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Invited review

Review of effects and mechanisms of forced imbibition on enhanced oil recovery: Huff-n-puff and improved wettability

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Abstract:
Imbibition plays a key role in the performance of injected fluids in enhanced oil recovery from low-permeability, tight reservoirs. Huff-n-puff with well-soaking and improving reservoir wettability can promote imbibition, resulting in forced imbibition. However, our understanding of its concept, influencing factors and the underlying mechanisms remains limited. Therefore, first, this work systematically reviews the relevant research and clarifies the concept of forced imbibition. Next, the mechanisms and enhanced oil recovery contributions of huff-n-puff and wettability improvement during the forced imbibition process are highlighted and summarized. Huff-n-puff and low-salinity water flooding are two key forced imbibition methods. Regarding huff-n-puff development, this work compares and analyzes the key controlling mechanisms and enhanced oil recovery effects of imbibition enhancement using three fluids: Water, gas and activated water. Gas is currently the most widely used huff-n-puff medium in oilfields because of its stronger mass transfer and diffusion capabilities, making it can enter smaller pore throats. Besides, water is also an irreplaceable huff-n-puff medium because of its fast energy replenishment, low cost, and environmentally friendly. Active water with the addition of surfactants, nanofluids and displacement systems can enhance the effect of water huff-n-puff, achieving a broader application potential. Subsequently, the enhanced oil recovery contribution rate of forced imbibition during the huff-n-puff process is discussed. Regarding low-salinity water flooding, this paper focuses on the mechanism of improving wettability and its effect on enhancing CO_2 imbibition. It not only offers a comprehensive understanding of the concepts mechanisms and enhanced oil recovery effects of the forced imbibition process but also provides valuable insights for theoretical research and field applications of forced imbibition-based enhanced oil recovery technologies.

1. Introduction

In China, the development of conventional sandstone reservoirs has entered its middle and late stages. A continued improvement of the recovery rate in these reservoirs constitutes the main source of energy, while strengthening the development of tight and shale reservoirs is the key guarantee for future energy succession (Malozyomov et al., 2023; Chen et al., 2024). Tight and shale reservoirs are characterized by extremely low porosity and permeability, poor oil fluidity and

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dispersed distribution, which leads to a rapid decrease in pressure and severe water breakthrough during their development, greatly reducing oil recovery (Chen et al., 2023).

Imbibition refers to the displacement of two-phase fluids within a porous medium under the influence of capillary forces and other factors (Morrow and Mason, 2001; Chen et al., 2025b). The imbibition process is influenced by numerous factors and has a complex mechanism. Changes in reservoir temperature and pressure conditions, fluid properties and rock properties can all affect the interaction between the rock face and the fluid, thereby altering the imbibition process. Furthermore, imbibition is a crucial enhanced oil recovery (EOR) mechanism that accompanies the entire development cycle of tight and shale reservoirs. Horizontal well fracturing can enhance the flow volume and pressure transmission efficiency, improving the imbibition effect during the development process (Li et al., 2015a; Afolabi, 2019). However, due to the low permeability of the reservoir matrix, the injected fluid is prone to abnormal injection pressure rise (large well spacing and poor fracture communication between wells) or fracture channeling (small well spacing and good fracture communication between wells), resulting in a poor displacement development effect (Bahadori, 2018; Burrows et al., 2020). Therefore, it is necessary to adjust the production measures to achieve a forced imbibition effect and further improve oil recovery (Cai et al., 2025). Theoretically, any measure that can improve imbibition efficiency can be called an enhanced imbibition process. To provide a clear definition, in this paper, these measures are named as "forced imbibition". Currently, the two main methods of forced imbibition involve increasing the imbibition pressure (i.e., huff-n-puff) and improving wettability (i.e., low-salinity water flooding or low-salinity water flooding (LSWF)).

Huff-n-puff development comprises the process of injecting fluid from a production well after reservoir depletion and then shutting down the well for a period to continue using it for oil production. This approach has gradually become the main development technology for unconventional reservoirs in recent years (Hoffman and Reichhardt, 2019; Tang et al., 2022). Huff-n-puff development does not rely on the connectivity between the injection well and the production well and is not affected by channeling. Single-well development also reduces costs. Meanwhile, the well-soaking stage can effectively exert the various recovery enhancement mechanisms by which huff-n-puff fluids act, improving the oil recovery effect and efficiency (Milad et al., 2021). Huff-n-puff development has been successfully applied in many oil fields at home and abroad (Shi et al., 2024; Wei et al., 2024), while certain problems persist in indoor (lab) research.

At present, the difference between forced imbibition and spontaneous imbibition during huff-n-puff development is not well understood (Sun et al., 2025). When the capillary force at the pore throat is dominant, it can be called spontaneous imbibition, while forced imbibition is controlled by the pore throat pressure difference (Rose, 2001). During huff-n-puff development, the pressure of fluid in the wellbore and fractures is higher than the pressure inside the reservoir, which is dominated by forced imbibition. Some studies have summarized this principle of improving oil recovery as spontaneous imbibition and pointed out that the higher the permeability is, the higher the spontaneous imbibition efficiency (Gu et al., 2017). Studies focusing on the difference between forced and spontaneous imbibition point out that the oil recovery of forced imbibition is more than twice that of spontaneous imbibition. In addition, forced imbibition and spontaneous imbibition mainly extracts crude oil from medium-large and micropores, respectively (Wang et al., 2018). Subsequent studies have also shown that this phenomenon is related to reservoir wettability (Wang et al., 2021). Yang et al. (2019) showed through theory and experiments that forward imbibition leads to higher recovery in low-permeability reservoirs, while reverse imbibition leads to higher recovery in high-permeability reservoirs. Therefore, clarifying the difference between forced imbibition and spontaneous imbibition is key to reveal the mechanism of EOR through huff-n-puff production.

There are various types of huff-n-puff development fluids; however, the understanding of their EOR mechanisms during the huff-n-puff process is still insufficient. Gas is the most used huff-n-puff fluid. Due to the variety of gas types and different main EOR mechanisms, although many studies have focused on gas huff-n-puff, the results and conclusions of scholars show significant variation (Wan et al., 2024). Nevertheless, the advantage of gas huff-n-puff in the process is good crude oil solubility: Gas dissolution can expand volume and reduce viscosity of crude oil, enhancing its mobility and promoting it to flow out of the pores (Hoffman and Reichhardt, 2020). In addition, gas also has good mass transfer and diffusion effects and can more fully dissolve, extract and replace crude oil (Yuan et al., 2023). CO_2, CH_4 and other gases exhibiting high solubility and miscibility with crude oil mainly improve oil recovery by dissolution and replacement (Alfarge et al., 2018; Tran et al., 2021), while N_2 mainly plays the role of energy replenishment and imbibition mechanism (Song et al., 2022). In addition, water huff-n-puff is also widely used because water is easy to obtain at low cost. Water huff-n-puff mainly functions as water replenishment, replacing crude oil in the pores by forced imbibition to improve oil recovery (Ji et al., 2023). The effect of water huff-n-puff is often worse than that of gas huff-n-puff. However, adding surfactants to water can effectively reduce the oil-water interfacial tension (IFT), improve reservoir wettability, and enhance oil-water imbibition and displacement (Lu et al., 2023; Scerbacova et al., 2023). The multi-fluid huff-n-puff derived on this basis can play the roles of profile control, IFT reduction, and energy supplement of each agent, comprising an enhanced huff-n-puff technology (Nowrouzi et al., 2020; Hao et al., 2024). However, the EOR mechanisms of multi-fluid huff-n-puff are complex and show great variation across different reservoirs. Thus, clarifying the EOR mechanism and contribution rate of different huff-n-puff fluids is conducive to optimizing the design of huff-n-puff schemes.

Low-salinity water flooding is another forced imbibition method with great potential (Chen et al., 2025a) that can make rocks more hydrophilic (Agbalaka et al., 2009). However, the discrepancies in the governing mechanisms and observed outcomes across different scales, from the pore to the reservoir

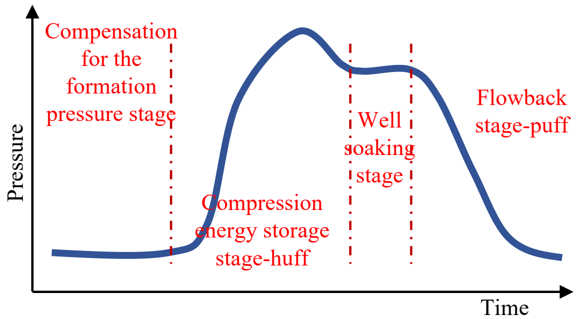

Fig. 1. Division of throughput development stages and pressure response, modified from Pu et al. (2023).

level, pose a significant challenge to current research (Muggeridge et al., 2014; Bartels et al., 2019). Consequently, the research frontier has shifted from the standalone application of LSWF to exploring its synergistic effects with chemical flooding, such as surfactant flooding. Extensive studies have shown that high salinity is a critical factor limiting surfactant performance, as it leads to increased adsorption loss on the rock and reduced stability (Massarweh and Abushaikha, 2020; Bashir et al., 2022). Therefore, utilizing low-salinity water as a carrier fluid or pre-flush for surfactants creates a favorable transport environment, thereby significantly improving imbibition efficiency (Chowdhury et al., 2022). Furthermore, hybrid flooding systems that combine nanoparticles, low-salinity water and surfactants have become a key research focus. These systems aim to simultaneously address multiple challenges, including wettability modification, IFT reduction, and sweep efficiency improvement (Isaac et al., 2022). LSWF has been proven as effective in enhancing oil recovery via forced imbibition. However, the effects of its improved wettability on promoting imbibition and the relevant influencing factors still lack systematic research.

In view of the above, this paper reviews forced imbibition technology based on the aforementioned challenges. The aim is to explain the concept of forced imbibition, clarify the EOR mechanisms of different huff-n-puff media and wettability-enhanced forced imbibition, and categorize their respective contributions. First, forced imbibition is defined and compared with spontaneous imbibition. Second, the current state of huff-n-puff development technology is described. Third, the advantages of different huff-n-puff media and their primary target reservoirs are summarized and compared. This paper focuses on the huff-n-puff process using water, CO_2 and N_2, comparing laboratory research and field applications of different huff-n-puff media, with the aim to identify the key controlling EOR mechanisms of these three media. Besides, the technical advantages of active water huff-n-puff are discussed. Fourth, the mechanism and effects of wettability-enhanced imbibition are introduced. Finally, this paper quantitatively categorizes the EOR contributions of the two main mechanisms of expansion displacement and imbibition displacement during huff-n-puff development, current challenges in forced imbibition are summarized and analyzed, and the key research areas and future development directions are identified.

2. Differences between forced imbibition and spontaneous imbibition

Reservoirs such as shale are characterized by dense pores, and more than 70% of crude oil is stored in about 30% of micro- and nanopores. An important development mechanism of this kind of reservoir is spontaneous imbibition (Qiao et al., 2017; Guo and Wortman, 2025), which means that fluid in the large pore throat, that can flow, enters and replaces the original fluid in the micro-pore throat, that can only diffuse and cannot flow, due to capillary force, diffusion, mass transfer, etc., under the prevailing conditions of the reservoir (Zheng et al., 2025). However, due to the wettability of the wall surface and capillary force, the ability of the fluid to enter the micro-pore throat is limited, restricting the oil recovery of spontaneous imbibition to often less than 20% (Morrow and Mason, 2001; Xu et al., 2025). Fluid huff-and-puff development can replenish the formation energy during the injection stage, replace the crude oil in the pores through imbibition during the well-soaking stage, and finally carry the crude oil out during the development stage (Pu et al., 2023), as shown in Fig. 1. The above imbibition process-called forced imbibition-has a recovery rate of more than twice that of spontaneous imbibition (Wang et al., 2018). In addition, improving the wettability of the rock surface can also enhance imbibition, which also constitutes a forced imbibition process. In this way, all processes that promote spontaneous imbibition under external interference can be called forced imbibition, and the corresponding measures are considered forced imbibition production technology.

Spontaneous imbibition mainly displaces crude oil in macropores (Zhang et al., 2023), while forced imbibition primarily displaces crude oil in mesopores, micropores and nanopores (Zhang et al., 2020). The main factors affecting imbibition recovery include reservoir temperature, wall wettability, and IFT (Adibhatla and Mohanty, 2008; Gu et al., 2017). In the process of forced imbibition, well soaking pressure, injection rate and well soaking time also play decisive roles in the imbibition effect (Dai et al., 2019). In general, reservoirs with higher reservoir permeability, higher porosity, and the thus enhanced hydrophilicity of the rock wall respond to a higher imbibition effect (Jing et al., 2019; Liu et al., 2024). The influence mechanism of oil-water IFT on forced imbibition is complex, and there is still controversy as to whether capillary force in the pores is the driving force or rather resistance to imbibition (Tu and Sheng, 2020; Yang et al., 2023). Besides, the most important factor affecting forced imbibition recovery is the huff-n-puff medium. Currently, the main huff-n-puff fluids include water, gas (N_2, CO_2, etc.) and active fluids. In the next section, the development effects and mechanisms of these three main huff-n-puff media will be discussed in detail.

3. Effect and mechanism of forced imbibition for different huff-n-puff processes

3.1 Huff-n-puff development status

Huff-and-puff development is a commonly used technology that injects fluid (or named solvent) to replace the reservoir

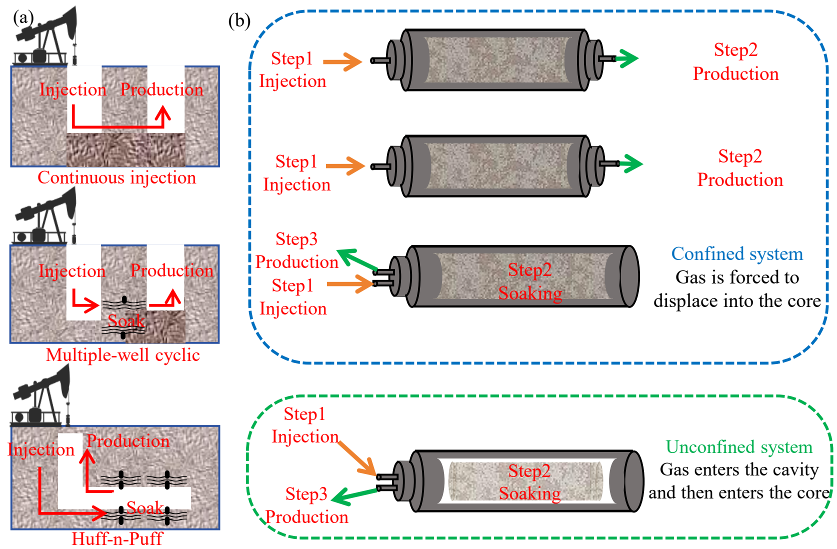

Fig. 2. Reservoir development modes of fluid injection, modified from Milad et al. (2021): (a) Three modes for field application and (b) four methods for indoor experimental simulation.

fluid (target crude oil). Oil production technologies can be divided into three categories according to the injection method (Milad et al., 2021) (Fig. 2(a)): Continuous injection, multiple-well cyclic, and huff-n-puff. The corresponding indoor experimental process is shown in Fig. 2(b). In the huff-n-puff method, fluid is injected into a well, and then the same well is used for production after the well is shut down (Haskin and Alston, 1989).

In well soaking, as a key stage of huff-and-puff development, the injected fluid will accelerate the imbibition and diffusion under high pressure to realize the swelling, stripping and replacement of crude oil. Huff-and-puff development is widely used in unconventional-low-permeability and tight-reservoirs because it is hard to establish an effective injection-production relationship between injection and production wells (Tang et al., 2023). From 1986 to the late 1990s, huff-n-puff was successfully applied in the Big Sinking Field (Lee County, Kentucky, U.S.), and it was also proved that the N_2 and CO_2 mixture gas can achieve better results than pure CO_2 after the well soaking time is extended (Miller and Hamilton-Smith, 1998). Since then, the Bakken Oilfield (North Dakota and Montana, U.S.) has become the main test area for huff-and-puff development (Alfarge et al., 2017; Liang et al., 2025). Field applications have also shown that water huff-n-puff can achieve the same impressive EOR effect (oil increase of 475 bbl, maximum oil production of 550 bbl) (Wood and Milne, 2011). After entering the 21st century, huff-and-puff development has been promoted and applied worldwide (Shi et al., 2024; DeLapp et al., 2025), and the types of huff-and-puff media have become more and more extensive. Currently, the commonly used huff-n-puff media include water, CO_2, N_2, natural gas, flue gas, mixed gas, active water, thickened water, etc., as shown in Table 1. Water has poor compressibility and injectability, while its energy replenishment rate is fast. Gases, on the other hand, have strong compressibility and expansion energy, while their low viscosity results in a smaller swept volume. Therefore, active water with interfacial activity and multi-component systems have been widely used.

3.2 Water huff-n-puff

Injected water is currently the most widely used huff-n-puff medium in oil and gas fields (Hu et al., 2021; Li and Liu, 2024), mainly because of its advantages such as wide source, low price, and eliminating the requirement for additional injection equipment (Liu et al., 2021). Water huff-n-puff originated from the steam huff-and-puff development test of the Duri oil field (Indonesia) in the 1970s (Atmosudiro, 1977). Subsequently, water huff-n-puff gradually proved its feasibility and advancement in the development of various oil reservoirs (Ostrovsky and Nestaas, 1987; Yusuf et al., 1999). During the water huff-n-puff development test in the Bakken tight oil block, a significant increase in oil well production could be observed after one year of water development (Todd and Evans, 2016). Moreover, the results of the Changqing tight oil field test (Ordos Basin, China) showed that water huff-n-puff can effectively reduce residual oil saturation, increasing crude oil production by 22.2% after two rounds of huff and puff (Chen et al., 2018). Since then, scholars have conducted multiple studies on the parameter optimization design of water huff-n-puff development based on indoor experiments. Zhang et al. (2024) studied the tight oil reservoir of Chang 7 in the Ordos Basin and compared the influencing factors of forced and spontaneous imbibition. They pointed out that a higher oil recovery can be gained when increasing the injection rate during the forced imbibition process. Using numerical simulation, Li et al. (2015b) further demonstrated the feasibility of further water huff-and-puff development after the exhaustion of tight oil reservoirs. The results showed that the daily oil production of the first round of water huff-n-puff of a single well could be increased by 78.3% compared with that before huff-n-puff. Yang et al. (2024a) studied the tight oil reservoir of Chang 8 in the Ordos Basin and conducted a huff-n-puff experiment

Table 1. Indoor research and field application of different huff-n-puff media.

Solvent	Main research content	Advantages
Water (Qin et al., 2021; Li et al., 2022b; Pu et al., 2023)	Influencing factors and parameter optimization	Low-cost, high-performance
N_2 (Lu et al., 2017; Meena et al., 2024)	Differences in the mechanisms of different gas huff-n-puff development and optimization design of parameters	Relatively low cost
CO_2 (Yang et al., 2024b; Zhao et al., 2025)		There are miscible and supercritical states, multiple crude oil replacement mechanisms, and beneficial huff-n-puff effects
CH_4 (Li and Sheng, 2016; Yao et al., 2023a; Guo and Wortman, 2025)		Similar solubility to crude oil and a good huff-n-puff effect
Flue gas		Low cost and environmentally friendly
Mixture gas (Jiang et al., 2024)	Gas type and mixing ratio	Can realize both cost and the huff-n-puff effect, and EOR may be the highest
Surfactant-activated water	Influence mechanism of low IFT on the imbibition process	Can reduce capillary force and promote water displacement of crude oil in pore throats
Multi-component fluid (Lv et al., 2024; Zhu et al., 2024b)	Including the research and development of multi-component huff-n-puff media, such as gel, foam, and steam etc.	Able to consider both the mass transfer effect of gas and the mobility control effect of liquid

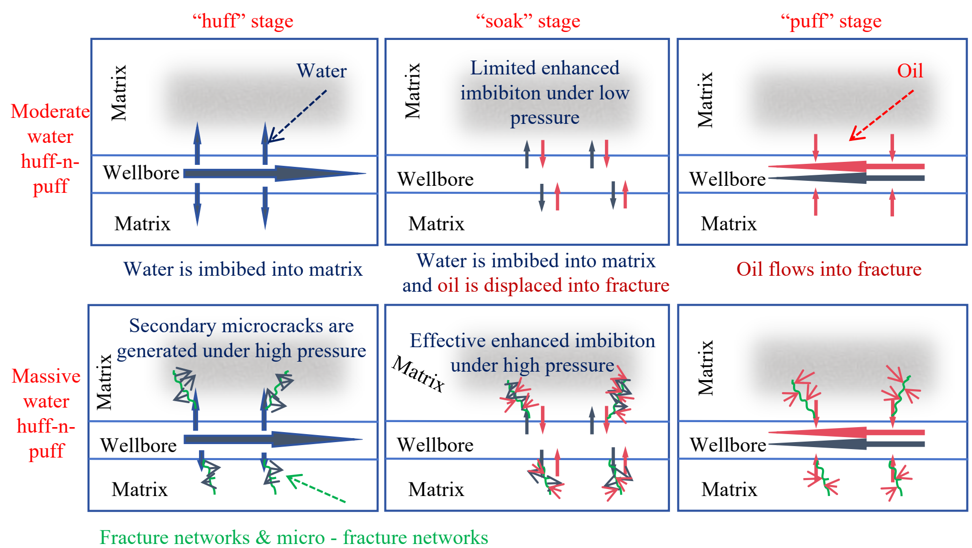

Fig. 3. Oil-water displacement process in the three stages of huff, soaking and puff, modified from Qin et al. (2021).

in a long core chamber. They studied the influencing factors of permeability, well soaking time, injected water volume, water injection rate, huff-n-puff cycle, and injection pressure on oil recovery from the Chang 8 tight oil reservoir. The above experiments and field application results collectively show that the larger the injection rate is, the longer the well soaking time is, the higher the reservoir permeability is, the hydrophilic the reservoir is, and the more developed the fractures are, the better the huff-n-puff development effect will be.

According to the injection method, water huff-n-puff can be divided into moderate-level and massive-level injection. The difference between the two is that massive level water huff-n-puff needs to inject water at a high injection rate to approach or reach the fracture pressure of the reservoir, playing a role in stimulating natural fractures and hydraulic fractures in the reservoir. Therefore, compared with moderate water huff-n-puff, massive water huff-n-puff can have more contact area with the reservoir and improve the efficiency of imbibition and diffusion. In the mechanism of water huff-n-puff to improve oil recovery, the capillary force is mainly used to make water enter the matrix pores or fractures and replace the original crude oil inside, as shown in Fig. 3. Massive water huff-n-puff can effectively improve the efficiency of this imbibition replacement while providing an effective fracture seepage channel, greatly improving the effect of huff-n-puff. Imbibition replacement mainly occurs in the soaking stage,

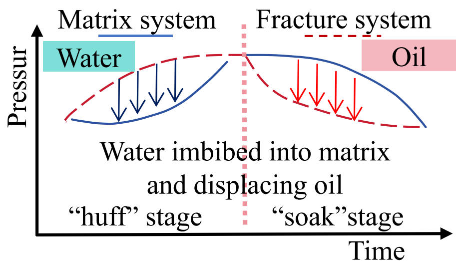

Fig. 4. Pressure change process in the matrix and fractures during the water injection and soaking stage, modified from Qin et al. (2021).

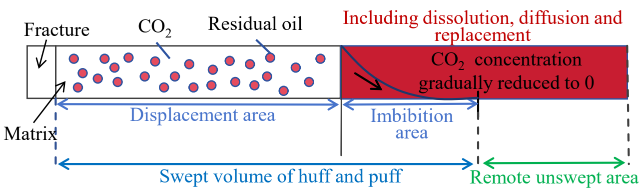

Fig. 5. Schematic diagram of flow sweep and diffusion sweep after Tang et al. (2021).

which is directly related to the pressure difference in the matrix pore throat and fracture (Meng et al., 2022). The water injection process can replenish the formation energy, and the replenished pressure in the injection stage is mainly concentrated in the fractures. As the well is soaked, fracture water enters the matrix pore throats under the pressure difference and replaces the crude oil, achieving the balance of pressure in the fractures and pore throats, as shown in Fig. 4. The injection of water to replace crude oil under the action of pressure difference and capillary force constitutes the main EOR mechanism of water huff-n-puff. At this time, forced imbibition has a significant advantage, as it can improve the replacement efficiency and shorten the soaking time. The existence of fractures can obviously improve the effect of water huff-n-puff.

3.3 Gas huff-n-puff

Compared with water, gas has superior injectability, flow diffusion and solubility (Wang et al., 2023). Besides, the cost of N_2 is also relatively low. Although the cost of CO_2 is high among the gases, it can play a role in a variety of EOR mechanisms and also the dual role of oil displacement and carbon utilization (Hu et al., 2021; Chen et al., 2024).

The EOR mechanism of N_2 huff-n-puff development may be energy enhancement, oil expansion, viscosity reduction, imbibition, and solution gas-driven (Sheng, 2017). The oil recovery of N_2 huff-n-puff significantly decreases with the increasing number of huff-n-puff rounds. In the fourth round, no crude oil is produced (Song et al., 2022). Meanwhile, the oil recovery of the first four rounds is about 40%. Bai et al. (2019) pointed out that the effect of N_2 huff-n-puff development is better when there are fractures in the reservoir. Yu et al. (2016) asserted that there is an optimal well-soaking time for N_2 huff-n-puff; a higher well-soaking pressure and a lower exhaustion development oil recovery will lead to a higher oil recovery of N_2 huff-n-puff. Nguyen et al. (2018) pointed out via microfluidic experiments that the main EOR mechanism of gas huff-n-puff is that the gas dissolved in the liquid phase precipitates and expands during the depressurization process. This indicates that the pores mobilized by N_2 huff-and-puff are mainly those containing the mobile crude oil in the macropores and medium pores, and the main controlling EOR mechanism is elastic expansion.

Furthermore, the EOR mechanisms of CO_2 huff-n-puff development include solubilization extraction, the improvement of reservoir wettability and oil-water IFT, etc. (Zuloaga et al., 2017; Li et al., 2019b). CO_2 huff-n-puff was first proposed by Monger et al. (1991) and Thomas and Monger-McClure (1991), who confirmed its feasibility in improving oil recovery. Later, it gradually became the main technical means for the development of tight reservoirs (Hawthorne et al., 2013). Unlike N_2 in N_2 huff-n-puff, the molecular diffusion of CO_2 enhances its solubility in the liquid, which can give full play to the expansion mechanism of gas (Li et al., 2019a). This results in a significantly better development effect of CO_2 huff-n-puff compared to that of N_2 huff-n-puff (Li et al., 2017; Bai et al., 2019). Tang et al. (2021) divided CO_2 huff-n-puff into four stages: CO_2 flowback, gas-carrying oil production, high-speed oil production, and slow oil production (Fig. 5). The gas-carrying oil production stage mainly includes free gas flooding, while high-speed oil production is mainly dissolved gas flooding. The so-called diffusion and CO_2 dissolution can be understood as the process of forced imbibition and the displacement of crude oil.

3.4 Comparison of water, N_2 and CO_2 huff-n-puff

There are significant similarities and differences between water, CO_2, and N_2 huff-n-puff. The similarities are mainly reflected in two points: (1) The first three rounds of huff-n-puff have the best effect on improving oil recovery, and the final oil recovery is stable after 5-6 rounds. Meanwhile, the first 1-2 rounds of huff-n-puff mainly mobilize the crude oil in large pore throats and fractures, whereas the subsequent rounds mobilize the crude oil in small pores and micropores through forced imbibition displacement, as shown in Fig. 6; (2) Although water huff-n-puff has a strong dependence on the existence of reservoir fractures, the EOR effect of different huff-n-puff media in fractured reservoirs and the performance of various EOR mechanisms are better than those in non-fractured reservoirs, as shown in Fig. 7.

In the process of forced imbibition, different injection media have different functions, as shown in Fig. 7. In terms of gas, it has viscosity reduction (Fig. 7(a)) and dissolution expansion characteristics (Figs. 7(b)-7(d)). CO_2 has a significantly better viscosity reduction effect than N_2, and its solubility in oil is also higher, which is an advantage of CO_2 huff-n-puff. The increase in CO_2 solubility has two advantages: (1) High-molecular-weight crude oil is replaced and produced via extraction, while water injection is mainly performed with C9, which makes the viscosity of residual oil increase and is not conducive to further improving the oil

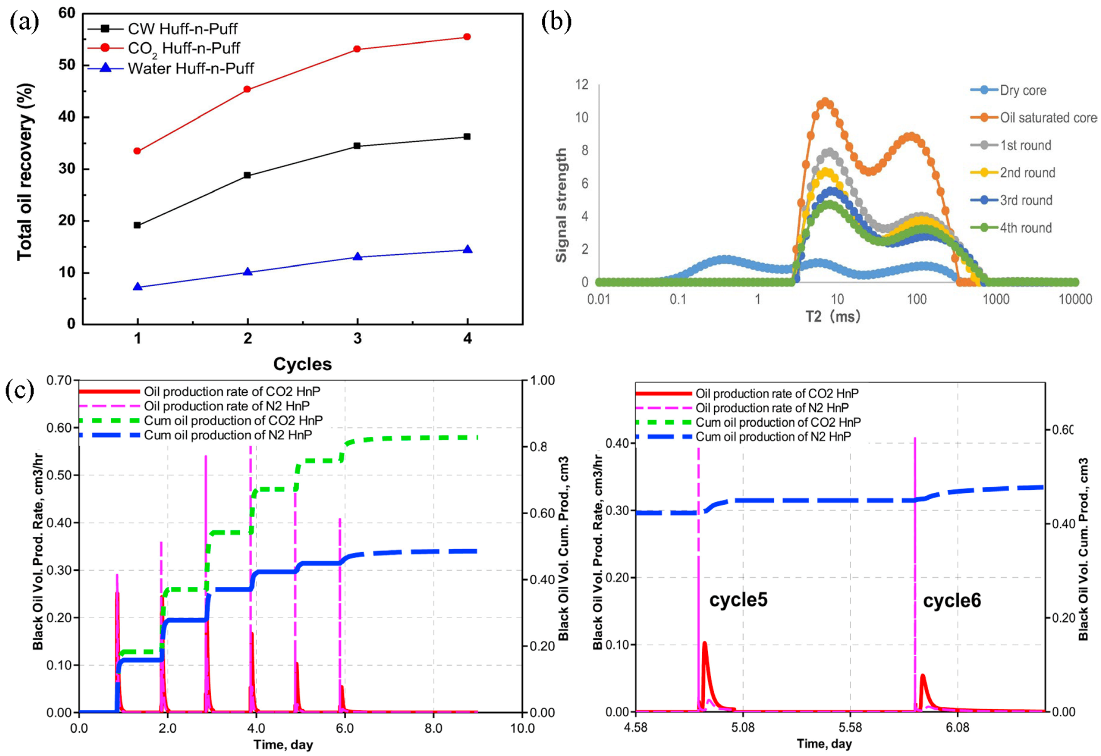

Fig. 6. EOR effects and pore throat characteristics of different huff-n-puff rounds of water, CO_2 and N_2. (a) Oil recovery in different cycles of HnP processes, and (b) NMR T_2 spectrum in various stages, cited from Du et al. (2021); and (c) oil recovery in different cycles of CO_2 and N_2 HnP process, cited from Li et al. (2019a).

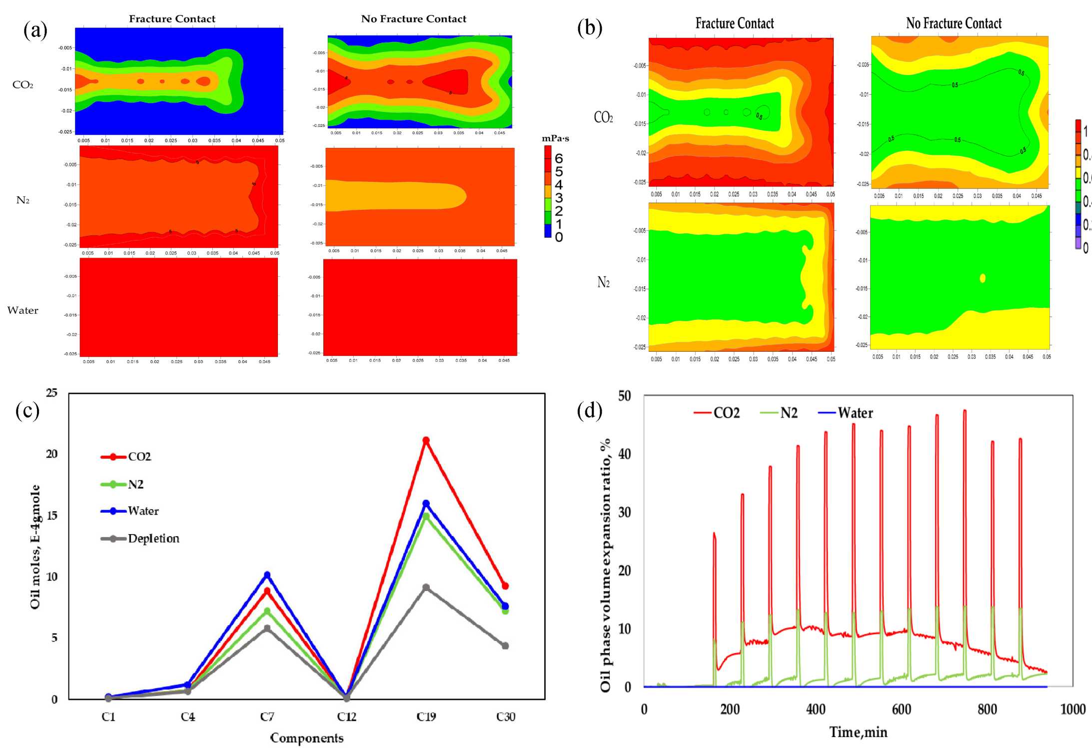

Fig. 7. Comparison of oil recovery mechanisms using forced imbibition of water, CO_2 and N_2 after Bai et al. (2019). (a) Oil viscosity of different HnP fluids; (b) mole fraction of injection fluid in oil; (c) production component comparison; and (d) oil volume and oil volume expansion ratio under the reservoir condition.

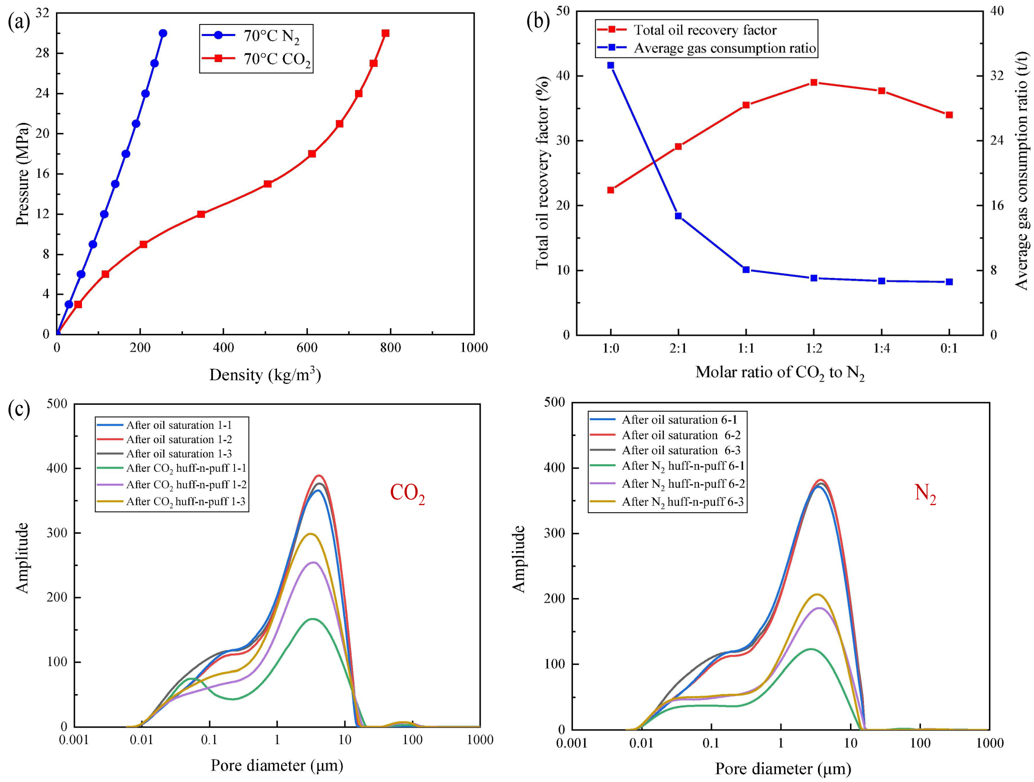

Fig. 8. Optimal mixing ratio and mechanism of CO_2-N_2 mixed huff-n-puff, cited from Li et al. (2022a). (a) Graph comparing the density and pressure of carbon dioxide and nitrogen at 70 °C; (b) crude oil recovery and average gas consumption rate under different molar ratios of carbon dioxide to nitrogen; and (c) amplitude distribution of nuclear magnetic signals before and after huff-n-puff for different pore sizes.

recovery; (2) the dissolution expansion multiple is significantly increased. The dissolution expansion ratio of CO_2 can reach 3 times that of N_2, greatly increasing the expansion energy of the crude oil itself. There is no dissolution, expansion or viscosity reduction mechanism for water injection; it mainly relies on external pressure difference and capillary force to achieve pore throat fluid replacement, hence it has a stronger demand for forced imbibition (Li et al., 2020; Cai et al., 2022).

Although CO_2 huff-n-puff has a better crude oil expansion and viscosity reduction effect than N_2 and water, excessive CO_2 dissolution under the premise of equal gas injection will reduce the wellbore pressure (Fig. 8(a)). The reduction of wellbore pressure will lead to a decrease in gas imbibition replacement efficiency. Although crude oil expansion can make up for this problem, the final oil recovery is often suboptimal. Therefore, both indoor research and oilfield application have considered mixing CO_2 and N_2, while collaborative effort has been put into studying the mass transfer effect of CO_2 and the energy enhancement effect of N_2. Many scholars have shown that N_2 and CO_2 have the best EOR effect at a certain mixing ratio, as shown in Fig. 8(b). Compared with CO_2 huff-n-puff alone, CO_2-N_2 mixed huff-n-puff can mobilize the remaining oil in smaller pores (Fig. 8(c)), which is also the result of forced imbibition enhancement due to increased pressure. The mixed gas containing CO_2 and N_2 can simultaneously play the mass transfer role of CO_2 and the energy replenishment role of N_2, enhancing the EOR effect.

Furthermore, steam-assisted CO_2 huff-n-puff (Wang et al., 2022), water-assisted CO_2 huff-n-puff (Han et al., 2024), and profile control agents-assisted CO_2 huff-n-puff (Kang et al., 2023; Li et al., 2025) are all based on the idea of supplementing the wellbore pressure after CO_2 dissolution to achieve better EOR effects.

3.5 Current status of active water huff-n-puff

Active fluids refer to solutions such as surfactants and nanoparticles that have certain interfacial activity and can effectively change the wettability and reduce IFT to promote the entry of water into micropore throats, thereby increasing the efficiency of crude oil displacement (Scerbacova et al., 2023). In addition, active fluids can effectively improve the flowability of crude oil in pores (Jadhav and Barigou, 2021). Shuler et al. (2016) switched to surfactant solution huff-n-puff development after water huff-n-puff, which could further increase the oil recovery by 20%. Balsamo et al. (2015) pointed out that temperature is the main controlling factor affecting the active water huff-n-puff, and there is an optimal temperature window range to obtain the best development effect. Lotfollahi et al. (2017) verified the improvement effect of active fluids on wall wettability through numerical simulation and pointed out that the capillary force reduction is conducive to enhancing reverse imbibition. Wang et al. (2008) combined active fluids with gel plugs for huff-n-puff development, and showed that the oil recovery of Daqing Oilfield mine could

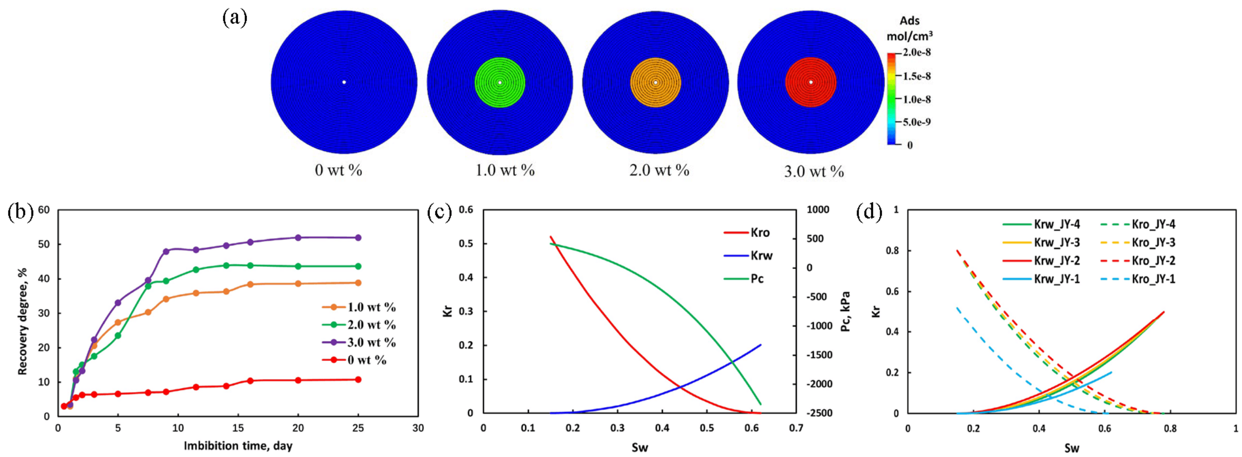

Fig. 9. Active water huff-n-puff effect and mechanism after Lu et al. (2023). (a) Core adsorption at different concentrations; (b) HnP results under different surfactant concentrations; (c) relative permeability and capillary force curves of water HnP; and (d) relative permeability curve and capillary force curve of surfactant HnP.

reach 59%. In addition, the type of surfactant and nanofluid, the concentration of the surfactant, etc., will affect the active water huff-n-puff development effect (Gogoi Subrata, 2011). Based on the experimental results of nano-active fluid huff-n-puff development, Nirmalkar et al. (2018) pointed out that it has a better EOR effect than surfactants, but the concentration of nanofluids needs to be controlled within a reasonable range to avoid the retention of nanoparticles and pore blocking caused by excessive concentration.

The amount of surfactant adsorbed on the reservoir wall increases with rising surfactant concentration, which also leads to a more obvious improvement in wettability and often to higher oil recovery (Figs. 9(a) and 9(b)). However, the concentration of surfactant used needs to be optimized based on economy considerations, and it is not the case of "the bigger, the better". Meanwhile, the critical association concentration of surfactants will also affect their effectiveness. Many experimental and simulation research results suggest that the optimal surfactant concentration should be around 0.5%-0.7% (Yao et al., 2023b; Ataceri et al., 2024), while the concentration in on-site applications is often lower. In addition, surfactants can improve the oil-water relative permeability curve and significantly increase the relative permeability of the oil-water phase. At the same time, when the surfactant has good compatibility with the reservoir, the isotonic point and residual oil saturation of the phase permeability curve will shift to the right, enhancing the water wettability of the reservoir and improving the final oil recovery, as shown in Figs. 9(c) and 9(d)).

4. Effect of wettability on forced imbibition

This section discusses the forced imbibition effects of different fluids and compares the influence of different imbibition parameters. The wettability of the rock surface is also a key factor influencing the imbibition exchange of two-phase fluids. The classic Lucas-Washburn model (Lucas, 1918; Washburn, 1921) reveals that when capillary and viscous forces are balanced, the fluid migration distance is proportional to the square root of time (Eq. (1)). This model is widely used for the percolation process of oil in the reservoirs. However, the Lucas-Washburn model ignores the effects of gravity and inertia and assumes constant fluid viscosity and contact angle. Therefore, while the model agrees well with the experimental results under macroscopic conditions, it exhibits significant deviations at the micro- and nanoscale, demonstrating the significant influence of wettability on the macroscopic forced imbibition effect. Changes in wettability arise from the interaction between reservoir rock, reservoir fluid and injected medium. This review discusses the effect of low-salinity water on wettability change and the subsequent changes in CO_2 imbibition:

$$z(t)=\sqrt{\frac{tR\sigma_{LV}\cos\theta_0}{2\eta}} \tag{1}$$

where $z(t)$ represents the fluid migration distance, m; R denotes the capillary radius, m; σ_{LV} denotes the fluid's surface tension, N/m; θ_0 stands for the equilibrium contact angle between the fluid and the wall surface, °; η represents the fluid viscosity, Pa·s; t is the time duration, s.

4.1 Effect of salt concentration on wettability

Lower-salinity water flooding can significantly increase oil recovery compared with reservoir water flooding. Compared to conventional water flooding, LSWF utilizes the differences in ion types and concentrations between the formation and injected water to improve rock surface wettability, resulting in forced imbibition. Numerous imbibition experiments, theoretical derivations and numerical simulations have clarified the role of wettability changes and reduced IFT in promoting imbibition and improving oil recovery. Furthermore, combined with the electric double layer theory, multi-ion exchange theory, and DLVO theory, the inherent dominant mechanism of the differential distribution of particles and fluids has been revealed (Dordzie and Dejam, 2022; Molinier et al., 2024). In addition, existing work has explored the mechanisms of pH

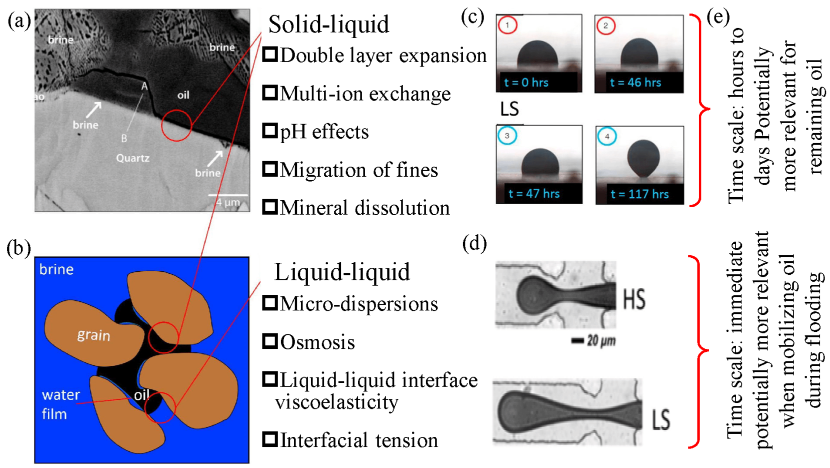

Fig. 10. Interface response mechanism of forced imbibition by LSWF (Lake, 1989; Morin et al., 2016; Bartels et al., 2019). (a) Illustration of the morphology of the solid-liquid interface. A thin layer of water film separates the oil from the quartz; (b) diagrams of the solid-liquid and the liquid-liquid interfaces; (c) and (d) are examples of the interaction mechanisms of solid-liquid and liquid-liquid interfaces; and (e) correspond to the durations of the mechanisms acting on the two interfaces.

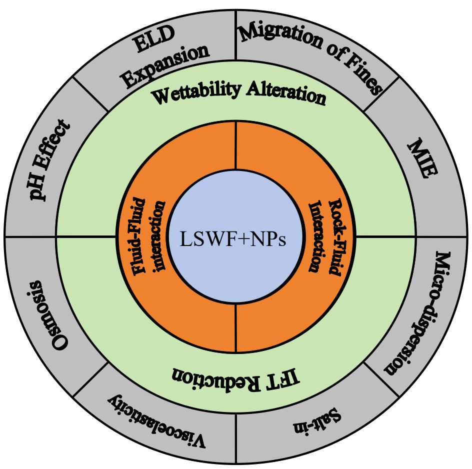

Fig. 11. Synergistic effect of LSWF and nanoparticles, cited from Arain et al. (2024a).

change effects, multi-component ion exchange effects, double layer expansion effects, and interfacial viscoelastic changes on the enhanced imbibition of LSWF at the sub-pore scale, core scale, and reservoir scale (Morin et al., 2016; Bartels et al., 2019), as shown in Fig. 10.

Lara Orozco et al. (2023) explored the mechanism of action of wettability modifiers (glycine and sulfate) in carbonate reservoirs and their impact on oil recovery. Their work successfully simplified the complex surface complexation model into a simplified physical model based on anion exchange, that is, the injected wettability modifier exchanges with the carboxylic acid adsorbed on the rock surface. Secondly, their analytical solution shows that the "wettability change wave" can improve the oil-water mobility ratio to enhance the forced imbibition effect. Wang et al. (2024) demonstrated that the desorption of polar asphaltene in a low-salinity environment leads to a shift in the wettability of the rock surface to a stronger water wettability, thereby enhancing imbibition. Further analysis based on the Zeta potential and the DLVO theory pointed out that the fundamental reason for the desorption of asphaltene is that under low-salinity conditions, a stronger electrostatic repulsion is formed between the oil droplets and the rock surface. Besides, displacement and imbibition experiments indicated that low-salinity water can significantly make the rock surface more water wetting and reduce the oil-water IFT (Gazem and Krishna, 2024). Meanwhile, the application of LSWF in secondary oil recovery mode can achieve a higher final oil recovery than the tertiary oil recovery mode. Sarma et al. (2023) conducted a variety of experiments-such as high-temperature and high-pressure displacement, real-time imbibition monitoring and Zeta potential measurement-for LSWF in carbonate reservoirs, and explored the main mechanism of imbibition enhancement by wettability. Their results showed that the key ions (especially sulfate ions, SO_4^{2-}) injected into the low-salinity water will be adsorbed on the surface of carbonate rocks, making them carry a stronger negative charge, thereby enhancing the electrostatic repulsion between the rock and the equally negatively charged crude oil, ultimately promoting the peeling of the oil film and the shift of the rock surface to water-wetting. Some scholars (Ali Buriro et al., 2023; Arain et al., 2024b) reviewed the current status of research on LSWF and its synergistic effect with nanoparticles to enhance imbibition. Microscopically, multiple ion exchange and electric double layer expansion are used to change rock wettability, thereby effectively improving imbibition efficiency. The synergistic effect of nanoparticles and low-salinity water can further change wettability, reduce IFT, and increase separation pressure. The synergistic mechanism of the two is depicted in Fig. 11 (Arain et al., 2024a).

4.2 Effect of wettability change on CO_2 imbibition

In the reservoir, CO_2 usually exists in the form of a supercritical fluid with a density lower than that of formation water (Arif et al., 2016; Arif et al., 2019). Experiments and

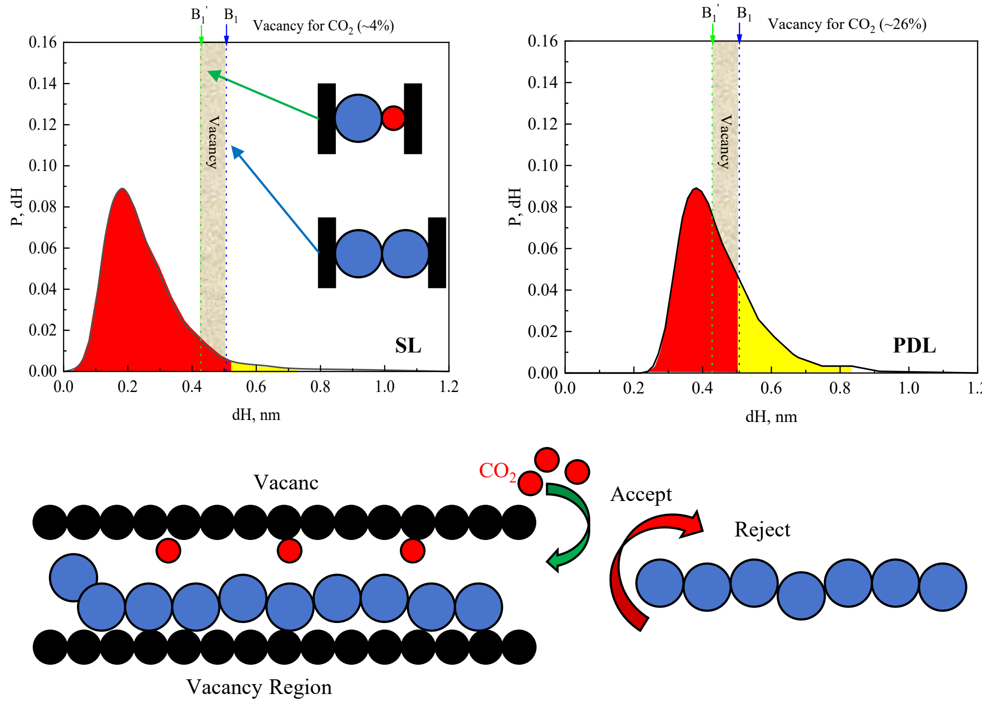

Fig. 12. Different molecular sizes-nanocavity mechanism and strong CO_2 adsorption phenomenon, cited from Zhang et al. (2025b).

simulations have indicated that water-wet surfaces are conducive to the adsorption and storage of CO_2 (Al-Khdheeawi et al., 2017; Iglauer, 2017), thereby promoting its mass transfer and diffusion to enhance the imbibition and EOR effect, as shown in Fig. 12. When the interface changes from oil-wet to water-wet, the imbibition efficiency of water-displaced oil in the oil-wet rock matrix increases (Al-Anssari et al., 2016). Experimental and simulation results revealed that increased reservoir pressure, increased salt ion concentration, decreased temperature, and decreased surface roughness all lead to enhanced water-wetness (Chavan et al., 2019; Ma and James, 2022), which is manifested macroscopically as a decrease in the rock/CO_2/brine three-phase contact angle. The change in contact angle can be used to standardize the change in wettability, which ultimately determines the fluid velocity distribution, distribution characteristics, displacement mechanism, and reservoir structural changes/capillary expansion dynamic changes (Yang et al., 2008).

Zhu et al. (2024a) systematically explored the effect of CO_2 foam in fractured low-permeability reservoirs through core and microscopic displacement experiments. During the soaking stage, the foam enters the matrix and breaks, and the surfactant can change the wettability and emulsify the crude oil, thereby enhancing the absorption of CO_2. Zhang et al. (2025b) performed molecular dynamics simulation to systematically explore the absorption and replacement behavior of hydrocarbons (n-hexadecane) and CO_2 in shale organic matter nanopores of different sizes (0.7-4.7 nm). Their study revealed and quantified the "subcontinuum effect" dominated by pore size and found that the critical pore size is about 0.9 nm. When the pore size shrinks to this size, due to the mismatch between molecular size and geometric space, the density of its first adsorption layer will decrease significantly. Therefore, the use of conventional fluid density calculation in confined space may overestimate the original oil and gas reserves. In terms of CO_2 displacement, the critical size theory shows that the first adsorption oil layer that is difficult to mobilize can be selectively permeated and effectively imbibed by CO_2 molecules in pores with a critical size of 0.9 nm, resulting in a nonlinear growth trend in oil recovery and CO_2 storage capacity with changes in pore size. Zhang et al. (2025a) studied the effects of chemical agents on interfacial properties and production capacity in shale oil reservoirs. Their results showed that among various fluids such as acid, alkali, slick water, and CO_2, the IFT between CO_2 and shale oil was the lowest (up to 0.982 mN/m), and it exhibited the advantages of viscosity reduction and miscibility. Besides, the injection of CO_2 could slightly increase the total porosity of the core (about 6.04%) by dissolving some organic matter. In the analysis of the EOR mechanism, they revealed that self-imbibition displacement energy is the most important controlling factor for EOR (contribution rate of 71.1%). Elkhatib et al. (2024) reviewed the influence of mineral wettability on oil and gas production. Their study proposed that intermolecular interaction forces dominate the wettability of CO_2 in reservoir rocks such as sandstone and carbonate. The wettability of CO_2 directly determines the efficiency of its residual and structural traps in underground reservoirs, which is conducive to accurately assessing the long-term stability and safety of carbon sequestration items. Green and new nanocomposite materials are regarded as a growth point of future technologies

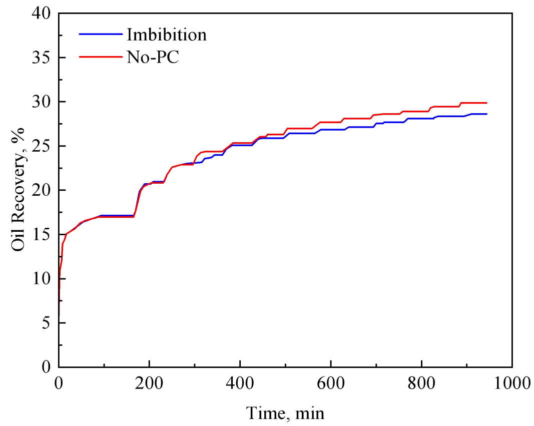

Fig. 13. Effect of capillary imbibition on EOR in each huff-n-puff cycle, cited from Bai et al. (2019).

in improving CO_2 flooding and related gas injection (Ahmadi and Kariminia, 2023). The application of new nanocomposites (such as urea/ZnO/γ-Al_2O_3) can significantly improve the effectiveness of gas-assisted EOR methods such as water-gas alternation. At the microscopic level, the imbibition effect is enhanced by regulating wettability, reducing IFT, and other mechanisms. Advanced nanomaterials provide a frontier research direction to improve the efficiency of CO_2-EOR and expand its application scenarios.

5. Contribution of forced imbibition to huff-n-puff recovery

The above studies collectively demonstrate that the EOR mechanisms of huff-n-puff development mainly includes elastic expansion and imbibition displacement. The expansion and flow diffusion properties of formation water are weaker than those of gas, so its huff-n-puff development effect is poorer. Surfactants can enhance the ability of formation water to improve wettability and reduce IFT, and they can increase its oil recovery based on formation water huff-n-puff. Accurately splitting the contribution of elastic expansion and imbibition displacement in huff-n-puff development can effectively guide the optimization design of development plans (Yao et al., 2021; Sheng et al., 2024). Using numerical simulation results, Li et al. (2023) explained that capillary imbibition has almost no effect on oil recovery in the first 2-3 rounds of huff-n-puff (Fig. 13), which shows that elastic expansion is the main oil recovery mechanism in the early stage of huff-n-puff development, and in subsequent huff-n-puff cycles, the presence of imbibition will further increase oil recovery.

Chen et al. (2025c) quantitatively split the oil production of elastic expansion and imbibition displacement based on active water and CO_2 huff-n-puff experiments with and without well soaking. They assumed that the oil production of the soaking process is contributed by both elastic expansion and imbibition displacement, while the oil production of the non-swelling process is entirely due to elastic expansion. From these experimental results shown in Fig. 14, we can find that elastic expansion is the main EOR contribution factor of active CO_2 and water huff-n-puff, and imbibition displacement contributes 31.52% and 20.86%, respectively, as shown in Fig. 14. Due to its good flow and diffusion properties, the effective action distance of CO_2 is greater than that of active water. It is important to note that this method was calculated using laboratory experimental data and therefore has limited applicability. In the laboratory experiment, a 24-hour well-soaking was maintained, and the soaking pressure elevated in just 0.5 hours. Furthermore, the average pressure during the pressurization process was low, so the imbibition displacement during the pressurization process can be ignored, and the oil production can be attributed entirely to elastic expansion. However, in actual field applications, the pressurization process is relatively slow, and using this method to split the imbibition contribution rate requires additional considerations.

6. Summary and discussion

This paper systematically reviews (i) the concept of forced imbibition, (ii) the EOR effects and mechanisms of different huff-n-puff media, and (iii) wettability improvement through forced imbibition. The contents are summarized and discussed from the following three perspectives:

1) Forced imbibition is a process that promotes imbibition by increasing pore pressure or improving wettability based on spontaneous imbibition. However, there is currently no clear definition of this concept, which is rather proposed in comparison with spontaneous imbibition: All processes that can enhance the effect of spontaneous imbibition can be called forced imbibition. For example, heating the reservoir to reduce crude oil viscosity, fracturing to create flow channels, and draining water to produce gas are all means of forced imbibition. To this end, this paper systematically explains the most common huff-n-puff and wettability improvement.
2) EOR effect of huff-n-puff using different fluids. Gas is currently the most widely used huff-n-puff medium in oilfields. This is mainly because gas has stronger mass transfer and diffusion capabilities and can enter smaller pore throats under high pressure. Meanwhile, it also has inherent features such as dissolution to reduce viscosity and expansion to increase oil production. However, water huff-n-puff exhibits the advantages of fast energy replenishment, low cost and environmental protection, and water is also an irreplaceable huff-n-puff medium. To enhance the effect of water huff-n-puff, active water huff-n-puff with the addition of surfactants, nanofluids, and displacement systems shows broader application potential. Low-salinity water also has the effect of improving wettability and this effect can also be improved based on conventional water huff-n-puff.
3) EOR mechanism of huff-n-puff. Different media act according to different mechanisms in EOR, among which the mechanism of gas huff-n-puff is complex and diverse. This paper groups these mechanisms into two categories: Elastic expansion and imbibition displacement. In the early stage of huff-and-puff, elastic expansion dominates; as the process progresses, oil production becomes increasingly governed by imbibition displacement. Special huff-n-puff media-such as CO_2-also act by extraction and

	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; Oil recovery without soaking; Oil recovery with soaking; Elastic displacement contribution rate; Huff-n-puff with soaking

Fig. 14. Design of the experimental scheme and key parameters for the quantitative splitting of huff-and-puff mechanisms, cited from Chen et al. (2025c).

viscosity reduction mechanisms, which are not studied separately here.

4) Improved wettability by LSWF. Improved wettability is the fundamental reason for enhanced imbibition by LSWF. The forced imbibition effect of LSWF is closely related to reservoir type and fluid properties and requires further in-depth research. Improving wettability and promoting imbibition can also be achieved through methods such as surfactant flooding and the injection of hot fluids.

7. Challenges and future prospects

This paper systematically expounds on the EOR effects and mechanisms of forced imbibition in current huff-n-puff development. It is established that there are still many problems in current research that need to be further studied. Based on the literature review and research experience, the following problems and research prospects are set forth:

1) Indoor experiments can guide the design of field parameters of the huff-n-puff process. For example, displacement experiments can be optimized and converted into field application parameters on the basis of similarity criteria. Indoor experiments can also study the effective distance of the huff-n-puff medium, the pore throat utilization limit, and the well soaking time. However, using these parameters, it is difficult to establish a corresponding relationship with field applications, particularly when defining the effective sweep radius of the huff-n-puff medium. The key future research direction in this context is how to connect the indoor results of the above parameters and the field effect through theoretical calculation and simulation research.
2) The intrinsic relationship between the enhanced imbibition mechanism of different huff-n-puff media should be studied. Huff-n-puff enhancement design can drive fluids into the pore throats to displace crude oil through high pressure. In addition, interactions among the different injected media, crude oil, formation water, and reservoir rock also determine the effect of enhanced imbibition. This also leads to differences in the huff-n-puff effects of different media. Revealing the essential mechanism of enhanced imbibition by different huff-n-puff media can clarify the reasons for the differences in the enhanced imbibition effects of different media, and ultimately establish a unified method for evaluating the huff-n-puff effects of these media.
3) Quantitative splitting of the huff-n-puff EOR mechanism. This paper splits the contributions of the two mechanisms of expansion displacement and imbibition displacement. However, EOR mechanisms vary markedly with the injected medium, particularly for gas huff-n-puff. Relatively few studies exist on the quantitative splitting of various mechanisms, and this review highlights the importance of expanding this research direction. Future work should further refine the types of huff-n-puff development mechanisms, classify the main controlling factors according to the huff-n-puff media type, and quantitatively split their contribution rates. Such quantitative insights can effectively provide a robust foundation for optimizing the parameter design in field applications.
4) Development of LSWF. Low-salinity water flooding is a potential physical EOR method with both environmental and economic benefits. However, due to the complex ion reactions within the reservoir, the mechanism of LSWF is unclear, and these reactions also lead to unstable EOR effects. A good combination in this context is carbonated water flooding-which dissolves CO_2 in water-and LSWF, which is a relevant direction for exploratory research.

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Conflicts of interest

The authors declare no competing interest.

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