Insights into Maintaining High Soaking Pressure during CO_2 Huff-n-Puff in Shale Oil Reservoirs

Introduction

Since 2008, shale gas and oil production has grown substantially, generating strong momentum for exploration and production efforts (Gasparik et al., 2012). After multi-stage fracturing in horizontal wells, oil production consistently demonstrates a sharp decline within the first year, followed by a prolonged low-production rate period. Notably, the predicted oil recovery factor during the primary depletion process is generally less than 10% (Du et al., 2019; Li et al., 2022). To enhance oil recovery in unconventional oil reservoirs, technologies i.e., nanoparticles, gas injection, etc. have been investigated to improve sweep and/or displacement efficiencies (Shi et al., 2024; Ji et al., 2024; Wang et al., 2025). Previous experimental results of injecting CO_2 have shown significant potential to improve shale oil recovery by molecular diffusion, oil swelling, interfacial tension and viscosity reduction, and light components extraction (Jiang et al.,2022; Yang et al., 2025). CO_2 huff-and-puff has been regarded as a reliable and effective strategy for enhancing oil recovery in shale oil reservoirs as the injectivity of CO_2 injection is favorable as a result of continuous gas pathways from fracture and penetrating into the rock matrix through the diffusion mechanism. In the meantime, the injected CO_2 could be trapped in shale formations permanently.

CO_2 huff-and-puff in shale oil reservoirs typically starts with the injection of CO_2 into a single well and the injected CO_2 mainly occupies in hydraulic or natural fractures. Then, a shut-in or soaking period is performed to allow the CO_2 to dissolve into the oil in matrix, swell its volume, and reduce its viscosity. The concentration gradient pushes CO_2 to permeate into the matrix, and the volume of CO_2 contacted with oil relies on the solubility and diffusivity of CO_2, which are dependent on the soaking pressure and time. Subsequently, the well is returned to production and the response is monitored. Many researchers have concluded that CO_2 dissolution and diffusion are the dominant mechanisms for CO_2 EOR in shale oil reservoirs (S. B. Hawthorne et al., 2013; Tovar et al., 2021). However, the CO_2 dissolution and diffusion would lead to the reservoir pressure drops during soaking processes. Field test in the Lucaogou tight oil reservoir show that the wellhead pressure decreased from 27.6 MPa to 11.5 MPa during soaking process as CO_2 migrated into deep matrix pores driven by pressure and concentration gradients (Shi et al., 2024). The decreased pressure near wellbore hole conversely reduces the CO_2 solubility and diffusion coefficient, and thus significantly affect the performance of CO_2 huff-and-puff. Therefore, maintaining injection pressure during soaking by continuous injecting CO_2 could enhance the solubility and diffusivity of CO_2, thus improve the sweep efficiency and performance of CO_2 huff-and-puff.

In this study, maintaining high soaking pressure was proposed to enhance CO_2 dissolution and diffusion during soaking process. Four cycles' CO_2 huff-and-puff experiments with and without pressure maintenance were conducted considering different soaking pressure and time. In addition, nuclear magnetic resonance (NMR) T_2 distributions after each soaking cycles were collected to investigate the oil mobilization in different pore sizes. The findings in this study provides new insights into the field application of CO_2 huff-and-puff in shale oil reservoirs.

Materials and Experimental Method

The synthetic shale oil used in this study was prepared by mixing the crude oil collected from Shengli Oilfield with C12 (in a 1:1 ratio). The CO_2 with a purity of 99.999% was purchased from Dongfeng gas supply company, Chengdu. Synthetic core plugs with a diameter of 38 mm and length of 50 mm in were used to eliminate the effect of rock petrophysical properties on the performance of CO_2 huff-n-puff experiment. The porosity and permeability of the core plugs are 7.5% and 0.1 mD, respectively. Before experiment, the core plugs were dried in an oven at 100°C for 24 hours to remove moisture and were then vacuumed and saturated with oil under 25 MPa pressure for 48 hours. The core plugs were weighed after saturation process and T_2 spectra were collected using the low-field Nuclear Magnetic Resonance (LF-NMR) apparatus.

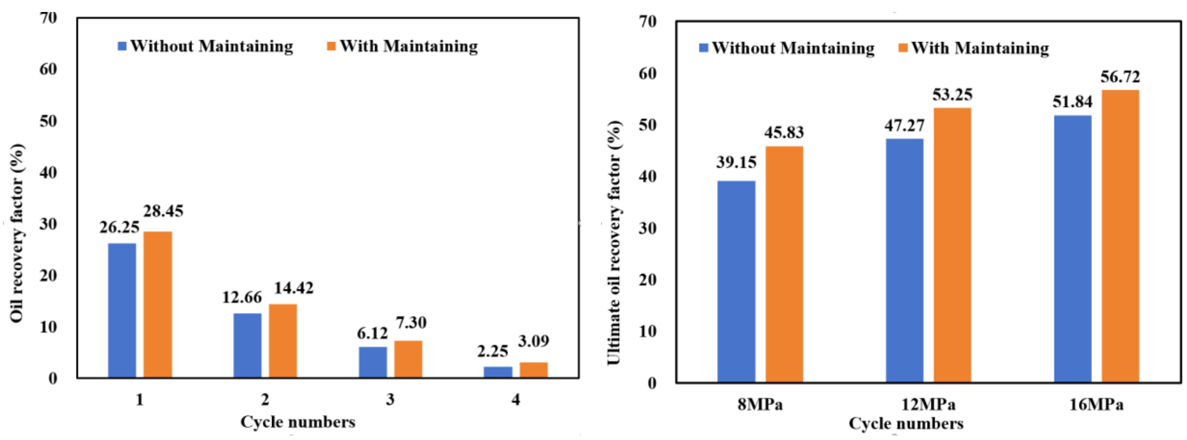
Ten cases of CO_2 huff-n-puff experiments with and without soaking pressure maintenance were designed considering different soaking pressure and time, as shown in Table 1. A brief introduction of the huff-n-puff experiment procedures are described as follows. (1) The core plug saturated with oil was placed vertically in the reactor and vacuumed for 2 hours. Then, the reactor was heated to maintain a constant temperature of 80°C. (2) CO_2 was injected into the reactor until the designated pressures were reached. The intake valve was then closed for the soaking propose. (3) After the soaking was complete, the pressure in the reactor was slowly reduced to atmospheric pressure. After cooling, the core plug was weighed and the T_2 spectrum was collected. (4) Steps (1) to (3) were repeated three times at the same injection pressure for the multicycle CO_2 huff and puff processes. (5) Oil recovery factor in each cycle was calculated based on the mass changes of the core plug after soaking.

Table 1. *Experimental design of CO_2 huff-n-puff.*

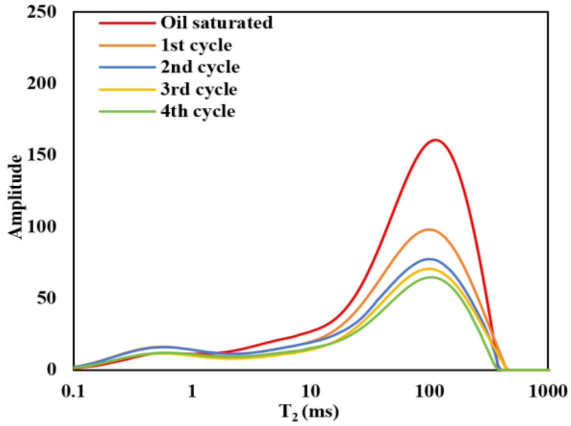
Scenario	Case	Soaking pressure (MPa)	Soaking time (h)	Cycle number
Without maintaining soaking pressure	1	8	4	4
	2	12	4	4
	3	16	4	4
	4	12	2	4
	5	12	6	4
Maintaining soaking pressure	6	8	4	4
	7	12	4	4
	8	16	4	4
	9	12	2	4
	10	12	6	4

Experimental Results and Discussion

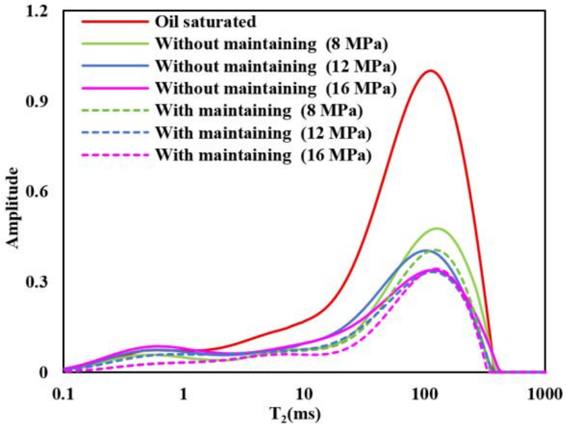
Figure 1(a) shows the oil recovery factor of four CO_2 huff-n-puff cycles at the pressure and temperature of 12 MPa and 80°C, and the soaking time is 4 hours (cases 2 and 7). The oil recovery diminishes from 26.25% to 2.25% after four cycles for both cases with and without maintaining soaking pressure. As is respected, the oil recovery factor increases slightly when the soaking pressure is maintained during soaking process, which is because more CO_2 contacts oil in inner pore spaces by gas diffusion. After four cycles, the overall oil recovery increased from 47.27% to 53.25%, as shown in Figure 1(b). On the other hand, the oil recovery for cases without soaking pressure maintenance increases with soaking pressure, which are 39.15%, 47.27% and 51.87% at 8, 12, 16 MPa, respectively. In comparison to cases without pressure maintenance, oil recovery increased 6.68%, 5.98%, 4.86% for cases with pressure maintenance at 8, 12, 16 MPa, respectively.



(a) (b)



(c)

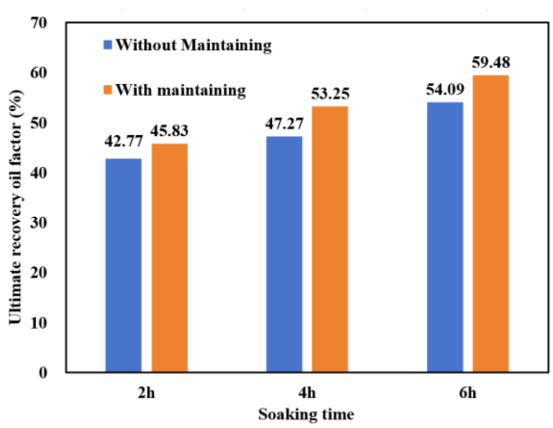


(d)

Figure 1 *(a) Oil recovery factor at different cycles for cases 2 and 7. (b) Oil recovery factor with and without maintaining pressure at different soaking pressures. (c) T_2 distributions at different cycles for case 2. (d) Normalized T_2 distributions of fully oil saturated, and after soaking at 8, 12 and 16 MPa.*

Oil mobilization in pore scale at different cycles for case 3 is evaluated from the NMR T_2 distribution results, as shown in Figure 1(c). Larger T_2 values corresponds the oil in larger pore spaces, and vice versa. In the first cycle, oil in larger pore spaces were recovered, and the amount of oil produced decreases with increasing cycles. This agrees with oil recovery factor showed in Figure 1(a). After four cycles, there are still unrecovered oil in larger pore spaces as well as smaller pore spaces. In addition, normalized T_2 distributions of fully oil saturated, and after soaking core plugs at 8, 12 and 16 MPa are showed in Figure 1(d). More oil can be recovered at higher soaking pressure, especially for cases with maintaining soaking pressure (dashed lines). It is interesting to note that oil in smaller pore spaces can be mobilized at the soaking pressure of 16 MPa, which is because the CO_2 solubility and diffusion coefficient are higher at larger pressure gradients. CO_2 can be transferred into inner and smaller pore spaces, and swells oil and reduces oil viscosity.

In addition to the soaking pressure, increasing soaking time also affects the amount of CO_2 transferred into inner and smaller pore spaces. Figure 2(a) shows the oil recovery factor at different soaking time for both with and without maintaining soaking pressure (soaking pressure: 12 MPa). The oil recovery factor increases with the soaking time of 2, 4, 6 hours, which are 42.77%, 47.27 and 54.09%, respectively. The oil recovery increasements with and without maintaining soaking pressure are 3.06%, 5.98% and 5.39% when soaking time increases from 2 hours to 6 hours, indicating an optimum soaking time can be determined depending on the amount of oil unrecovered. Similar to soaking pressure cases, more oil can be mobilized by prolonging the soaking time. However, maintaining soaking pressure at longer soaking time still cannot mobilize oil in smaller pore spaces.



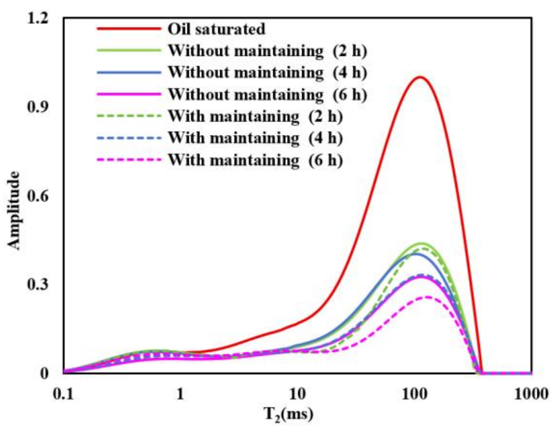


Figure 2 *(left) Ultimate oil recovery factor at different soaking times. (right) Normalized T_2 distributions of fully oil saturated, and after 2-, 4- and 6-hours' soaking.*

Conclusions

CO_2 dissolution and diffusion would lead to the reservoir pressure drops during soaking processes, which conversely reduce the CO_2 solubility, diffusion coefficient, and thus lead to the decrease of the ultimate oil recovery. Increasing soaking pressure and time can enhance the CO_2 dissolution and diffusion during CO_2 huff-n-puff in shale oil reservoirs. In this study, maintaining high soaking pressure was proposed in this study and the CO_2 huff-and-puff experiments with four cycles considering different soaking pressure and w/wo pressure maintenance were conducted. Experimental results show that the oil recovery factor for each cycle and the ultimate oil recovery factor increases by maintaining soaking pressure and prolonging the soaking time. The high soaking pressure maintenance technique proposed in this study effectively addresses the issue of pressure drop during the soaking phase, thereby increasing oil recovery. The findings in this study provides new insights into the field application of CO_2 huff-and-puff in shale oil reservoirs.

References

Du, F., & Nojabaei, B. (2019). A review of gas injection in shale reservoirs: enhanced oil/gas recovery approaches and greenhouse gas control. Energies, 12(12), 2355.

Gasparik, M., Ghanizadeh, A., Bertier, P., Gensterblum, Y., Bouw, S., & Krooss, B. M. (2012). High-pressure methane sorption isotherms of black shales from the Netherlands. Energy & fuels, 26(8), 4995-5004.

Ji, Z., Wang, H., Wang, M., Lv, W., Wang, S., Kou, Z., ... & Wang, L. (2024). Experimental and modeling study of CO_2 solubility in formation brines at in-situ conditions. Journal of Cleaner Production, 438, 140840.

Jiang, S., Li, Y., Wang, F., Sun, H., Wang, H., & Yao, Z. (2022). A state-of-the-art review of CO_2 enhanced oil recovery as a promising technology to achieve carbon neutrality in China. Environmental Research, 210, 112986.

Li, S., Sun, L., Wang, L., Li, Z., & Zhang, K. (2022). Hybrid CO_2-N_2 huff-n-puff strategy in unlocking tight oil reservoirs. Fuel, 309, 122198.

S. B. Hawthorne, C. D. Gorecki, J. A. Sorensen, E. N. Stead-man, J. A. Harju, and S. Melzer, Hydrocarbon mobilization mechanisms from upper, middle, and lower Bakken reservoir rocks exposed to CO_2, in Proceeding of SPE Unconventional Resources Conference, SPE paper SPE-167200-MS, Calgary, Alberta, Canada, November 2013

Shi, Y., Wu, B., Wang, H., Li, Y., Liu, Z., Xu, C., ... & Liu, H. (2024). Insights into CO_2 huff-n-puff mechanisms from laboratory experiment and single-well pilot test in the Lucaogou tight oil reservoir, Jimsar sag, China. Geoenergy Science and Engineering, 232, 212456.

Tovar, Francisco D., Maria A. Barrufet, and David S. Schechter. Enhanced oil recovery in the wolf camp shale by carbon dioxide or nitrogen injection: An experimental investigation. SPE Journal 26.01 (2021): 515-537.

Wang, H., Xin, Y., Gong, Y., He, C., Xiao, P., Zhu, Y., ... & Medina-Rodriguez, B. X. (2025). Characterizations of phase behavior and miscibility of CO_2-hydrocarbon mixtures in bulk and porous media using low-field NMR technique. Geoenergy Science and Engineering, 251, 213900.

Yang, H., Wang, H., Wang, X., Xin, Y., He, L., Jiao, Z., & Zou, J. (2025). Experimental and modeling assessment of CO_2 EOR and storage performances in tight oil reservoir, Yanchang oilfield, China. Journal of CO_2 Utilization, 97, 103125.