Experimental investigation on influencing factors of CO$_2$ huff and puff under fractured low-permeability conditions

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**Abstract**
The fracture system is a vital component of fractured low-permeability reservoirs. The presence of fractures can improve reservoir flow capacity and injected carbon dioxide (CO$_2$) utilization, thus leading to higher oil recovery. In this study, the effects of the presence of fracture, fracture morphology, soaking time, and CO$_2$ injection volume on CO$_2$ huff and puff were investigated through 11 low-permeability cores with different properties. The experimental results indicated that the presence of fractures enhanced cyclic oil recovery and increased the effective cycle numbers during CO$_2$ huff and puff in low-permeability cores. Moreover, compared with low-permeability cores without fractures, ultimate oil recovery of CO$_2$ huff and puff was risen up by ~11% in fractured cores. Longer soaking time was conducive to enhancing ultimate oil recovery of CO$_2$ huff and puff in fractured low-permeability cores, but the excessive soaking time had little effect on ultimate oil recovery. Meanwhile, excessive CO$_2$ injection volume did not significantly improve the performance of CO$_2$ huff and puff, but it did reduce the CO$_2$ utilization. Moreover, gravity caused the produced oil to deposit on the bottom surface of the blowout end of the fracture, which made oil recovery of the core with a horizontal fracture slightly higher (~7%) than that of the core with a vertical fracture. In addition, variation in the intersection angle of fractures had little effect on ultimate oil recovery of CO$_2$ huff and puff in fractured low-permeability cores. It, however, did change the conductivity of the entire core, thus affecting oil recovery during the first two cycles remarkably.

**Keywords**
CO$_2$ huff and puff, CO$_2$ injection volume, fracture, fracture morphology, oil recovery, soaking time

**1 | INTRODUCTION**

In recent years, increasing global carbon dioxide (CO$_2$) emissions have led to the intensification of the greenhouse effect, and the research of CO$_2$ capture, utilization, and storage has become a hot topic in the fields of environment and energy. Low-permeability oil reservoirs have insufficient natural energy because of their poor physical properties and low fossil pressure, which has resulted in the lack of natural productivity. Accordingly, artificial fractures need to be formed through hydraulic fracturing to enhance the fluid flowability in low-permeability oil reservoirs. After the fracturing construction, CO$_2$ is injected into formation to dissolve with the oil. As a consequence, more oil can be produced and oil recovery can be enhanced by reducing oil viscosity, expanding oil volume, and extracting the light components of...
crude oil.9-12 Today, methods of CO₂ injection enhanced oil recovery (EOR) are used widely in oil field practice, including CO₂ flooding (CO₂ miscible flooding, CO₂ near-miscible flooding, and CO₂ immiscible flooding), CO₂ huff and puff, and CO₂-water alternate injection. Among above methods, CO₂ huff and puff has attracted more attention as an efficient and important technique.13-17

Both soaking time and CO₂ injection volume are important operation parameters to improve the performance of CO₂ huff and puff.18-23 Mohammed-Singh et al.24 summarized the cases of CO₂ huff and puff in oil fields over the past two decades. They found that the best soaking time was 2-4 weeks and massive CO₂ injection enhanced the oil recovery of CO₂ huff and puff. Sun et al.25 used the EDFM method to build a numerical compositional model for simulating CO₂ huff and puff under tight conditions. Their study showed that CO₂ injection volume had a moderate slight effect on CO₂ huff and puff, and soaking time had a slight effect on CO₂ huff and puff. Firouz and Torabi26,27 studied the operation parameters of CO₂ huff and puff via core flooding experiments. They found that longer soaking time could enhance oil recovery during the first cycles but that the ultimate oil recovery did not change noticeably. Li et al.28 studied the key operation parameters and mechanism of the CO₂ huff and puff assisted by surfactant. Their experimental results indicated that larger injection amount and excessive soaking time were not good for ultimate oil recovery.

Generally, low-permeability reservoirs have a lot of natural microfractures,29,30 and a large amount of artificial fractures are formed after hydraulic fracturing. The presence of these fractures will make the pressure-sensitive effect of low-permeability reservoir more obvious. Moreover, the opening and closing of the fracture have a significant impact on the flowability of the formation.31,32 Therefore, the effect of a low-permeability oil reservoir EOR is influenced by fractures to a great degree.33 Alfarge et al.34 found that the performance of CO₂-EOR in shale oil reservoirs was mainly determined by the natural fracture intensity and oil-pathway conductivity. Gharbi et al.35 used a random fracture distribution to simulate irregularity in a fracture network. They studied the imbibition phenomenon of the water-oil displacement process using a dual-porosity and dual-permeability model. The results showed that fracture intensity significantly affected reservoir performance, and intermediate-fracture intensity adversely affected oil recovery. Ruiz and Babadagli36 conducted static tests of hydrocarbon solvent and air injection under low-temperature oxidation conditions and considered the effect of different matrix size as well as the change in matrix-to-fracture volume ratios on oil recovery. By analyzing their results, they found that the matrix-to-fracture volume ratios played a critical role in enhancing oil recovery. In another study, Ding et al.37 systematically investigated the effect of fracture density on CO₂ flooding potential under low-permeability conditions. They found that the increase in fracture density obviously did good to recovery factor, although the presence of fractures reduced the displacement efficiency of CO₂ flooding. These previous studies and the literatures show that the fracture system is a vital component of a fractured low-permeability reservoir. Additionally, fracture conductivity and oil flow characteristics in fractures will have a remarkable impact on oil recovery.

In short, CO₂ huff and puff technology has been studied extensively in low-permeability reservoirs after fracturing,38-42 but most researchers have only paid attention to the overall performance of CO₂ huff and puff and the operation parameters. The existence of artificial fractures and the different fracture morphologies, however, will influence the fluid flowability remarkably in fractured low-permeability formations, thus affecting the production effect of CO₂ huff and puff in the end. Therefore, it is essential to study the effect of fracture and different fracture morphology on CO₂ huff and puff in fractured low-permeability reservoirs. Meanwhile, the effects of soaking time and CO₂ injection volume on CO₂ huff and puff under fractured low-permeability conditions are also worth further discussion. In this paper, the effects of the presence of fracture, fracture morphology, soaking time, and CO₂ injection volume were studied using 11 cores with different properties and the experimental results were analyzed reasonably. This study provided a basis for evaluating oil recovery of fractured reservoirs and improving production performance.

# 2 | EXPERIMENT SECTION

## 2.1 | Materials

### 2.1.1 | Oil sample

The light crude oil was sourced from an oilfield located in western China, and it was dehydrated and degassed in the laboratory. A MCR-302 Anton Paar rheometer (Anton Paar Co., Ltd.) and a density bottle were used to determine the viscosity and density of the oil sample, respectively. Its basic properties are tabulated in Table 1.

| Oil sample | Density at 338 K/(kg/m³) | Viscosity at 338 K/(mPa·s) | Wax/(wt%) | Saturate/(wt%) | Aromatic/(wt%) | Resin/(wt%) | Asphaltene/(wt%) |
|------------|--------------------------|----------------------------|-----------|----------------|---------------|-------------|-----------------|
| Light Oil  | 893.2                    | 4.5                        | 7.75      | 44.05          | 29.76         | 25.80       | 0.39            |
2.1.2 | Gas

The CO₂ used in the experiments has a purity of 99.999 mol%, which was supplied by Tianyuan Inc. It was applied in the entire research process.

2.1.3 | Brine

Deionized water was prepared by a deionizer (Ulupure Inc.), and the brine was obtained by laboratory preparation. The ionic composition of the brine is shown in Table 2.

2.1.4 | Core samples

The artificial cylindrical core samples with a diameter of 1 in. and a length of 3.74 in. were supplied by Bangda Co., Ltd., and were used to model the porous media in the experiments. The main properties of these core samples are given in Table 3.

2.2 | Apparatus

The schematic diagram of the core CO₂ huff and puff setup is shown in Figure 1. As shown, the setup consists of a high-pressure piston pump, a core holder, a temperature controlling and recording system, a data acquisition system, a manual pump, pressure sensors, back-pressure regulators (BPRs), etc. The piston pump (Model 100DX; Teledyne Co., Ltd.) was used for feeding varying fluids into the core. The core holder (Haian Oil Scientific Research Apparatus Co., Ltd., China) was placed horizontally and contained the core samples, in order to allow the fluids to flow in and out under high temperature and pressure. The pressure at different times was monitored by pressure sensors (Shanghai automation instrument Co., Ltd., China).

2.3 | Experimental procedures

In this study, the experiments were carried out at 338 K and 14 MPa, respectively. And the experimental procedures were as follows:

1. Proceed to the experiments, the core was placed in an oven and dried at 393K for 2 days. Then, it was completely vacuumed for at least 24 hours. Next, porosity (φ) and permeability (k) of the core were determined through brine injection (0.2 mL/min) by applying single-phase Darcy’s Law.

2. The oil sample was pumped into the core (0.1 mL/min) from End A until the water cut at End B reached 0%; afterward, the initial oil saturation (Sオリ) was obtained.③

3. The core sample was placed in the core holder according to the preset fracture characteristics. Afterward, End B of the core holder was closed, and the core was aged for at least 12 hours.

### Table 2  Ionic composition of the brine

| Total salinity/(mg/L) | Na⁺ | K⁺ | Ca²⁺ | Mg²⁺ | Cl⁻ | \(\text{CO}_3^{2-}\) | \(\text{SO}_4^{2-}\) | \(\text{HCO}_3^{2-}\) |
|----------------------|-----|-----|------|------|-----|----------------|----------------|----------------|
| 24 468.9             | 7074| 1049| 722.2| 118.2| 8037.2| 1132           | 2705           | 3631.3         |

### Table 3  Properties of core samples and operation parameters of CO₂ huff and puff

| Test number | Fracture condition | Porosity/(%) | Permeability/\(\times 10^{-3}\) μm² | Soaking time/(h) | CO₂ injection volume/(PV) | Blowout speed/(MPa/min) |
|-------------|--------------------|--------------|-------------------------------------|------------------|----------------------------|-------------------------|
| #1          | Free               | 7.3          | 6.86                                | 6                | 0.2                        | 1                       |
| #2          | Horizontal         | 7.4          | 5.93                                | 6                | 0.2                        | 1                       |
| #3          | Vertical           | 8.2          | 6.37                                | 6                | 0.1                        | 1                       |
| #4          | Vertical           | 8.0          | 6.37                                | 0.5              | 0.2                        | 1                       |
| #5          | Vertical           | 7.6          | 5.79                                | 2                | 0.2                        | 1                       |
| #6          | Vertical           | 7.8          | 5.79                                | 6                | 0.2                        | 1                       |
| #7          | Vertical           | 7.7          | 5.79                                | 12               | 0.2                        | 1                       |
| #8          | Vertical           | 8.1          | 6.37                                | 6                | 0.3                        | 1                       |
| #9          | 43° intersection   | 7.2          | 6.86                                | 6                | 0.2                        | 1                       |
| #10         | 68° intersection   | 7.1          | 6.53                                | 6                | 0.2                        | 1                       |
| #11         | 90° intersection   | 7.3          | 6.53                                | 6                | 0.2                        | 1                       |
4. Given amount of CO$_2$ was pumped into the core from End A (1 mL/min). After that, End A was closed, and the core was aged for given time.

5. The oil was produced at a certain pressure fall gradient after End A was opened, and the pressure and oil recovery were both recorded at different times.

6. After the first cycle of CO$_2$ huff and puff, the same amount of CO$_2$ was injected into the core again to start the next cycle; the experiment was over, while a certain cycle numbers were completed.

7. Fracture characteristics were changed, and procedures 1˜6 were repeated to investigate the effects of varying influencing factors on CO$_2$ huff and puff.

The operation parameters of cores CO$_2$ huff and puff are tabulated in Table 3.

### 3 | RESULTS AND DISCUSSION

#### 3.1 | Effect of fracture on CO$_2$ huff and puff

A large amount of fractures and microfractures are formed and distributed in low-permeability reservoirs. The presence of fractures makes the pressure-sensitive effect of low-permeability reservoirs more obvious. At the same time, the opening and closing of fractures also can have a significant impact on reservoir flow capacity. Therefore, fractures usually affect the performance of EOR in low-permeability reservoirs.29-33 In this study, a laboratory simulation experiment was carried out to investigate the effect of fractures on the CO$_2$ huff and puff of low-permeability cores. A diagram of the artificial fracture of the core sample is exhibited in Figure 2. On the basis of the results of tests #1 and #6, Figure 3 shows the comparison of oil recovery between fractured core and fracture-free core.

As shown in Figure 3A, the presence of a fracture has a significant impact on cyclic oil recovery of CO$_2$ huff and puff under similar permeability conditions. For a fractured low-permeability core (test #6), oil recovery during the first cycle was the highest (~22.94%), and compared with the first cycle, oil recovery during the second cycle decreased by ~15.11%. The oil recovery of the subsequent three cycles declined but was relatively stable, and the oil recovery of the last cycle rapidly dropped to zero. For the low-permeability core without fracture (test #1), the cyclic oil recovery was not only remarkably lower than that of the fractured low-permeability core but also could not maintain stability. As the cycle number increased, the cyclic oil recovery decreased obviously. In addition, the fractured low-permeability core could maintain CO$_2$ huff and puff in five effective cycles, whereas the low-permeability core without fracture maintained only three effective cycles during CO$_2$ huff and puff. It is evident that the core without a fracture maintained less effective cycles during the CO$_2$ huff and puff simulation and that cyclic oil recovery was lower and declined more quickly. Obviously, the presence of a fracture can enhance cyclic oil recovery, increase the effective cycle numbers, and keep the oil recovery stable for a
certain cycle numbers during CO₂ huff and puff in low-permeability cores. Figure 3B shows that as the cycle number increased, the cumulative oil recovery also increased, but the increasing trend gradually slowed down. Comparing the ultimate oil recovery of the low-permeability cores with or without fracture, it can be seen that the presence of fractures could enhance the oil recovery remarkably: For a fractured low-permeability core, ultimate oil recovery reached ~37.42%, which was ~11.1% higher than the low-permeability core without fractures (~26.32%). This difference in oil recovery could be attributed to the following: The presence of a fracture caused a large amount of CO₂ to be stored inside the fracture, and the CO₂ gradually diffused into the core matrix, which effectively increased the CO₂ sweep area and enhanced the elastic energy of the formation. This enhanced the cyclic oil recovery and increased the effective cycle numbers of CO₂ huff and puff, and as a result, produced more crude oil. Figure 4 exhibits the schematic of the CO₂ huff and puff process in fractured low-permeability cores.

The curve of pressure vs time can reflect the effect of fracture on the blowout process during CO₂ huff and puff. In this study, a BPR was used to control the blowout speed to 1 MPa/min during the blowout process. When the pressure decreased by 1 MPa, the back-pressure then was lowered by 1 MPa. Figure 5 compares the pressures of CO₂ huff and puff blowout in low-permeability cores with and without fractures.

Figure 5 shows that for a fractured low-permeability core, the pressure decreased rapidly in the initial stage of each adjustment of the back-pressure, and then, it tended to stabilize during the process of blowout. For a fracture-free low-permeability core, however, it maintained a constant pressure drop in the initial and subsequent stages after the back-pressure adjustment. Under the fracture condition, CO₂ could be stored inside a fracture, and it had a strong ability to flow. Therefore, when the back-pressure was lowered, the CO₂ in the fracture was quickly ejected because of the pressure difference between the inside and outside of the fracture. The CO₂ stopped spraying outward when the pressure dropped to back-pressure, resulting in the storage of CO₂ in the fracture. Conversely, under a fracture-free condition, the CO₂ slowly escaped outside the matrix because of the pressure fall during the blowout process, which resulted in a slower constant pressure drop. Thus, the presence of a fracture could reduce the resistance of fluid flow in the core and is beneficial to crude oil production.
3.2 | Effect of soaking time on CO₂ huff and puff

Soaking time is an essential operation parameter of CO₂ huff and puff. The reasonable soaking time can make the injected CO₂ diffuse farther into the formation, effectively increasing the CO₂ sweep area and causing CO₂ to dissolve better in crude oil. Consequently, better CO₂ utilization and higher oil recovery can be achieved.

In this study, the effect of different soaking times (0.5, 2, 6, and 12 hours) on the performance of CO₂ huff and puff was investigated (tests #4, #5, #6, and #7) under similar permeability conditions. The results are shown in Figures 6 and 7. It can be seen from Figure 6 that with an increase in soaking time, the cyclic oil recovery in the first two cycles was enhanced to varying degrees, whereas cyclic oil recovery in the third cycle remained almost the same. In particular, during the first cycle, while the soaking time increased from 0.5 to 2 hours, the cyclic oil recovery did not increase much. The cyclic oil recovery sharply increased by ~14.75% as the soaking time increased from 2 to 6 hours. When the soaking time continued to increase to 12 hours, the rise of cyclic oil recovery was smaller (only ~4%). Figure 7 indicates that when the soaking time was <6 hours, ultimate oil recovery of CO₂ huff and puff increased significantly with the increase in soaking time. But when the soaking time continued to increase to 12 hours, ultimate oil recovery was just slightly higher than that at 6 hours. When the soaking time was <6 hours, as the soaking time increased, CO₂ continued to diffuse farther into the core from the injection end. Therefore, the CO₂ could interact with more crude oil in the core, which improved crude oil production. After the soaking time was more than 6 hours, as the soaking time increased, the CO₂ moving front preceded the pressure wave front in the core, causing more CO₂ to move outside the pressure drop funnel. Thus, the energy of CO₂ was lost and CO₂ played a weak role during the process of production, resulting in less oil production. According to this finding, it could be concluded that an increase in soaking time was conducive to improving ultimate oil recovery of CO₂ huff and puff, but excessive soaking time had little effect on ultimate oil recovery. Therefore, under the experimental conditions of this study (temperature at 338 K, pressure at 14 MP, and permeability at $6 \times 10^{-3} \mu m^2$), the optimal soaking time was 6 hours.

3.3 | Effect of injection volume on CO₂ huff and puff

CO₂ injection volume is another operation parameter of CO₂ huff and puff. Reasonable CO₂ injection volume not only
ensures higher oil recovery but also achieves higher CO\textsubscript{2} utilization.\textsuperscript{25,28} In this study, effect of different CO\textsubscript{2} injection volumes (0.1 PV, 0.2 PV, and 0.3 PV) on the performance of CO\textsubscript{2} huff and puff was investigated (tests #3, #6, and #8; see the results in Figures 8 and 9). Figure 8 clearly shows that with an increase in CO\textsubscript{2} injection volume, oil recovery during each cycle varied inconsistently. Specifically, the oil recovery during the first cycle increased remarkably with CO\textsubscript{2} injection volume and then decreased slightly; the oil recovery of the subsequent two cycles both increased slightly with CO\textsubscript{2} injection volume. As shown in Figure 9, when the CO\textsubscript{2} injection volume increased from 0.1 to 0.2 PV, ultimate oil recovery of CO\textsubscript{2} huff and puff was risen up significantly by ~10.36%. Ultimate oil recovery increased only by ~0.17%, however, as the CO\textsubscript{2} injection volume increased from 0.2 PV to 0.3 PV. These results suggested that the process of CO\textsubscript{2} huff and puff in fractured low-permeability reservoirs has two main mechanisms, and they interact with each other:\textsuperscript{45} (a) The CO\textsubscript{2} had a viscosity reduction and swelling effect on the crude oil, and (b) the CO\textsubscript{2} pushed the crude oil farther into the core. At the beginning of CO\textsubscript{2} injection, the main mechanism was a viscosity reduction and swelling effect of CO\textsubscript{2} on crude oil, and oil production increased. As CO\textsubscript{2} continued to be injected, however, it could not be dissolved any more in the crude oil; thus, the second mechanism worked more obviously, and the CO\textsubscript{2} pushed the oil to the deeper core. Additionally, CO\textsubscript{2} was prone to gas breakthrough at this time, and the CO\textsubscript{2} sweep volume increased slightly. When considered in real oil field practice, it is not necessary to use excessive CO\textsubscript{2} injection for CO\textsubscript{2} huff and puff in fractured low-permeability reservoirs. Excessive CO\textsubscript{2} injection will not significantly improve the performance of CO\textsubscript{2} huff and puff, but it will reduce CO\textsubscript{2} utilization. Therefore, an optimal CO\textsubscript{2} injection volume should be selected to maximize economic benefits and oil recovery. In this study, 0.2 PV was the optimal CO\textsubscript{2} injection volume.

3.4 | Effect of fracture morphology on CO\textsubscript{2} huff and puff

The fracture system is an important component of fractured low-permeability reservoirs, and its main features include high permeability, strong flow capacity, and high oil production. The change in fracture morphology in the core directly affects the flow capacity of the fracture and the flowing characteristics of crude oil during CO\textsubscript{2} huff and puff, which in turn will affect ultimate oil recovery of CO\textsubscript{2} huff and puff. In this study, the production characteristics and ultimate oil recovery of CO\textsubscript{2} huff and puff in cores with horizontal fractures, vertical fractures, and complex fractures with different intersection angles were studied and compared under conditions of similar permeability and with the same operating parameters.

Tests #2 and #6 were carried out to investigate the effects of vertical and horizontal fractures on CO\textsubscript{2} huff and puff of low-permeability cores under conditions of similar permeability. The correlation between the cycle number of cores and cyclic oil recovery with different fracture morphologies was identified, as illustrated in Figure 10. It was noted that oil recovery during the first two cycles in the core with a horizontal fracture (permeability at 5.93 × 10\textsuperscript{-3} μm\textsuperscript{2}) was slightly higher (~3%) than that in the core with a vertical fracture (permeability at 5.79 × 10\textsuperscript{-3} μm\textsuperscript{2}); however, the gap between the oil recoveries in the third cycle was reduced to ~1%.

This difference in oil recovery of CO\textsubscript{2} huff and puff was caused by the horizontal and vertical fracture morphologies. This difference was mainly attributed to the fact that during the blowout process in the core with a vertical fracture, the produced light oil was transported from the core matrix to the
fracture. Because of gravity, a large amount of produced oil could not be carried out by the CO2 and then was deposited on the bottom surface of the blowout end of fracture in the core. Figure 11 presents the sectional view of the vertical fracture in the core after CO2 huff and puff (test #6). As Figure 11 demonstrates, the lower right end of the core, which was also at the bottom of the blowout, was darker than other parts of the core because of the remaining oil deposition. For the core with a horizontal fracture, the produced oil was transported to the fracture without being affected by gravity, so there was no remaining oil deposition. Therefore, the oil recovery of the core with a horizontal fracture was higher than that of the core with a vertical fracture under similar permeability conditions.

In this study, the CO2 huff and puff simulation of low-permeability cores with different fracture intersection angles was conducted to further investigate the effect of fracture morphology on CO2 huff and puff under complex fracture conditions. Figure 12 shows a schematic diagram of the artificial fracture intersection angles in the cores. The CO2 huff and puff simulations of cores with fracture intersection angles of 43°, 68°, and 90° were performed (tests #9, #10, and #11); the results are shown as Figures 13 and 14.

According to Figure 13, the intersection angle of fractures in the cores had a significant effect on the CO2 huff and puff during the first two cycles, whereas oil recovery during the third cycle remained at a lower value. In the third cycle, the maximum difference of oil recovery among the different fracture angles was only ~0.49%. For the first cycle, when the intersection angle of the fracture was 43°, the oil recovery was ~32.47%. It decreased sharply to ~26.16% as the intersection angle increased to 68°. As the fracture intersection angle continued to increase to 90°, however, oil recovery increased significantly up to ~34.19%. For the second cycle, the variation in oil recovery under different fracture intersection angle conditions was exactly opposite. Specifically, the oil recovery was ~9.48% when the intersection angle of the fracture was 43°, and it increased to ~12.5% as the intersection angle increased to 68°. The oil recovery decreased to ~8.55%, however, when the intersection angle continued to increase to 90°. Figure 14 compares ultimate oil recovery at different fracture intersection angles. As Figure 14 shows, ultimate oil recovery at an intersection angle of 68° was lower (only ~41.57%) during CO2 huff and puff. 
And ultimate oil recovery at intersection angles of 43° and 90° was almost the same, respectively, at 44.45% and 45.16%.

According to these results, variation in the intersection angle of the fracture did affect oil recovery during the first two cycles. This was caused by the impact of the fracture intersection angle on the fracture conductivity of the entire core. When the intersection angle increased from 43° to 68°, the fracture conductivity was significantly reduced. This made it difficult for some of the crude oil to be carried outside the core by the CO2 because of high flow resistance during the first cycle, which greatly reduced oil recovery. During the second cycle of CO2 huff and puff, however, crude oil that was not produced outside the core continued to be produced, resulting in an increase in oil recovery during the second cycle and a smaller difference in ultimate oil recovery.

4 | CONCLUSIONS

In this study, CO2 huff and puff simulation of the 11 low-permeability cores with different properties was conducted to investigate the effects of the presence of fracture, fracture morphology, soaking time, and CO2 injection volume. On the basis of the study, the following conclusions can be drawn:

1. The presence of a fracture enhanced cyclic oil recovery, increased the effective cycle numbers, and kept recovery stable for a certain cycle numbers during CO2 huff and puff in low-permeability cores. Moreover, compared with low-permeability cores without fractures, ultimate oil recovery of CO2 huff and puff was risen up by ~11% in fractured low-permeability cores. In addition, the fracture reduced the resistance of fluid flow in the core, which was beneficial to crude oil production.

2. Longer soaking time was conducive to enhancing ultimate oil recovery of CO2 huff and puff in fractured low-permeability reservoirs, but the excessive soaking time had little effect on ultimate oil recovery. Meanwhile, a reasonable CO2 injection volume was also critical. Excessive CO2 injection volume did not significantly improve the performance of CO2 huff and puff, but it did reduce CO2 utilization.

3. Gravity caused the produced oil to deposit on the bottom surface of the blowout end of the fracture, which made oil recovery of CO2 huff and puff in the core with a horizontal fracture slightly higher (~7%) than that in the core with a vertical fracture. Additionally, variation in the intersection angles of the fracture had little effect on ultimate oil recovery of fractured low-permeability cores. It did change, however, the conductivity of the entire core, thus affecting oil recovery during the first two cycles remarkably.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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