants based on complex fracture networks for a single horizontal well was proposed and then investigated in terms of the effects of injection and fracture parameters on the oil recovery for water-wet extralow-permeability models. The pore-scale mechanisms of huff-n-puff with surfactants at different threshold injection pressures and soaking time were analyzed by combining the technology of nuclear magnetic resonance (NMR). Moreover, based on different fracture distributions, the experiments of cyclic huff-n-puff were conducted in six plate-fractured models to investigate the effects of surfactants, primary fracture, and secondary fracture on each cycle of huff-n-puff. This work can provide a meaningful guide to the development of extralow-permeability oil reservoirs.

2. Experimental Section

2.1. Materials. The experimental water was ordinary water or deuterium oxide, and the total salinity was 20697 mg/L. The ion composition was shown in Table 1. The experimental

TABLE 1: Ion composition.

Cation (mg/L)				Anion (mg/L)			Total salinity (mg/L)
Na ⁺ +K ⁺	Ca ²⁺	Mg ²⁺	HCO ₃ ⁻	Cl ⁻	SO ₄ ²⁻	CO ₃ ²⁻	
7694	245	52	458	11876	312	60	20697

oil was obtained from Dagang Oilfield, with a viscosity of 23.8 mPa·s at 75°C. The imbibition agent was a kind of surfactant called PO-FASD with an effective content of 35% provided by CNOOC oilfield service company.

The water-wet experimental cores were made of quartz sand, curing agent phenolic, ordinary epoxy resin, as well as modified water-wet epoxy resin with modifier polyethylene glycol, propylene glycol methyl ether, and ammonium persulfate which was similar to the wettability of extralow-permeability reservoir in Dagang Oilfield [31–34]. Cylindrical cores and plate-fractured models were used in experiments. The geometric size of the cylindrical cores is about $\Phi 2.5 \text{ cm} \times 6 \text{ cm}$ with a gas permeability of about $5 \times 10^{-3} \mu\text{m}^2$, while flat fractured models have a length, width, and height of 32 cm, 9 cm, and 4.5 cm, respectively, with a matrix gas permeability of about $5 \times 10^{-3} \mu\text{m}^2$. The whole flat fractured models are sealed with epoxy resin (as shown in Figure 1(a)). A horizontal well with an inner wellbore diameter of 2 mm and a length of 25 cm is placed in the middle of the fractured model. Six inlets are set in the different place for saturating oil and water. The primary and secondary fractures are set in the models, in which the primary fractures with a half-length of 3 cm and a spacing of 5 cm are vertical to the horizontal well, and the secondary fractures with a length of 15 cm and a spacing of 3 cm are vertical to the primary fractures. Six fractured models with different fracture distributions have been made in advance (as shown in Figure 1(b)).

2.2. Instruments. Experimental instruments of huff-n-puff using cylindrical cores mainly include displacement pump, pressure sensor, core holder, hand pump, and intermediate vessel. All instruments were placed in heating box at 75°C except for displacement pump and hand pump. The instruments and procedure diagram are shown in Figure 2. NMR T_2 spectrum was measured by MacroMr12-150H-I NMR analyzer, produced by Niumag Analytical Instrument in Suzhou, China. The plate-fractured models used in cyclic huff-n-puff were placed in large-scale pressure vessel with heating function (as shown in Figure 3); the other experimental instruments are similar to the experiments using cylindrical cores. The water contact angle was measured using the contact angle meter (OCA20, DataPhysics, Germany), and the IFT was measured using the spinning drop interface tensiometer (Tx-500C, CNG USA Co.).

2.3. Methods and Procedures

2.3.1. Contact Angle Measurement. The contact angle was measured by OCA20 optical contact angle measuring instrument. In order to determine the ability of wettability alteration with surfactants, the cylindrical cores were cut into thin slices and were immersed in surfactant solution with different concentrations for 24 hours at 75°C before testing.

FIGURE 1: Plate-fractured models.

FIGURE 2: Diagram of experimental instruments and procedures.

2.3.2. IFT Measurement. The IFT between oil and water was measured by TX-500C spinning drop interfacial tensiometer at 75°C.

2.3.3. Huff-n-Puff with Surfactants Using NMR Measurements. The cylindrical cores were used in huff-n-puff experiments. The experiment procedures were as follows:

- (1) The core was dried and weighed and then saturated by deuterium oxide water. The core was weighed again, and the pore volume was calculated through the mass difference
- (2) The core was placed into the core holder to saturate oil, and oil saturation was calculated after aging time of 24 hours. The initial T_2 spectrum after saturating oil was measured by NMR

FIGURE 3: Large-scale pressure vessel.

- (3) The core was placed into core holder with the outlet closed after adding confining pressure. The surfactant solution with a concentration of 0.2% prepared by deuterium oxide water was injected with a constant rate of 0.2 mL/min until the injection pressure came to the setting maximum injection pressure that was called threshold injection pressure, and then, the inlet was closed. The inlet was opened after a specific soaking time, and the oil recovery was calculated after almost none fluid was produced
- (4) The T_2 spectrum was finally tested after huff-n-puff

The above experiments were conducted at 75°C except for saturating deuterium oxide water.

2.3.4. Cyclic Huff-n-Puff for Fractured Model. Plate-fractured models were used to conduct cyclic huff-n-puff experiments. The experimental procedures were as follows:

- (1) The plate-fractured model was saturated with experimental water at a room temperature, and the pore volume was calculated
- (2) The plate-fractured model was put into the large-scale pressure vessel in which the water was heated to 75°C, and then, the confining pressure was increased to 8 MPa
- (3) The experimental oil was injected into plate-fractured model through six inlets in turn to saturate oil, and the original oil saturation was calculated after almost none water was produced
- (4) The surfactant solution with a concentration of 0.2% prepared by ordinary water was injected with a constant rate of 0.5 mL/min from the horizontal well into the fractured model until the pressure came to 6 MPa, and then, the horizontal well was closed for soaking
- (5) The horizontal well was opened after 2-day soaking, and the oil and water production volume at different

times was recorded until almost no liquid was produced. The oil recovery was eventually calculated

- (6) The next three cycles of huff-n-puff were conducted separately by repeating steps 4 and 5

3. Results and Discussions

3.1. Effects of Surfactants on Oil-Water Interfacial Tension.

The IFT between oil and water can be much related to the capillary force and adhesive work that will influence the displacement efficiency as well as the imbibition effect, where the capillary force depends on the IFT, contact angle, and pore radius [35], and the adhesive work can be associated with the flow resistance and depends on the IFT and contact angle [36]. The oil-water IFT with different surfactant concentrations was measured as shown in Figure 4. The oil-water IFT without surfactants was 29.36 mN/m, which was much higher than that with surfactants. The oil-water IFT decreased to 0.35 mN/m with the increase in the surfactant concentration from 0 to 0.32%, whereas it increased to 0.82 mN/m with the increase in the surfactant concentration from 0.32% to 0.64%. The critical micelle concentration (CMC) could be approximately 0.32%. When the concentration comes to be more than CMC, the micelles will be gradually formed from single molecule surfactant to collective multi-molecule surfactants, which has little surface activity. In this work, the surfactant concentration in the experiments was chosen as 0.2%.

3.2. Effects of Surfactants on Water Contact Angle.

The contact angle has an important influence on the capillary force and adhesive work and then can change the huff-n-puff effect. The water contact angle with different surfactant concentrations was measured by the pendant drop method in the water-oil-rock system with the core sample slices as shown in Figure 5. The water contact angle with brine was 56.79° that indicated that the modified core samples were water-wet and water could be spontaneously imbibed into the samples by the capillary force. Moreover, the water contact angle declined with the increase in the surfactant concentration, and it could decrease to 13.82° when the surfactant concentration came to be 0.32%. The addition of surfactants could result in wettability alteration and make the samples more water-wet, which would enhance the capillary force and reduce the oil adhesive work. That was to say that water could be more easily imbibed into the samples, and oil could be more smoothly driven out from the samples, which would play a prominent role in the imbibition and displacement effects, especially for the intermediate or oil-wet reservoirs [37].

3.3. Pore-Scale Mechanisms of Huff-n-Puff at Different Threshold Injection Pressures.

The experiments of huff-n-puff at different threshold injection pressures by NMR measurements were carried out to investigate the effects of threshold injection pressure on oil recovery as well as the pore-scale mechanisms of huff-n-puff with surfactants in extralow-permeability sandstones. The oil recovery for each experiment at different threshold injection pressure is listed in Table 2.

FIGURE 4: Relationship between IFT and surfactant concentration.

FIGURE 5: Relationship between water contact angle and surfactant concentration.

As can be seen from Table 2, the total oil recovery of huff-n-puff with surfactants could come to be 38.6% when the threshold injection pressure was 5 MPa. The oil recovery increased with the threshold injection pressure, which could rise to 45.1% at the threshold injection pressure of 20 MPa that was 6.5% higher than that at 5 MPa. The increase in threshold injection pressure, on the one hand, can effectively increase the fluid pressure in the matrix and displace more crude oil in the subsequent production process; on the other hand, it can also expand the sweep volume of injected water entering the matrix through fractures and improve the imbibition effect between injection water and crude oil in the matrix, which will make more crude oil extracted from the matrix. The two aspects are related to the displacement and imbibition processes, respectively. In order to clarify the effects of displacement and imbibition, the T_2 spectrums were obtained before and after huff-n-puff at different threshold injection pressures (as shown in Figure 6). The longer T_2 is, the larger the pore radius is. The pore size can be classified into three types according to T_2 , namely, micro-

pores ($T_2 < 1$ ms), mesopores ($1 \text{ ms} < T_2 < 10$ ms), and macropores ($T_2 > 10$ ms). The oil recovery in each type of pores was equal to the ratio of the area between T_2 spectrums before and after huff-n-puff to the area of T_2 spectrum before huff-n-puff [38, 39]. The oil recovery calculated was shown in Figure 7.

As can be seen from Figure 6(a), the initial T_2 spectrums before huff-n-puff were similar to each other, which could also validate the core samples to be employed for the comparison of the subsequent experiments. It can also be seen from Figures 6 and 7 that the oil recovery in micropores changed little with the threshold injection pressure, whereas the oil recovery in mesopores and macropores increased evidently. The displacement force can be raised by improving threshold injection pressure and will drive out more oil from the matrix to enhance the oil recovery. However, the oil resistance and capillary force in micropores is much higher due to the small pore radius, and thus, the oil in micropores is mainly driven out by capillary force rather than the displacement force, which eventually results in the little change of oil recovery in micropores.

3.4. Pore-Scale Mechanisms of Huff-n-Puff at Different Soaking Time. The experiments of huff-n-puff at different soaking time by NMR measurements were also carried out to investigate the effects of injection pressure on oil recovery as well as the pore-scale mechanisms of huff-n-puff with surfactants in extralow-permeability sandstones. The oil recovery for each experiment at different soaking time is listed in Table 3.

As can be seen from Table 3, the huff-n-puff recovery increased 4.1% from 45.1% to 49.2% with the increase in soaking time from 24 hours to 72 hours at the same threshold injection pressure. During the soaking period, the pressure spreads deeply into the matrix, and makes more injected water enter into the deep part of the matrix. At the same time, the imbibition will occur between injected water and oil in the matrix by the actions of capillary and gravity forces, and the distributions of water and oil will be reconstructed. Therefore, with the increase in soaking time, the sweep volume of the injected water as well as the area and time of imbibition can be improved, which will result in higher oil recovery and better huff-n-puff effect.

At the same time, T_2 spectrums before and after huff-n-puff under different soaking time were also obtained as shown in Figure 8, and the oil recovery in each type of pores at different soaking time was calculated as shown in Figure 9 to analyze the pore-scale mechanisms of huff-n-puff. It can be seen that the oil recovery in each type of pores increased with the soaking time, especially in micropores. During the soaking stage, the pressure gradient come rapidly to be constant and the corresponding displacement force will be weakened, whereas the capillary and gravity forces will gradually dominate the imbibition process. Water can be imbibed into the smaller pores by the action of the capillary force, and the water imbibition volume will be enhanced with the increase in the soaking time. Meanwhile, the oil can be driven more easily out from the larger pores by the action of gravity; however, the effects of gravity will be limited due to extralow permeability.

TABLE 2: Oil recovery for each experiment at different threshold injection pressure.

Sample	Gas permeability ($\times 10^{-3} \mu\text{m}^2$)	Oil saturation (%)	Threshold injection pressure (MPa)	Soaking time (hour)	Oil recovery (%)
Core 1 [#]	5.2	60.28	5	24	38.6
Core 2 [#]	4.9	60.35	10	24	42.2
Core 3 [#]	5.1	60.37	20	24	45.1

FIGURE 6: T_2 spectra (a) before and (b) after huff-n-puff at different threshold injection pressures.

FIGURE 7: Oil recovery in each type of pores at different threshold injection pressures.

Therefore, the oil recovery in micropores increased more evidently than that in mesopores and macropores.

3.5. Effects of Surfactants on Cyclic Huff-n-Puff. The experiments of cyclic huff-n-puff with brine and surfactants using

the plate-fractured models 4[#] and 5[#] with the same fracture distribution were conducted to investigate the effects of surfactants on oil recovery of huff-n-puff for extralow-permeability sandstones. The cumulative oil recovery as well as the oil recovery of each cycle for each experiment is shown in Figure 10.

As can be seen from Figure 10, the addition of surfactants could apparently improve the cumulative oil recovery as well as oil recovery of each cycle, and the cumulative oil recovery could be more than 10% higher than that with brine. With the increase in huff-n-puff cycle, the oil recovery of each cycle decreased quickly. The surfactants can evidently lower the oil-water IFT and turn the core samples to be more water-wet and then reduce the oil adhesive work, which will weaken the oil flow resistance, and the oil can be extracted from the matrix more easily as a result. In addition, without considering the reduction of IFT, the more water-wet the rock is, the more easily the water can be imbibed into the pores. Even though the reduction of IFT will cut down the capillary force, it will enhance the displacement efficiency as well as the action of gravity. Meanwhile, the W/O/W, O/W, W/O/W, and W/O emulsions can be formed with surfactants as shown in Figure 11, which will improve the sweep efficiency, and the oil can also be extracted more smoothly as micro-emulsions [30]. Therefore, the oil recovery can be eventually enhanced by the above aspects. However, with the increase in huff-n-puff cycle, the oil volume adjacent to

TABLE 3: Oil recovery for each experiment at different soaking time.

Sample	Gas permeability ($\times 10^{-3} \mu\text{m}^2$)	Oil saturation (%)	Threshold injection pressure (MPa)	Soaking time (hour)	Oil recovery (%)
Core 3 [#]	5.3	60.37	20	24	45.1
Core 4 [#]	4.8	59.96	20	48	47.8
Core 5 [#]	5.0	60.12	20	72	49.2

FIGURE 8: T_2 spectrums (a) before and (b) after huff-n-puff at different soaking time.

FIGURE 9: Oil recovery in each type of pores at different soaking time.

FIGURE 10: Cumulative oil recovery and oil recovery of each cycle.

FIGURE 11: Emulsion images of the effluent.

the fracture will decrease rapidly and the injected water can interact with less oil, which will result in the reduction of oil recovery of the subsequent cycle. Thus, there is no need to carry out huff-n-puff again after several cycles.

3.6. Effects of Primary Fracture on Cyclic Huff-n-Puff. The experiments of cyclic huff-n-puff with surfactants using the plate-fractured models 1[#], 2[#], and 3[#] with different number of primary fractures were conducted to investigate the effects of primary fracture on oil recovery of huff-n-puff for extralow-permeability sandstones. The cumulative oil recovery as well as the oil recovery of each cycle for each experiment are shown in Figure 12.

As can be seen from Figure 12, the cumulative oil recovery as well as the oil recovery of each cycle increased with primary fracture number and the total recovery could be improved from 19.92% to 29.31%. The primary fracture has a significant effect on the oil recovery of huff-n-puff in extralow-permeability reservoirs. The longer the whole primary fracture is, the larger the contact area between fracture and matrix will be, which can effectively increase the interaction volume between water and oil and then bring to better effects of imbibition and emulsification. Meanwhile, more water can be injected into the rock with longer fractures and dominate larger swept volume, because of which more oil along with the effluent can be produced. Therefore, more primary fractures can contribute to higher oil recovery in extralow-permeability reservoirs. Also, other methods should be taken after several cycles of huff-n-puff due to the rapid reduction of oil recovery of each cycle.

3.7. Effects of Secondary Fracture on Cyclic Huff-n-Puff. The experiments of cyclic huff-n-puff with surfactants using the plate-fractured models 2[#], 4[#], and 6[#] with different number of secondary fractures were conducted to investigate the effects of secondary fracture on oil recovery of huff-n-puff for extralow-permeability sandstones. The cumulative oil recovery as well as the oil recovery of each cycle for each experiment is shown in Figure 13.

It can also be seen from Figure 13 that the cumulative oil recovery as well as the oil recovery of each cycle increased with secondary fracture number, and the total recovery could be improved from 24.33% to 40.00%. The secondary fracture also has an important effect on the oil recovery of huff-n-puff in extralow-permeability reservoirs. More secondary fractures can also improve the interaction

FIGURE 12: Cumulative oil recovery and oil recovery of each cycle.

FIGURE 13: Cumulative oil recovery and oil recovery of each cycle.

volume between water and oil for better effects of imbibition and emulsification and can make more water be injected into the rock and more oil be produced as well. The secondary fracture can effectively extend the dominated area of the primary fracture. Thus, the complex fracture networks including both primary and secondary fractures will bring to a higher oil recovery.

4. Conclusions

This work was conducted with two kinds of core samples to investigate the mechanisms and effects of injection and fracture parameters on huff-n-puff in water-wet oil reservoirs with extralow permeability. The cylindrical core samples were employed to analyze the pore-scale mechanisms at different threshold injection pressures and soaking time by combining the NMR technology, while six plate-fractured models were employed to determine the effects of surfactants, primary fracture, and secondary fracture on each cycle of huff-n-puff. The main conclusions are as stated below.

- (1) The oil recovery of huff-n-puff increases with threshold injection pressure mostly in mesopores and macropores, whereas that increases with soaking time mostly in micropores, which can be much related to the domination of the displacement force in the injection period and the capillary force in the soaking period
- (2) In spite of the reduction of capillary force due to low IFT, the addition of surfactants can evidently turn the core samples to be more water-wet and then lower the oil adhesive work, which will result in lower oil flow resistance, and enhance the displacement efficiency as well as the action of gravity. Moreover, emulsions can be formed with surfactants, and the oil will also be extracted more smoothly as microemulsions
- (3) Cyclic huff-n-puff with surfactants assisted by complex fracture networks including both primary and secondary fractures will bring to a higher oil recovery. However, other methods should be taken after several cycles of huff-n-puff due to the rapid reduction of oil recovery of each cycle

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.

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