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Investigation of effect and mechanism of active water and CO_2 huff-and-puff on enhanced oil recovery in tight reservoirs

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Abstract:
Huff-and-puff is a key technology for the efficient recovery of oil and gas from tight reservoirs. Active water and CO_2 are two huff-and-puff media with great development potential; however, their effects on enhanced oil recovery and the contribution of imbibition displacement to enhanced oil recovery need further investigation. In this paper, short cores were spliced into long cores for huff-and-puff experiments, and then nuclear magnetic resonance testing was performed to test the transverse relaxation time spectrum of different core sections at different huff-and-puff cycles. Subsequently, the enhanced oil recovery effects, limited effective distances, and influencing factors of active water and CO_2 huff-and-puff were evaluated. Meanwhile, a comparative experiment without well soaking in some specific huff-and-puff cycles was designed to quantitatively split the contribution rate of elastic displacement and imbibition displacement. The results show that active water huff-and-puff mainly mobilizes crude oil in large pores, while CO_2 huff-and-puff can also mobilize crude oil in small pores. The cumulative oil recovery of active water and CO_2 after 4 cycles of huff-and-puff was 24.78% and 40.89%, respectively, and the limited effective distances were 6-8 cm and 8-10 cm, respectively. Elastic displacement is considered the main enhanced oil recovery mechanism of active water and CO_2 huff-and-puff, while imbibition displacement accounts for 20.86% and 31.52%, respectively. Due to its good diffusion and mass transfer ability, CO_2 can more fully participate in the mechanism of imbibition displacement and further improve oil recovery. The findings of this paper can provide valuable theoretical and field data support for the application of huff-and-puff technology in tight reservoirs.

1. Introduction

The recently discovered oil and gas reserves in China are mainly in tight and shale oil reservoirs, indicating that unconventional oil and gas exploration and development is expected to become the main playing field for the extraction of oil and gas resources. Tight reservoirs are characterized by slow pressure transmission, fast energy decline, and difficulty in energy replenishment, which leads to low oil recovery rates in the development of depleted resources (Ahmed and Meehan, 2016). In oilfield practice, fluid media are usually injected after fracturing to replenish the formation energy, and

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the development method of energy replenishment and huff-and-puff is normally used to improve the recovery rate of tight reservoirs (Yu et al., 2018; Liu et al., 2020; Shun et al., 2020). The most commonly used energy replenishment media are formation water (Chen et al., 2018; Qin et al., 2021), active water (surfactant aqueous solution) (Maurich, 2019), and gas (air, CH_4, N_2, CO_2, etc.) (Ganjdanesh et al., 2020; Liu et al., 2022; Sie and Nguyen, 2022). Formation water huff-and-puff operation has been regarded as simple and cost-effective, with the low interfacial tension characteristics of active water and the high compressibility of gas giving it considerable application potential. However, the complex mechanism of active water and CO_2 energy replenishment and huff-and-puff still requires in-depth indoor theoretical and experimental research (Cai et al., 2010; Wei et al., 2018).

Active water can reduce the oil-water interfacial tension, play a role in reducing pressure and increasing injection, and allow for increasing the amount of water injected during the energy replenishment process (Meng and Cai, 2018; Liu et al., 2023). Meanwhile, surfactants can play a role in wetting reversal, enhance the hydrophilicity of rocks and facilitate the stripping and recovery of oil films adhering to the pore walls (Lotfollahi et al., 2017). Lower oil-water interfacial tension and wetting reversal can promote the oil-water replacement effect inside the pore throat and enhance the water-phase imbibition effect (Cai et al., 2020). Core flooding experiments combined with nuclear magnetic resonance scanning are currently the main methods to study the effect of huff-and-puff in enhanced oil recovery (Cudjoe et al., 2021). The experimental and simulation research results of Lu et al. (2023) showed that surfactant energy replenishment can increase the oil recovery rate of unconventional reservoirs by 2.55%-17.12%. Shuler et al. (2016) found that active-water huff-and-puff experiments can further increase the oil recovery rate by 20% after five rounds of formation water huff-and-puff. Ataceri et al. (2024) introduced the field application cases of surfactant huff-and-puff in two wells of the Eagle Ford Shale. A high proportion (95%) of the injected surfactant could be stably adsorbed in the reservoir, continuously improving the reservoir's physical properties and increasing the oil production by 2-5 times, and the effective period could last for more than two years. The experimental results of Hao et al. (2024) showed that the final oil recovery factors of brine, surfactant and CO_2 huff-and-puff were 11.5%, 29.3%, and 45.9% respectively. In addition, the effect of active water huff-and-puff was significantly better than that of brine, while the effect of CO_2 huff-and-puff was the best. This is mainly because CO_2 has stronger compression and expansion properties (Zhou et al., 2020), thus can fully play the role of elastic displacement to replace crude oil. Besides, CO_2 has the beneficial characteristics of diffusion mass transfer, extraction and the reduction of crude oil viscosity, leading to efficient permeation and displacement. In addition, CO_2 huff-and-puff and other technologies for improving oil recovery also have the function of CO_2 geological storage, making it a hot topic of research (Chen et al., 2023, 2024; Yin and Zhang, 2024). Experimental and simulation studies on CO_2 huff-and-puff originated in the 1990s (Thomas and Monger-McClure, 1991). Yu et al. (2014) analyzed the production data of the Bakken shale reservoir gathered for nearly 30 years and showed that CO_2 huff-and-puff technology can improve the oil recovery factor by 9.4%. Zuloaga et al. (2017) established a large reservoir model based on the Bakken reservoir and verified that, for tight reservoirs with a matrix permeability of less than 0.1 mD, the CO_2 huff-and-puff development effect is obvious due to the continuous displacement of CO_2 (Yu et al., 2014). The experimental results of Ding et al. (2021) showed that the final oil recovery rate of CO_2 huff-and-puff can reach 58%, which is more than 10% higher than that of CH_4 huff-and-puff. The experimental data of Huang et al. (2023) showed that the final oil recovery rate of CO_2 huff-and-puff gradually increased with the experimental temperature, and the overall recovery rate was between 23.1% and 46.1%. Li et al. (2018) compared the development effects of miscible CO_2 huff-and-puff and immiscible CO_2 huff-and-puff via experiments. The final oil recovery rate after 7 rounds of huff-and-puff could reach 68%, and the miscible CO_2 huff-and-puff was 9.1% higher than the immiscible CO_2 huff-and-puff. In addition, surfactant-assisted CO_2 huff-and-puff was also shown to have considerable synergistic effects (Adel et al., 2018; Zhang et al., 2018a; Wei et al., 2020). Lv et al. (2024) used a non-ionic surfactant to assist CO_2 huff-and-puff, and its oil recovery rate could be increased by 9.7%-13.2% compared with CO_2 huff-and-puff development.

The above research results consistently show that activated water and CO_2 huff-and-puff have considerable development effects, while the range of ultimate oil recovery obtained by different scholars varies greatly. This is mainly because huff-and-puff is greatly affected by core permeability and pore throat structure. Thus, the use of different types of cores (varying in pore throat size, permeability, fractures, etc.) will have a significant impact on the final oil recovery rate (Ma et al., 2019; Wan et al., 2024). On the other hand, the huff-and-puff development effect is jointly affected by the number of huff-and-puff rounds, well soaking time, medium injection volume, mining pressure difference, and other injection and production parameters (Yu et al., 2018; Zhang et al., 2018b; Wang et al., 2021b; Ding et al., 2024). Differences in the indoor research and mine application parameter settings will cause large variation in the results. Therefore, although it is difficult to compare data among different literatures horizontally, it is generally accepted that the CO_2 huff-and-puff effect is better than that of active water and formation water. In addition, the pore-throat-produced characteristics of active water and CO_2 are also the focus of research, which are usually studied using nuclear magnetic resonance technology, CT scanning technology, and large-scale three-dimensional physical simulation technology (Adel et al., 2018). The liquid-phase medium mainly produces crude oil in large pore throats, and the development effect of cores with small pore throats is even more significant during CO_2 huff-and-puff development. The crude oil in large pores is mainly produced through the elastic energy of the injected fluid, while the crude oil in small pores is mainly produced through fluid imbibition. Huff-and-puff is a forced imbibition process, which can more fully replace the crude oil in small pores and improve oil recovery.

Although the current research on the active water and CO_2 huff-and-puff development is relatively comprehensive and systematic, two shortcomings still exist:

1) Active water and CO_2 huff-and-puff have a certain effective range of action. The existing research focuses on the pore throat utilization limit but lacks research on the limited effective distance of the two processes.
2) The mechanisms of active water and CO_2 huff-and-puff development mainly include elastic displacement and imbibition displacement. Imbibition displacement is a process that can further improve the oil recovery through scheme optimization, reagent development, etc., therefore it is necessary to quantitatively split its enhanced oil recovery (EOR) proportion.

On the basis of the existing research foundation and problems, this paper uses an experimental method combining multi-section splicing core displacement with nuclear magnetic resonance monitoring technology to study the action limit, pore throat utilization characteristics, and action mechanism splitting of active water and CO_2 huff-and-puff development. Firstly, 5 core sections were spliced into long cores to carry out 4 rounds of active water and CO_2 huff-and-puff. After each round, nuclear magnetic resonance tests were conducted to clarify the development effect, effective distance, and pore throat utilization characteristics. Meanwhile, the EOR effects of different huff-and-puff rounds and well soaking time on the oil recovery factor could also be analyzed. Secondly, the contribution rates of elastic displacement and imbibition displacement of active water and CO_2 huff-and-puff processes were quantitatively split through the combination of soaking and non-sewage in specific huff-and-puff rounds. The results can provide ideas and data support for indoor research and oilfield application of active water and CO_2 huff-and-puff.

2. Materials and methods

2.1 Materials

Natural cores with a diameter of 2.5 cm and a gas permeability of about 0.250 mD were cut into blocks (2 cm) using a cutter. The core was dense sandstone with a bimodal distribution of pore throats ranging from 0.001 to 50 μm. Five short core blocks were spliced into a long core with a total length of 10 cm for the huff-and-puff experiment. The EOR effect and residual oil change law in different pore throat sizes could be evaluated through the crude oil signal value recorded by nuclear magnetic resonance.

The simulated oil was a compound of degassed and dehydrated crude oil and kerosene, with a viscosity of 1.85 cP at 55 °C; the simulated formation water with a salt content of 5,000 mg/L was prepared from heavy water; the surfactant was SDS, with a mass concentration of 0.1 wt%; the CO_2 used had a purity of 99%.

2.2 Experimental process

This paper conducted huff-and-puff experiments with active water and CO_2. The experiment uses a core holder to simulate the reservoir, injects formation water to simulate the original formation pressure of the reservoir of 25 MPa, and employs a back pressure valve to control the minimum bottom hole flow pressure (after literature research and field practice, the bottom hole flow pressure is selected as 5 MPa). After injecting the energy replenishment medium and soaking the well, the fluid in the core will be produced under a constant pressure difference, constituting a huff-and-puff cycle. By comparing the huff-and-puff oil recovery rate and the degree of utilization of each core under different experimental conditions, the EOR effect of active water/CO_2 huff-and-puff and the limited effective distance can be clarified. The specific experimental plan is shown for Experiments 1-8 in Table 1.

The following experimental scheme was implemented:

1) Number 5 cores in order, dry them in an oven and weigh their dry weight as m_1 after cooling. Place the cores in a column container filled with simulated formation water and use a vacuum pump to evacuate them for more than 24 hours. Take out the cores, wipe off the floating water on the surface, and weigh their wet weight m_2 to calculate the core porosity;
2) Put the cores saturated with water into the core holder in turn, connect the experimental process according to the flowchart shown in Fig. 1 and check for air tightness;
3) Use a hand pump to apply a confining pressure of 20 MPa to the core holder, saturate the simulated oil at a constant pressure of 5 MPa, and when oil is seen at the outlet of the holder, continue to saturate at a constant pressure of 10 MPa until the oil output at the outlet reaches 2 times the pore volume. Close the valves at both ends of the core and age it for 48 hours under experimental conditions. Then, take the cores out and perform the first nuclear magnetic resonance scan to obtain the saturated oil signal;
4) Load the core into the core holder again in order, use the injection fluid to drain the injection end and the production end, close the outlet valve, and check the process for air tightness;
5) Inject active water/CO_2 into the holder inlet at a constant pressure, increase the injection pressure in a stepwise manner until it reaches 17 MPa, then close the inlet valve. Set the outlet pressure to be constant at 12 MPa through the back pressure valve after well soaking according to the experimental plan, open the outlet valve, and use the oil-gas-water metering device to collect the produced fluid until the outlet does not produce liquid. Record the oil and water production during the huff-and-puff process, take out the core, and perform nuclear magnetic resonance testing to obtain the oil phase signal value of each core after this round of huff-and-puff;
6) Repeat step (5) to perform 4 rounds of active water/CO_2 huff-and-puff processes;
7) Clean up the experimental process, replace the cores and continue the experiment according to the experimental plan.

The nuclear magnetic resonance test requires three parallel runs. If the error does not exceed 10%, the average value of the three groups is taken as the final result; otherwise, the

Table 1. Schemes of active water/CO_2 supplementary energy huff-and-puff experiment.

Medium	Target	Huff-and-puff cycle	Time (h)
Active water	Comparative analysis of the imbibition oil production rules of different energy-replenishing media under different well soaking times	4	4
		4	12
		4	24
		4	48
CO_2	Comparative analysis of the imbibition oil production rules of different energy-replenishing media under different well soaking times	4	4
		4	12
		4	24
		4	48
Active water	Quantitative splitting of the EOR contribution of elastic displacement and imbibition displacement in different cycles of active water huff-and-puff	1 round without soaking	/
		1 round with soaking and 1 round without soaking	24
		2 rounds with soaking and 1 round without soaking	24
		3 rounds with soaking and 1 round without soaking	24
CO_2	Quantitative splitting of the EOR contribution of elastic displacement and imbibition displacement in different cycles of CO_2 huff-and-puff	1 round without soaking	/
		1 round with soaking and 1 round without soaking	24
		2 rounds with soaking and 1 round without soaking	24
		3 rounds with soaking and 1 round without soaking	24

experiment needs to be repeated.

2.3 Quantitative splitting of the EOR mechanisms

Elastic displacement and imbibition displacement are the two main EOR mechanisms during the active water or CO_2 huff-and-puff process (Wang et al., 2021a; Zhao et al., 2021). Elastic displacement refers to the process in which the injected fluid strips off and carries the produced crude oil due to its elastic energy during the huff-and-puff process. Imbibition displacement is the process in which the injected fluid imbibes and replaces crude oil under the action of capillary force during the well soaking period (Zhang et al., 2024). The preliminary experimental results show that the imbibition displacement of tight reservoirs is a lengthy process. The imbibition oil production of the core is almost zero within the initial 2 hours of the soaking duration. This section assumes that the imbibition oil production of the core from the injection of active water/CO_2 to the preset pressure stage is zero, that is, oil production is all derived from the elastic displacement mechanism when the well is not soaked, and the oil production is derived from the elastic displacement mechanism and imbibition displacement mechanism when the well soaking time is greater than zero. Therefore, this paper carried out a specific round of huff-and-puff without well soaking as shown in Experiments 9-16 in Table 1. The displacement oil production of each round was obtained through the non-soaking experiment and compared with Experiment 3 and Experiment 7 in Table 1. The difference in oil production in each round was calculated to be the imbibition displacement oil production in that round. The specific experimental steps are consistent with those in Section 2.2.

3. Results and discussion

3.1 Active water huff-and-puff

The oil recovery rate of each round and the cumulative oil recovery rate of the five core sections during the active water huff-and-puff process is significantly different, as shown in Fig. 2(a). The stage oil recovery rate of active water huff-and-puff gradually decreases from 13.56% in the first round to 0.66% in the fourth round, indicating a certain limit to the effect of energy replenishment and displacement. When the well soaking time and pressure are the same, the distance that active water huff-and-puff can effectively spread to is limited, as shown in Fig. 2(b). The figure shows that after the first round of huff-and-puff, the oil saturation of each core decreases significantly. After the third and fourth rounds of huff-and-puff, the oil saturation of each core decreases by about 0.6%, which is consistent with the conclusion in Fig. 2(a) of the core production fluid calculation results. As the core position moves away from the injection end, the decrease in oil saturation gradually diminishes. The oil saturation of the fourth core (i.e., 8 cm away from the core injection end) remains almost unchanged during the 4 rounds of huff-and-puff (there are slight fluctuations, since there is a certain error in the nuclear magnetic test after each round of huff-and-puff), which shows that under this experimental condition, the limited effective distance of active water huff-and-puff is less

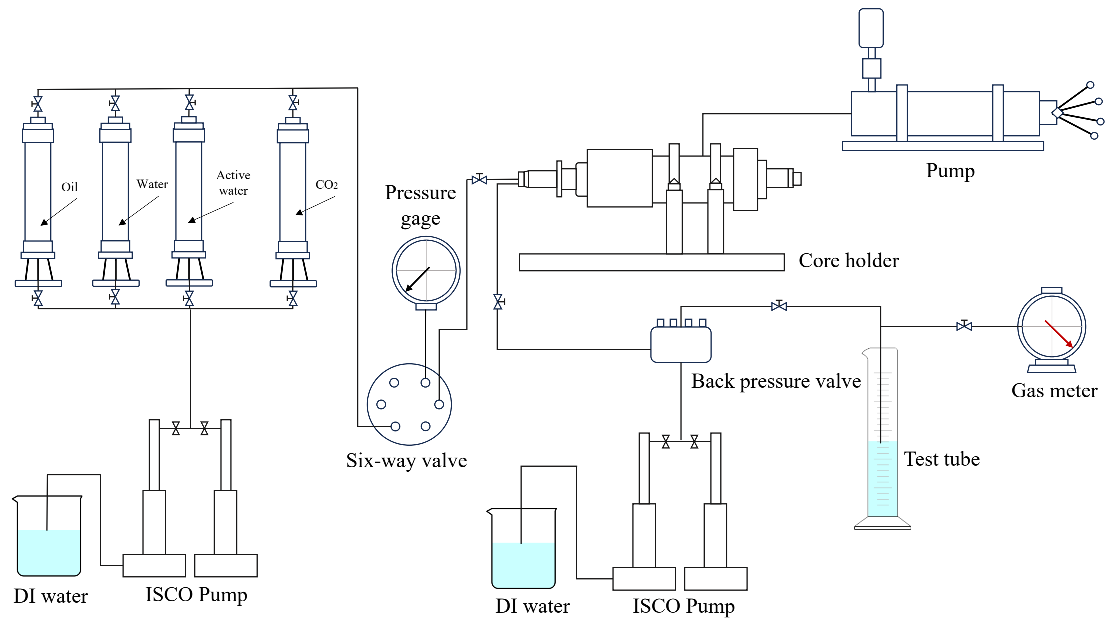

Fig. 1. Flowchart of active water/CO_2 supplementary energy huff-and-puff experiment.

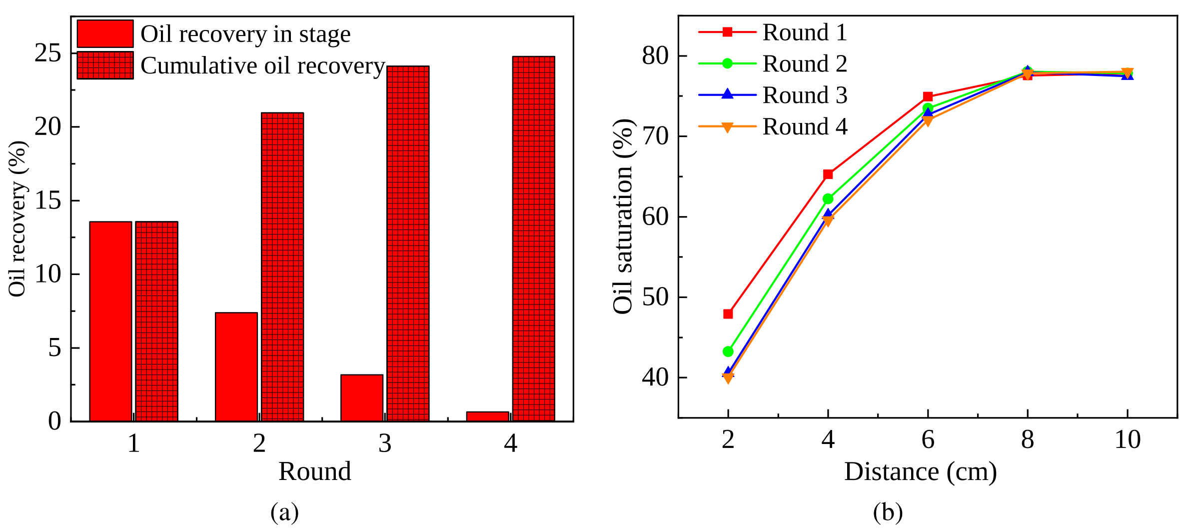

Fig. 2. EOR effect of active water huff-and-puff. (a) Stage oil recovery and cumulative oil recovery and (b) changes in oil saturation of each core under different huff-and-puff cycles.

than 8 cm.

During the active water huff-and-puff process, the nuclear magnetic resonance T_2 spectra of the first and second cores in four rounds are shown in Fig. 3. Under normal circumstances, the area of the T_2 spectrum less than 1 ms corresponds to micropores, the area greater than 10 ms corresponds to macropores, and the area between the two is medium pores (Wang et al., 2024). The T_2 spectra of the two cores show a double signal peak structure, corresponding to macropores and micropores, respectively. The peak value of the macropore signal is lower than the peak value of the micropore signal, indicating that more crude oil is stored in the micropores. With the increase in the number of huff-and-puff cycles, the decline in the macropore signal peak is significantly greater than that of the micropore signal peak, indicating that the active water mainly displaces the macropores. Compared with the first core, the T_2 spectrum of the second core still shows a significant decrease after the third round of huff-and-puff, indicating that as the core moves away from the injection end, it takes a longer period to reach the limit of displacement effect.

The ultimate oil recovery factor and limited effective distance of active water huff-and-puff under four different well soaking times are shown in Fig. 4. As illustrated in Fig. 4(a), the soaking time for huff-and-puff is key to improving the development effect: as the soaking time increases from 4 to 48 hours, the final oil recovery can be increased by 4.66%. However, the efficiency will be significantly reduced as the well soaking time reaches 24 hours and continues to

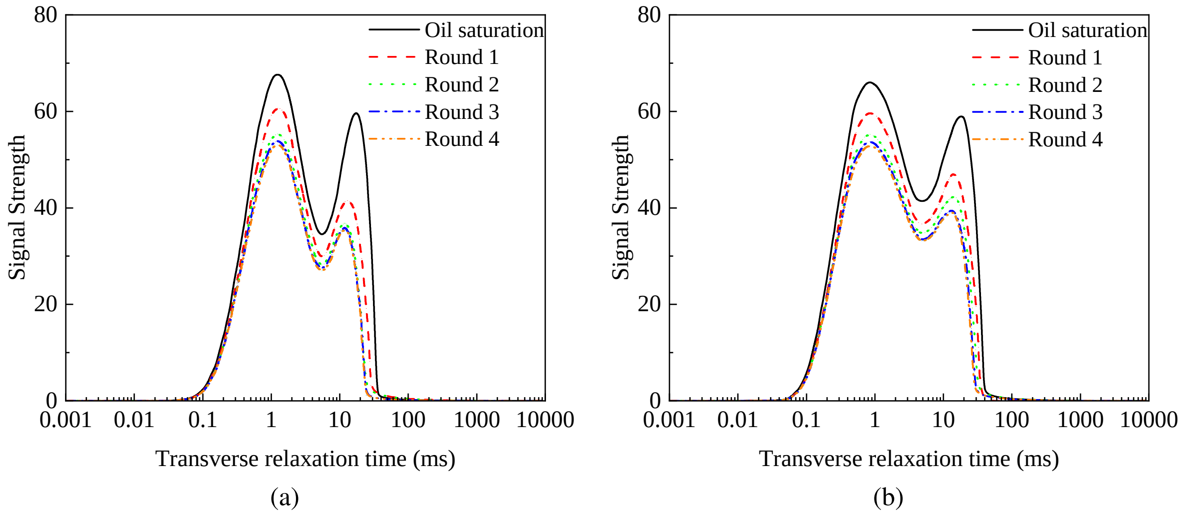

Fig. 3. NMR T_2 spectra of cores from different rounds of active water huff-and-puff. (a) First core and (b) second core. (T_2 spectrum refers to the time constant of the recovery process of the transverse component of nuclear magnetization intensity, and the corresponding longitudinal magnetization recovery process is T_1).

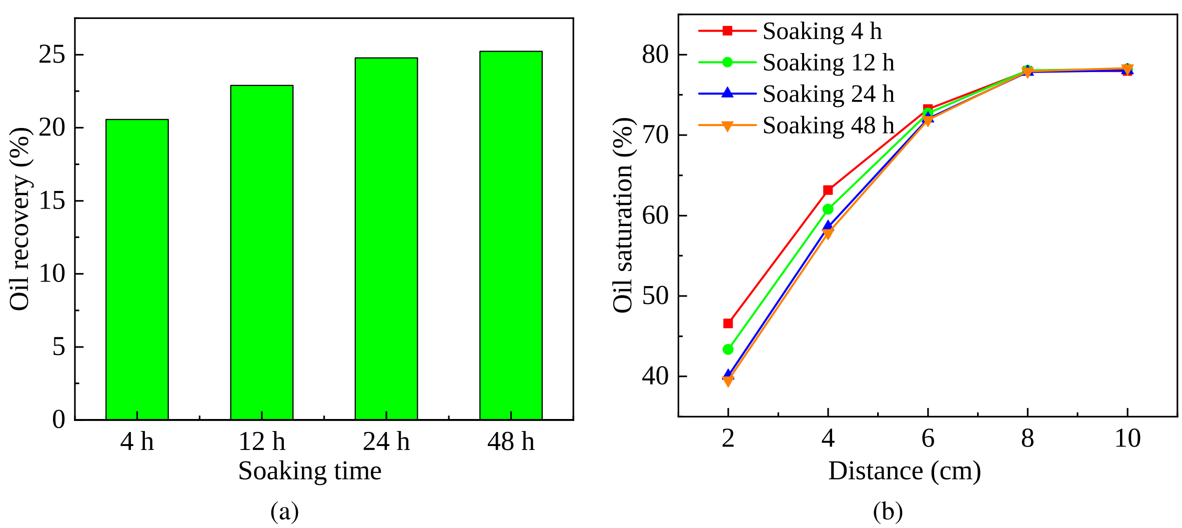

Fig. 4. Effects of soaking time of active water huff-and-puff. (a) Final oil recovery rate and (b) limited effective distance.

increase. Fig. 4(b) shows that although the soaking time will significantly affect the mobilization effect of each core within the affected area, its limited effective distance will not change. The swept distance of the huff-and-puff mainly depends on the difference between well pressure and production pressure (Huang et al., 2023).

The T_2 spectra of each round of active water huff-and-puff in the first and second cores under different soaking times are shown in Fig. 5. It can be found that, compared with the first core, the decrease in the T_2 spectrum of the second core is more uniform with the increase in soaking time, which is consistent with the conclusion shown in Fig. 3. The produced oil of the first round of active water huff-and-puff mainly comes from the first core. Increasing the huff-and-puff rounds can continue to mobilize the crude oil in the core far away from the injection end. However, the mobilization limit of the core far away from the injection end is reduced and active water has a limited effective distance, which leads to a gradual decrease in the oil recovery rate with the increasing number of huff-and-puff rounds.

3.2 CO_2 huff-and-puff

The stage oil recovery of each round and cumulative oil recovery during the CO_2 huff-and-puff process of the five core sections is shown in Fig. 6(a). The stage oil recovery rate of CO_2 huff-and-puff gradually decreases from 21.56% in the first round to 0.46% in the fourth round, indicating that CO_2 also has a limit to its effect and displacement. When the well soaking time and pressure are the same, the distance that CO_2 huff-and-puff can effectively spread is limited, as shown in Fig. 6(b). As illustrated in the figure, after each round of huff-and-puff, the oil saturation of each

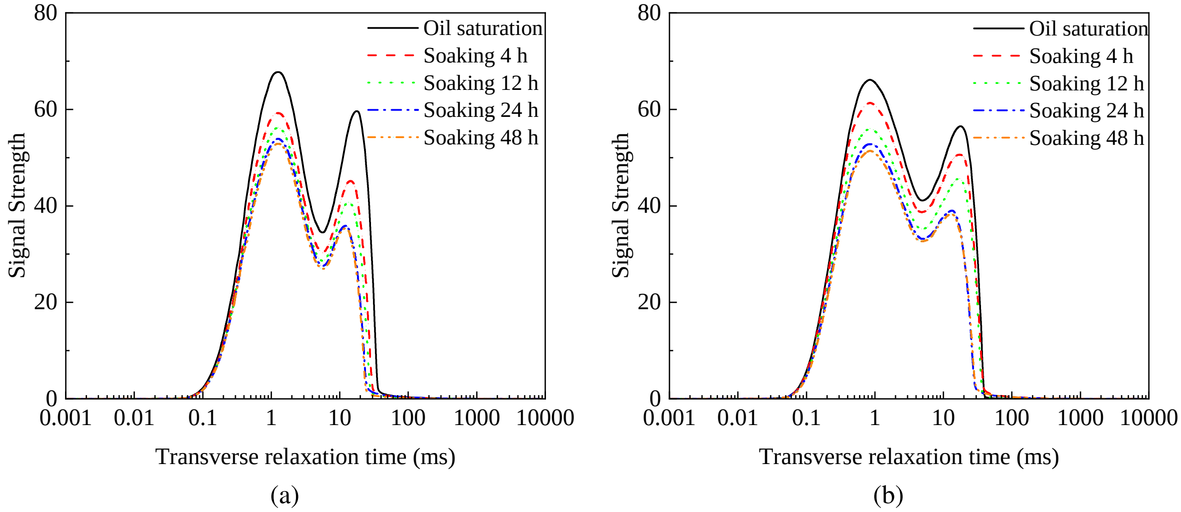

Fig. 5. NMR T_2 spectra of active water huff-and-puff at different soaking times. (a) First core and (b) second core.

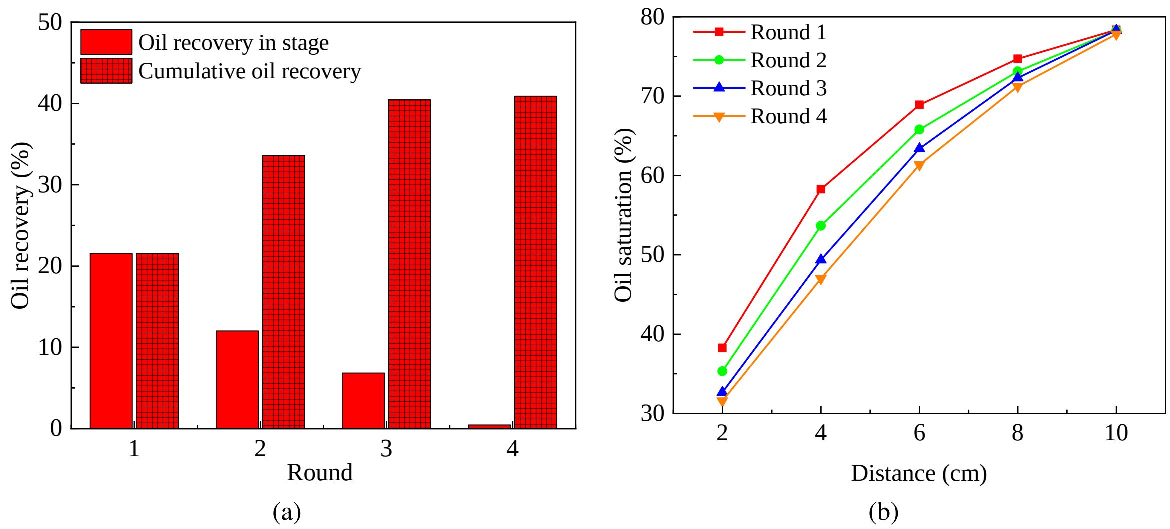

Fig. 6. EOR effect of CO_2 huff-and-puff. (a) Stage oil recovery and cumulative oil recovery and (b) changes in oil saturation of each core under different huff-and-puff cycles.

core decreases significantly. As the core position moves away from the injection end, the decrease in oil saturation gradually diminishes. The oil saturation of the fifth core (i.e., 10 cm away from the core injection end) remains almost unchanged during the 4 rounds of huff-and-puff, showing that under this experimental condition, the limited effective distance of CO_2 huff-and-puff is within 8 to 10 cm.

During the CO_2 huff-and-puff process, the nuclear magnetic resonance T_2 spectra of the first, second and third cores during four rounds are shown in Fig. 7. The T_2 spectra of the three cores also show a double signal peak structure, corresponding to macropores, and micropores, respectively. With the increase in the number of huff-and-puff cycles, both the macropore and micropore signal peaks significantly decrease, indicating that CO_2 can simultaneously displace macropores and micropores. Compared with the first core, the decrease in the peak value of T_2 spectrum in each round of the second and third cores is delayed, indicating that a longer period is needed to reach the ultimate displacement effect for the cores far away from the injection end.

The ultimate oil recovery factor and limit effective distance of CO_2 huff-and-puff under four different well soaking times are shown in Fig. 8. As illustrated in Fig. 8(a), as the soaking time increases from 4 hours to 48 hours, the final oil recovery rate can increase by 6.54%. After the well soaking time reaches 24 hours, the efficiency will be significantly reduced with the continuous increase in the well soaking time. Fig. 8(b) shows that although the soaking time will significantly affect the mobilization effect of each core within the affected area, its limited effective distance will not change. CO_2 has a strong diffusion effect, but its diffusion distance is also limited under certain temperature and pressure conditions, so there is

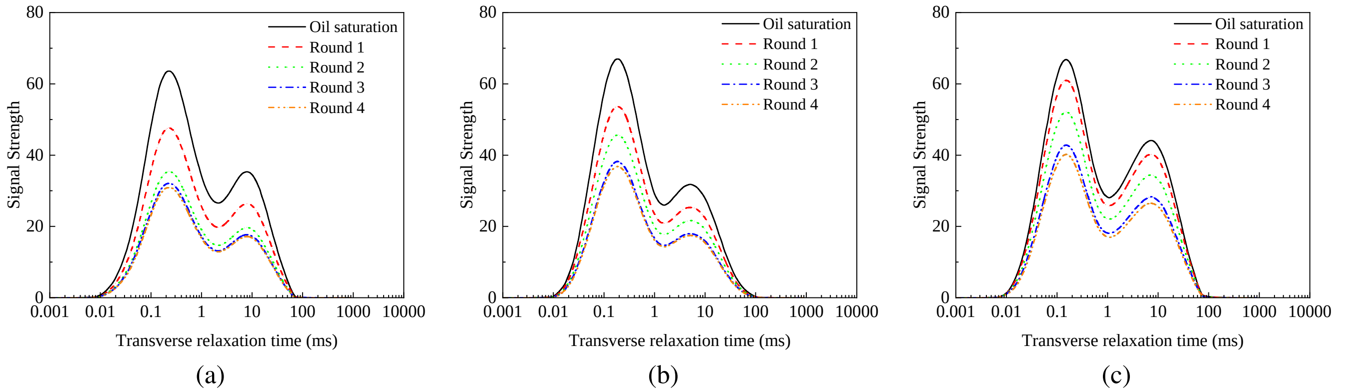

Fig. 7. NMR T_2 spectra of cores from different rounds of CO_2 huff-and-puff. (a) First core, (b) second core and (c) third core.

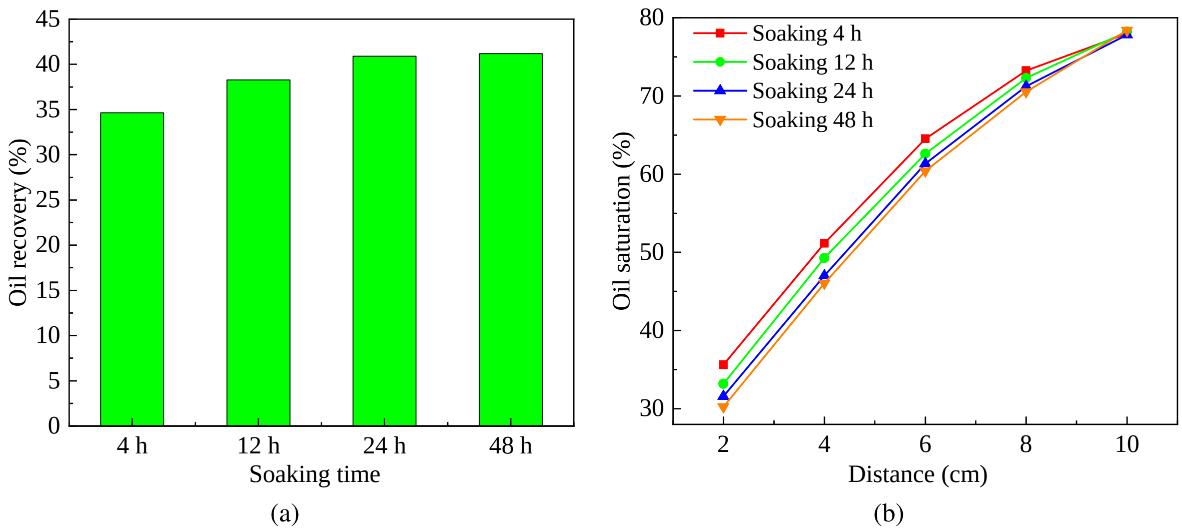

Fig. 8. Effects of different soaking times of CO_2 huff-and-puff. (a) Final oil recovery rate and (b) limited effective distance.

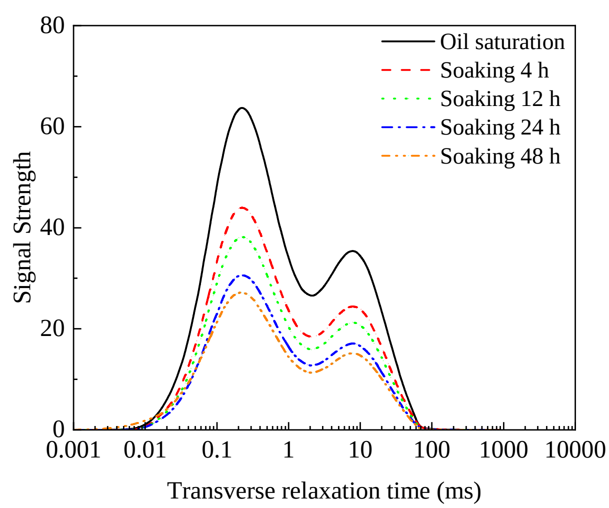

Fig. 9. NMR T_2 spectra of the first core during active water huff-and-puff at different soaking times.

still a limited distance within a certain time range.

The T_2 spectra of each round of CO_2 huff-and-puff of the first core at different well soaking times are shown in Fig. 9. Combined with Fig. 8, it can be found that the signal peak of the T_2 spectrum decreases the most when the well soaking time is 4 hours. After that, the T_2 spectrum decreases evenly as the well soaking time increases, which shows that the response of CO_2 to the well soaking time is more significant. Although continuing to increase the well soaking time can achieve a higher oil recovery, its increase rate is reduced from 22.65% to 18.87% compared with active water huff-and-puff.

From Fig. 2, the following differences can be found between CO_2 and active water huff-and-puff energy:

1) The final oil recovery of CO_2 huff-and-puff can be increased by 16.11% compared with active water huff-and-puff;
2) The decline rate of the EOR in each round of CO_2 huff-and-puff is greater, indicating that CO_2 huff-and-puff is more efficient;
3) The limited effective distance of CO_2 huff-and-puff is longer, which is mainly due to its strengthen expandability and diffusion ability;
4) CO_2 huff-and-puff increases the ultimate utilization of

	Target	Round 1	Round 2	Round 3	Round 4	Oil recovery during well soaking	Elastic displacement contribution rate
Active water	Round 1	12.24	×	×	×	13.56	90.27
	Round 2	Soaking	5.67	×	×	7.39	76.73
	Round 3	Soaking	Soaking	1.62	×	3.17	51.10
	Round 4	Soaking	Soaking	Soaking	0.08	0.66	12.12
CO_2	Target	Round 1	Round 2	Round 3	Round 4	Oil recovery during well soaking	Elastic displacement contribution rate
	Round 1	19.91	×	×	×	21.56	92.35
	Round 2	Soaking	6.65	×	×	12.02	55.32
	Round 3	Soaking	Soaking	1.44	×	6.85	21.02
	Round 4	Soaking	Soaking	Soaking	0	0.46	0.00

× No huff-and-puff; (blue) Oil recovery without soaking; (yellow) Oil recovery with soaking; (green) Elastic displacement contribution rate; (red) Huff-and-puff with soaking

Fig. 10. Design of the experimental scheme and key parameters for the quantitative splitting of huff-and-puff mechanisms.

each core, which also leads to a more uniform decrease in the T_2 spectrum of each core in each round. Meanwhile, the delay in oil recovery increase caused by the core being far away from the injection end is more significant;

5) CO_2 can simultaneously displace crude oil in macropores and micropores, which is also the fundamental reason for its higher oil recovery effect;
6) The effect of CO_2 huff-and-puff responds more significantly to well soaking time.

3.3 Contribution of elastic and imbibition displacement to EOR

The contribution rates of elastic and imbibition displacement to the oil recovery in each round were split through the specific round of huff-and-puff development experiments without well soaking. For example, in Experiment 10 shown in Table 1, two rounds of huff-and-puff experiments were conducted, in which the well was soaked in the first round and not soaked in the second round. It can be considered that the oil recovery rate in the second round of Experiment 10 was entirely attributed to elastic displacement, while the oil recovery rate in the second round of Experiment 3 was jointly attributed to elastic and imbibition displacement. The contribution of elastic and imbibition displacement can be quantitatively split by combining Experiment 10 and Experiment 3. According to the above ideas, the experimental design and key parameters of each round of active water and CO_2 huff-and-puff are summarized as shown in Fig. 10.

The dynamic changes in the contribution rates of elastic and imbibition displacement in each round of active water and CO_2 huff-and-puff can be further compared on the basis of Fig. 10, as shown in Fig. 11. It can be found that the contribution rate of elastic displacement gradually decreases with the increase in the number of huff-and-puff rounds; however, it is the main contribution mechanism of the full huff-and-puff development. The contribution of imbibition displacement of active water and CO_2 huff-and-puff accounts for 20.86% and 31.52% of the total oil recovery, respectively. It can be found that the proportion of imbibition displacement is significantly higher during the CO_2 huff-and-puff process, which is due to its good diffusion ability, and it can displace the residual oil in the micropores through imbibition (Cai, 2021; Ji et al., 2023).

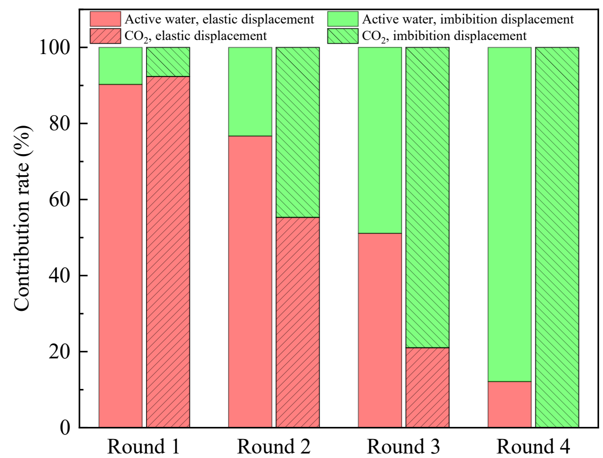

Fig. 11. Comparison of contribution rates of elastic and imbibition displacement during active water and CO_2 huff-and-puff.

The contribution rate of elastic displacement in the first round of CO_2 huff-and-puff is higher, which is caused by its stronger elastic compression and expansion performance than those of liquid-phase medium. The contribution rate of elastic displacement in the fourth round is 0, which shows again that the utilization of CO_2 huff-and-puff has certain limits. The utilization limits of elastic and imbibition displacement for the CO_2 huff-and-puff are both greater than those of active water huff-and-puff. Besides, CO_2 can reach its limited effective distance earlier, that is, CO_2 huff-and-puff has both a higher EOR effect and better efficiency.

The two most common huff-and-puff media are studied in this paper, which are consistent with the existing technology in terms of application direction (Shi et al., 2022; Wu et al., 2025). While the current research focuses on the innovation of the reagent system, it ignores the optimization design of technical solutions. The improvement of reagent performance will definitely bring about the gain effect of EOR, but it will also cause economic and environmental problems. The research content of this paper builds on the two mechanisms of elastic and imbibition displacement in the throughput process and quantitatively splits their contribution rate and action stage, which can be used for targeted scheme design and adjustment during the development process and also has an important EOR gain effect and applicability. In addition, the results obtained in this paper show that CO_2 can better play its role of percolation displacement due to its excellent mass transfer effect. This also provides a sound theoretical basis for the development of CO_2 huff and puff in the tight reservoirs. CO_2 huff-and-puff can simultaneously achieve underground storage of CO_2, which has the dual effects of improved economy and environmental protection, making it a hot topic and an effective EOR technology in the future.

4. Conclusions

This paper compared the EOR effects, limited effective distance, pore throat utilization characteristics, and influencing factors of active water and CO_2 huff-and-puff by combining core experiments with nuclear magnetic resonance testing. Meanwhile, the contribution rates of elastic displacement and imbibition displacement to huff-and-puff were quantitatively split by setting up a comparative experiment without well soaking for a specific huff-and-puff round. The specific conclusions are as follows:

1) The cumulative oil recovery rate after four rounds of active water and CO_2 huff-and-puff was 24.78% and 40.89%, respectively, and the limited effective distances were 6-8 cm and 8-10 cm, respectively. CO_2 has a higher oil recovery rate and limited effective distance, mainly because it can displace the residual oil in the micropores owing to its stronger elastic expansion and diffusion properties.
2) The stage oil recovery of active water and CO_2 huff-and-puff decreases significantly with the increase in the number of huff-and-puff rounds: the stage oil recovery after three rounds was less than 1%. A longer well soaking time of huff-and-puff will result in a higher final oil recovery, while this increase slows down after 24 hours. CO_2 huff-and-puff is more sensitive to the well soaking time.
3) Elastic displacement is the main mechanism contributing to active water and CO_2 huff-and-puff, and imbibition displacement accounts for 20.86% and 31.52%, respectively. The utilization limits of CO_2 elastic displacement and imbibition displacement are greater than those of active water. CO_2 can reach its utilization limit earlier, meaning that CO_2 huff-and-puff has a higher EOR effect and efficiency.

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Conflict of interest

The authors declare no competing interest.

References

Adel, I. A., Tovar, F. D., Zhang, F., et al. The impact of MMP on recovery factor during CO_2-EOR in unconventional liquid reservoirs. Paper SPE 191752 Presented at SPE Annual Technical Conference and Exhibition, Dallas, Texas, USA, 24-26 September, 2018.

Ahmed, U., Meehan, D. N. Unconventional Oil and Gas Resources: Exploitation and Development. Boston, USA, CRC Press, 2016.

Ataceri, I., Haddix, G., Schechter, D., et al. Surfactant huff n puff field trials in eagle ford shale-A treatment design comparative analysis. Paper SPE 218135 Presented at SPE Improved Oil Recovery Conference, Tulsa, Oklahoma, USA, 22-25 April, 2024.

Cai, J. Some key issues and thoughts on spontaneous imbibition in porous media, Chinese Journal of Computational Physics, 2021, 38(5): 505-512. (in Chinese)

Cai, J., Li, C., Song, K., et al. The influence of salinity and mineral components on spontaneous imbibition in tight sandstone. Fuel, 2020, 269: 117087.

Cai, J., Yu, B., Zou, M., et al. Fractal characterization of spontaneous co-current imbibition in porous media. Energy & Fuels, 2010, 24(3): 1860-1867.

Chen, T., Yang, Z., Ding, Y., et al. Waterflooding huff-n-puff in tight oil cores using online nuclear magnetic resonance. Energies, 2018, 11(6): 1524.

Chen, X., Li, Y., Sun, X., et al. Investigation of polymer-assisted CO_2 flooding to enhance oil recovery in low-permeability reservoirs. Polymers, 2023, 15(19): 3886.

Chen, X., Zhang, Q., Trivedi, J., et al. Investigation on enhanced oil recovery and CO_2 storage efficiency of temperature-resistant CO_2 foam flooding. Fuel, 2024, 364: 130870.

Cudjoe, S. E., Barati, R., Tsau, J.-S., et al. Assessing the efficiency of saturating shale oil cores and evaluating hydrocarbon gas huff 'n'puff using nuclear magnetic resonance. SPE Reservoir Evaluation & Engineering, 2021, 24(2): 429-439.

Ding, C., Chen, J., Yang, G., et al. Novel method for the rapid evaluation of pressure depletion in tight oil reservoirs. Advances in Geo-Energy Research, 2024, 11(1): 74-80.

Ding, M., Wang, Y., Liu, D., et al. Enhancing tight oil recovery using CO_2 huff and puff injection: An experimental study of the influencing factors. Journal of Natural Gas Science and Engineering, 2021, 90: 103931.

Ganjdanesh, R., Eltahan, E., Sepehrnoori, K., et al. A field pilot of huff-n-puff gas injection for enhanced oil recovery in Permian Basin. Paper SPE 201622 Presented at SPE Annual Technical Conference and Exhibition, Virtual, 26-29 October, 2020.

Hao, Y., Wu, Z., Chen, Z., et al. The characteristics and effects of huff-n-puff in shale with brine, aqueous surfactant solutions and CO_2. Journal of CO_2 Utilization, 2024, 79: 102655.

Huang, X., Wang, X., He, M., et al. The influence of CO_2 huff and puff in tight oil reservoirs on pore structure characteristics and oil production from the microscopic scale. Fuel, 2023, 335: 127000.

Ji, H., Zhang, L., Zhang, L,. et al. Measurement and characterization of mixed wettability for tight sandstone based on spontaneous imbibition contact angle distribution. Journal of Northeast Petroleum University, 2023, 47(2): 117-124. (in Chinese)

Li, L., Sheng, J., Su, Y., et al. Further investigation of effects of injection pressure and imbibition water on CO_2 huff-n-puff performance in liquid-rich shale reservoirs. Energy & Fuels, 2018, 32(5): 5789-5798.

Liu, J., Li, H., Tan, Q., et al. Quantitative study of CO_2 huff-n-puff enhanced oil recovery in tight formation using online NMR technology. Journal of Petroleum Science and Engineering, 2022, 216: 110688.

Liu, J., Liu, S., Chen, X., et al. A method for synergistic oil recovery based on imbibition agent and imbibition agent. CN117072125A, 2023.

Liu, S., Liu, X., Zhou, Z. Method and device for simulating fracturing fluid imbibition and production enhancement in dual-porosity and dual-permeability medium reservoirs. ZL201910431122.9, 2020.

Lotfollahi, M., Beygi, M. R., Abouie, A., et al. Optimization of surfactant flooding in tight oil reservoirs. Paper URTEC 2696038 Presented at SPE/AAPG/SEG Unconventional Resources Technology Conference, Austin, Texas, USA, 24-26 July, 2017.

Lu, C., Zhang, M., Hua, Y., et al. Investigation of surfactant huff-n-puff injection for enhanced oil recovery in unconventional reservoirs: An integrated experimental and numerical simulation approach coupled with the HLD-NAC methodology. Energy & Fuels, 2023, 38(1): 356-373.

Lv, W., Gong, H., Dong, M., et al. Potential of nonionic polyether surfactant-assisted CO_2 huff-n-puff for enhanced oil recovery and CO_2 storage in ultra-low permeability unconventional reservoirs. Fuel, 2024, 359: 130474.

Ma, Q., Yang, S., Lv, D., et al. Experimental investigation on the influence factors and oil production distribution in different pore sizes during CO_2 huff-n-puff in an ultra-high-pressure tight oil reservoir. Journal of Petroleum Science and Engineering, 2019, 178: 1155-1163.

Maurich, D. Experimental study of the effect of continuous surfactant injection alternating cyclic huff & puff stimulation on oil efficiency recovery in a 3D reservoir physical model. Journal of Applied Science (Japps), 2019, 1(2): 18-30.

Meng, Q., Cai, J. Recent advances in spontaneous imbibition with different boundary conditions. Capillarity, 2018, 1(3): 19-26.

Qin, G., Dai, X., Sui, L., et al. Study of massive water huff-n-puff technique in tight oil field and its field application. Journal of Petroleum Science and Engineering, 2021, 196: 107514.

Shi, X., Sun, L., Zhan, J., et al. Carbon dioxide huff-puff technology and application in tight oil horizontalwells in the northern Songliao Basin. Acta Petrolei Sinica, 2022, 43(7): 998-1006. (in Chinese)

Shuler, P. J., Lu, Z., Ma, Q., et al. Surfactant huff-n-puff application potentials for unconventional reservoirs. Paper SPE 179667 Presented at SPE Improved Oil Recovery Conference, Tulsa, Oklahoma, USA, 11-13 April, 2016.

Shun, L., Jun, N., Xianli, W., et al. A dual-porous and dual-permeable media model for imbibition in tight sandstone reservoirs. Journal of Petroleum Science and Engineering, 2020, 194: 107477.

Sie, C. Y., Nguyen, Q. Laboratory experiments of field gas huff-n-puff for improving oil recovery from Eagle Ford Shale reservoirs. Arabian Journal of Geosciences, 2022, 15(21): 1634.

Thomas, G., Monger-McClure, T. Feasibility of cyclic CO_2 injection for light-oil recovery. SPE Reservoir Engineering, 1991, 6(2): 179-184.

Wang, J., Liu, H., Qian, G., et al. Mechanisms and capacity of high-pressure soaking after hydraulic fracturing in tight/shale oil reservoirs. Petroleum Science, 2021a, 18(6): 546-564.

Wang, S., Zheng, G., Guo, P,. et al. Comparative laboratory wettability study of sandstone, tuff, and shale using 12-MHz NMR T_1-T_2 fluid typing: Insight of shale. SPE Journal, 2024, 29(9): 4781-4803.

Wang, X., Xie, K., Zhang, J., et al. Study on the key influential factors on water huff-n-puff in ultralow-permeability reservoir. Geofluids, 2021b, 2021: 5885366.

Wan, Y., Jia, C., Lv, W., et al. Recovery mechanisms and formation influencing factors of miscible CO_2 huff-n-puff processes in shale oil reservoirs: A systematic review. Advances in Geo-Energy Research, 2024, 11(2): 88-102.

Wei, J., Zhou, X., Zhou, J., et al. CO_2 huff-n-puff after surfactant-assisted imbibition to enhance oil recovery for tight oil reservoirs. Energy & Fuels, 2020, 34(6): 7058-7066.

Wei, W., Cai, J., Xiao, J., et al. Kozeny-Carman constant of porous media: Insights from fractal-capillary imbibition theory. Fuel, 2018, 234: 1373-1379.

Wu, H., Wang, L., Yang, Y., et al. Experimental study on optimization of CO_2 huff-n-puff demixing agent for tight conglomerate reservoirs. Petroleum Geology and Recovery Efficiency, 2025, 32(1): 147-155. (in Chinese)

Yin, Y., Zhang, H. Advances in tight oil reservoir development: A review of CO_2 huff and puff technology. Advances in Resources Research, 2024, 4(3): 280-299.

Yu, H., Yang, Z., Ma, T., et al. The feasibility of asynchronous injection alternating production formultistage fractured horizontal wells in a tight oil reservoir. Petroleum Science Bulletin, 2018, 3(1): 32-44. (in Chinese)

Yu, W., Lashgari, H., and Sepehrnoori, K. Simulation study of CO_2 huff-n-puff process in Bakken tight oil reservoirs. Paper SPE 191873 Presented at SPE Western Regional Meeting, Brisbane, Australia, 23-25 October, 2014.

Zhang, F., Adel, I. A., Park, K. H., et al. Enhanced oil recovery in unconventional liquid reservoir using a combination of CO_2 huff-n-puff and surfactant-assisted spontaneous imbibition. Paper SPE 191502 Presented at SPE Annual Technical Conference and Exhibition, Dallas, Texas, USA, 24-26 September, 2018a.

Zhang, T., Dai, C., Wang, K., et al, Analysis of spontaneous and dynamic imbibition characteristics of silica-based nanofluid in microscopic pore structure of tight oil reservoirs. Langmuir, 2024, 40(47): 25250-25261.

Zhang, Y., Yu, W., Li, Z., et al. Simulation study of factors affecting CO_2 Huff-n-Puff process in tight oil reservoirs. Journal of Petroleum Science and Engineering, 2018b, 163: 264-269.

Zhao, X., Liu, X., Yang, Z., et al. Experimental study on physical modeling of flow mechanism in volumetric fracturing of tight oil reservoir. Physics of Fluids, 2021, 33(10): 107118.

Zhou, X., Wang, Y., Zhang, L., et al. Evaluation of enhanced oil recovery potential using gas/water flooding in a tight oil reservoir. Fuel, 2020, 272: 117706.

Zuloaga, P., Yu, W., Miao, J., et al. Performance evaluation of CO_2 Huff-n-Puff and continuous CO_2 injection in tight oil reservoirs. Energy, 2017, 134: 181-192.