

Article

Control Mechanism of Water Shield on Pressure Dynamics of CO₂ Huff-n-Puff and Crude Oil Mobilization Effect in Tight Reservoirs

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Abstract

Tight oil reservoirs are characterized by poor petrophysical properties, ultra-low permeability, and limited pressure-transmission capacity. After hydraulic fracturing, retained fracturing fluid can accumulate near the fracture–matrix interface and form a water shield, which restricts carbon dioxide (CO₂) seepage, CO₂–oil contact, and crude-oil mobilization during CO₂ huff-n-puff. To clarify the control mechanism of a fracture-adjacent water shield on pressure dynamics and pore-scale oil mobilization in tight reservoirs, three stepwise core experiments were designed: a non-fractured core without a water shield (#E1), a single-fracture core without a water shield (#E2), and a single-fracture core with a MnCl₂-induced water shield (#E3). Pressure monitoring, cumulative nuclear magnetic resonance (NMR) T_2 spectra, and NMR imaging were integrated to compare the matrix, fracture, and water-shield effects. The results show that the water shield does not act as a constant resistance during cyclic CO₂ huff-n-puff. In Cycle 1, the water shield restricts CO₂–oil contact, and the relative pressure-decline amplitude of #E3 is approximately 10% lower than that of #E2. In Cycle 2, the relative pressure-decline amplitude of #E3 increases to 18.4%, approximately 1.8 times that of #E2, indicating a local water-shield transition rather than uniform matrix sweeping. The T_2 -derived recovery degrees of #E3 are 7.24%, 15.34%, 7.96%, and 4.07% from Cycles 1 to 4, respectively, and its cumulative recovery after four cycles is 34.61%, which is 7.32 percentage points lower than that of #E2. NMR imaging further shows that the swept region in #E3 is mainly concentrated near the fracture after Cycle 2, while matrix regions away from the fracture retain strong oil signals. These results indicate that the water shield first acts as a fracture-adjacent water-phase barrier and then undergoes a local transition into a preferential pressure-dissipation pathway. The findings provide a basis for interpreting pressure decline together with NMR evidence and for optimizing CO₂ huff-n-puff operations in tight reservoirs affected by retained fracturing fluid.



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1. Introduction

Tight oil reservoirs are commonly characterized by nano- to micro-scale pore throats, ultra-low permeability, strong heterogeneity, and limited natural energy. Horizontal wells combined with multistage hydraulic fracturing have become the primary development strategy for such reservoirs because artificial fractures provide the main pressure-transmission and production pathways between the wellbore and the tight matrix [1–3]. However, field and laboratory studies have shown that a considerable fraction of the injected fracturing fluid may remain in the fracture network and imbibe into the adjacent matrix after flow-back [4–7]. This retained aqueous phase changes the local saturation distribution near the fracture–matrix interface, occupies effective pore throats, and may generate water blocking or a water-shield barrier between the fracture and the oil-bearing matrix [8–11].

CO₂ huff-n-puff has received increasing attention as an enhanced-oil-recovery method for tight and shale oil reservoirs [12]. Its performance relative to other gas-injection schemes has been evaluated in prior reviews and comparative studies [13,14]. Compared with water or N₂, CO₂ can dissolve in crude oil, swell the oil phase, reduce viscosity, extract light components, and provide dissolved-gas drive during depressurized production [15–19]. NMR-based studies further indicate that CO₂ huff-n-puff mainly mobilizes oil in relatively large pores, whereas oil stored in smaller pores is more difficult to recover [20–22]. Therefore, CO₂ huff-n-puff performance depends not only on the injected CO₂ volume and pressure but also on effective pressure transmission from fractures into the matrix and sustained CO₂ contact with matrix oil during soaking [23–25]. Pressure-decay and NMR diffusion experiments in oil-saturated porous media also show that CO₂ diffusion coefficients are generally on the order of 10^{−8} m²/s and that low permeability limits the effective CO₂-rich region, even when the apparent diffusion front changes only slightly [26].

Fractures play a dual role in this process. On the one hand, fractures improve injectivity, enlarge the contact area between CO₂ and the matrix, and accelerate pressure propagation, thereby promoting crude-oil mobilization in tight reservoirs [27–31]. Reservoir-scale production and injection design are also sensitive to fracture configuration and geomechanical effects [19,32,33]. On the other hand, because fracture conductivity is much higher than matrix permeability, fractures may become preferential gas-flow channels after a local transition, especially when a continuous water film or water-rich zone near the fracture is disrupted. Under such conditions, a rapid pressure decline during soaking does not necessarily represent stronger CO₂–oil mass transfer; it may instead indicate energy dissipation through gas channeling. Thus, pressure dynamics should be interpreted together with pore-scale oil distribution rather than used alone.

Existing studies have addressed fracturing-fluid imbibition and water blocking [4,8–11], CO₂ huff-n-puff mechanisms [5,15,18,20], fracture-controlled production behavior [28–32], and optimized CO₂ injection strategies for low-permeability reservoirs [33,34]. Pore–fracture connectivity controlled by laminae in unconventional shales [35], water-invasion-zone damage [36], and CO₂ diffusion in oil-saturated porous media [26] have also been investigated. However, the retained water layer near the fracture is often simplified as a static resistance term or an initial water-saturation condition. This simplification overlooks an important dynamic feature: the water shield may block CO₂–oil contact in the early cycle and later undergo a local transition that creates a preferential fracture-dominated pressure-dissipation pathway. To separate these coupled effects, this study adopts a stepwise comparative design. Recent water-invasion experiments further indicate that a water-invasion zone can occupy effective pore throats, form a water-phase barrier, and reduce cumulative CO₂ huff-n-puff recovery after multiple cycles [36].

To address this gap, this study uses a stepwise experimental comparison from simple to complex conditions. A non-fractured core without a water shield (#E1) identifies the basic

CO₂ huff-n-puff behavior of the tight matrix. A single-fracture core without a water shield (#E2) isolates fracture-assisted pressure propagation and oil mobilization. A single-fracture core with a water shield (#E3) identifies how retained aqueous phase near the fracture changes pressure dissipation and pore-scale oil redistribution. The principal novelty is the combined interpretation of pressure curves, T_2 -derived recovery degrees, and NMR images to distinguish the early blocking effect from the subsequent local transition of the water shield.

2. Experimental Section

2.1. Materials and Apparatus

In tight reservoirs, the water shield is mainly developed around fractures, as shown in Figure 1. The reservoir background of this study is the Chang 7 tight oil interval of the Ordos Basin. Because the purpose was to isolate the influence of a fracture-adjacent water shield, artificial tight-sandstone analogue cores were used instead of heterogeneous natural cores. Two core configurations were prepared: a non-fractured matrix core and a single-fracture core. The core size was 4.5 cm × 4.5 cm × 15 cm, the matrix porosity was 9.3%, and the matrix permeability was 0.10 mD. These values represent an ultra-low-permeability tight core. The fracture geometry and quantity are reported in Table 1.

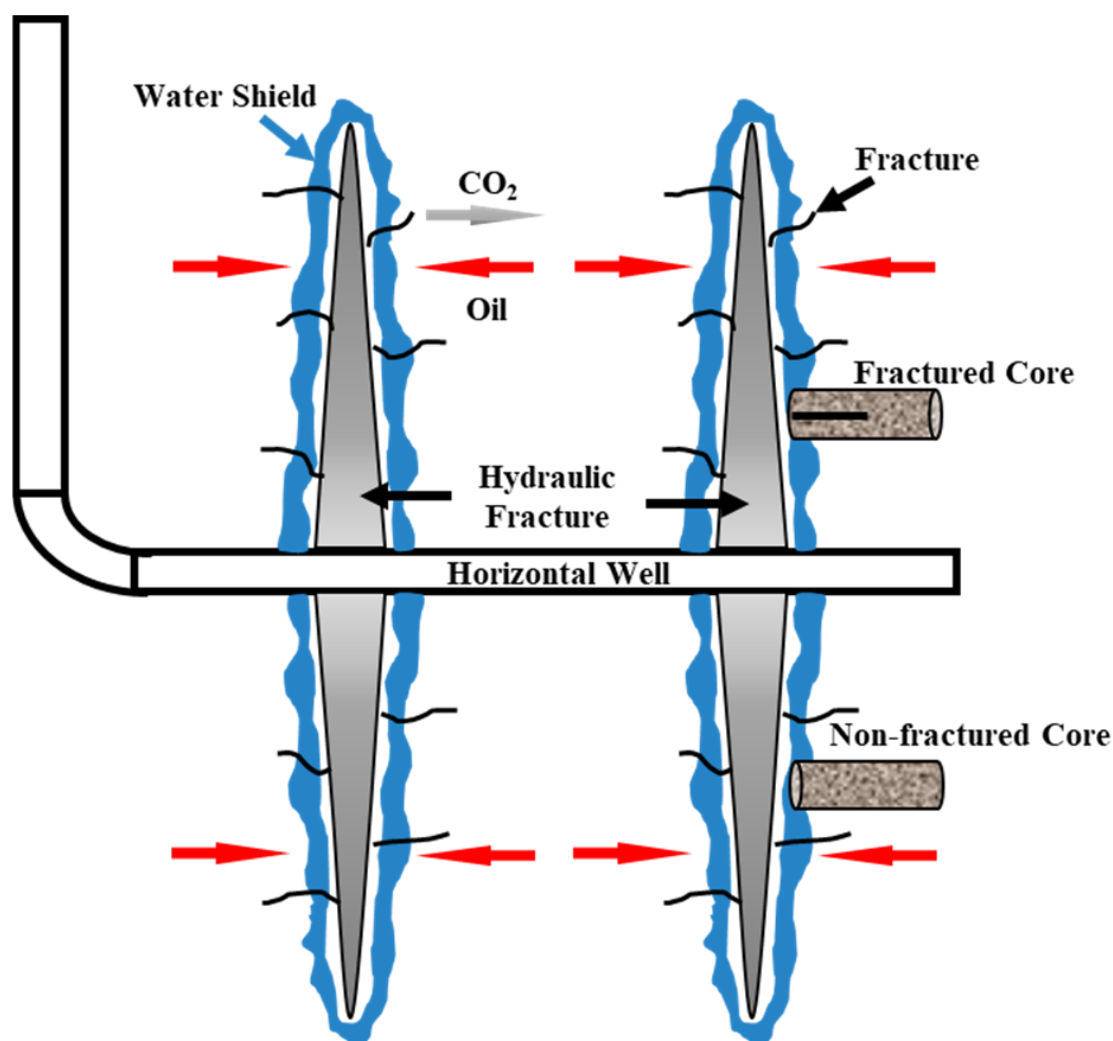


Figure 1. Conceptual field condition and laboratory-core analogue for a fracture-adjacent water shield in a tight reservoir. Retained aqueous phase is concentrated near the fracture–matrix interface and can restrict CO₂ contact with matrix oil before an inferred local transition.

Table 1. Petrophysical properties of the artificial cores used in the CO₂ huff-n-puff experiments.

(a)						
Core ID	Effective Porosity (%)	Effective Permeability (mD)		Matrix Porosity (%)	Matrix Permeability (mD)	
#1	9.3	0.09		9.3	0.09	
#2	10.1	5.89		9.3	0.12	
(b)						
Fracture Parameters of the Experimental Cores						
Core ID	Fracture Type	Length (cm)	Height (cm)	Aperture (μm)	Quantity	Dip Angle (°)
#1	Non-fractured	/	/	/	/	/
#2	Single fracture	7.5	3	80	1	0

The simplified single-fracture configuration was selected to keep the comparison mechanism clear. A complex fracture network would be closer to field conditions, but it would also make it difficult to separate matrix diffusion, fracture-assisted pressure propagation, and water-shield breakthrough. Therefore, the present design should be regarded as a mechanism-identification experiment rather than a direct field-scale reproduction. Natural-core mineral composition, laminae, and wettability heterogeneity were not used as variables in this stage.

The artificial cores were manufactured as homogeneous tight-sandstone analogues targeting the measured matrix porosity and permeability. During artificial-fracture preparation, a polyvinyl alcohol (PVA) water-soluble film was embedded in the compacted core model before consolidation; because PVA dissolves rapidly in hot water above 90 °C and is insoluble in oil, controlled dissolution produced a repeatable planar fracture. Core #2 contained a single planar fracture with a length of 7.5 cm, a height of 3 cm, and a nominal aperture of 80 μm. These measured or controlled petrophysical and fracture parameters are reported in Tables 1 and 2.

Table 2. Experimental design and comparison logic.

Test No.	Core No.	Fracture	Water Shield
#E1 (Baseline)	#1	No	No
#E2 (Fracture)	#2	Yes	No
#E3 (Water shield)	#2	Yes	Yes

The oil sample was degassed crude oil from the Chang 7 Member of the Ordos Basin. At 75 °C, its density was 0.747 g/cm³ and its viscosity was 2.15 mPa·s. The injected gas was CO₂ with a purity of 99.9%. The experimental device included an ISCO pump, vacuum pump, core holder, confining-pressure system, intermediate container, constant-temperature oven, back-pressure/production unit, and a low-field NMR analyzer. The NMR system was operated for T_2 spectra using the Carr–Purcell–Meiboom–Gill (CPMG) sequence and for NMR imaging; the experimental report gives a nominal magnetic-field range of 0.3 ± 0.05 T and a center frequency of 12 MHz. Pressure transducers recorded the injection, soaking, and production stages.

In Figure 2, the six-way valve is used to switch among injection, soaking, and production paths without rebuilding the flow line. Valve control between the pressure source and the core holder is required for isolating the core during soaking and production. The two

valves connected with the hand-pump/confining-pressure line are used for independent pressure loading, pressure holding, and unloading of the core holder. These valves prevent backflow and keep the boundary condition stable during the huff-n-puff cycle.

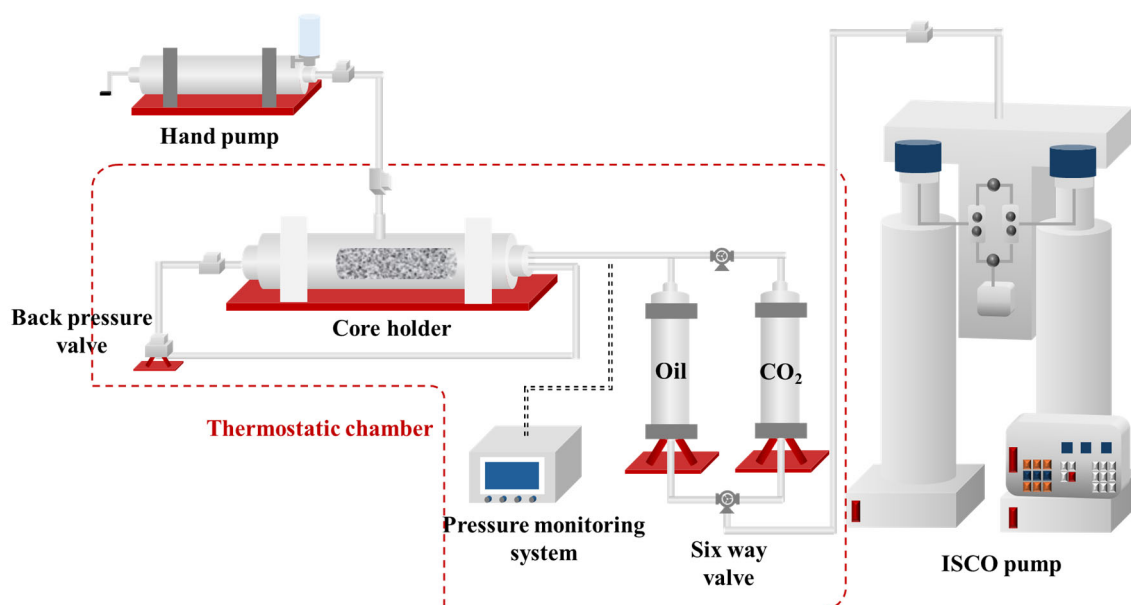


Figure 2. Schematic diagram of the CO₂ huff-n-puff apparatus, including the ISCO pump, core holder, confining-pressure system, temperature-control oven, pressure transducers, production/back-pressure unit, and low-field NMR analyzer used for T_2 spectra and imaging.

2.2. Experimental Procedure and Water-Shield Construction

Table 2 gives the three experimental groups. #E1 is the reference group, with no fracture and no water shield. #E2 uses single-fracture Core #2 without a water shield. After #E2 was completed, Core #2 was cleaned to remove residual fluids, dried, and resaturated with crude oil. The MnCl₂ water-shield treatment was then applied to the same fractured core before conducting #E3. Reusing Core #2 for #E2 and #E3 minimized differences in fracture geometry between the two cases and isolated the water-shield effect. The temperature was maintained at 75 °C, the maximum CO₂ injection pressure was 850 psi, and four huff-n-puff cycles were conducted for each case.

The experimental procedure was as follows:

- (1) The cores were cleaned according to the core-analysis procedure, dried in an oven at 100 °C to constant mass, and tested for porosity and permeability before saturation.
- (2) The dried cores were evacuated under vacuum for 24 h and then saturated with degassed Chang 7 crude oil under pressure for 24 h. The saturated mass and initial NMR response were recorded as the baseline state.
- (3) The saturated cores were aged at 75 °C for 24 h. After aging, the initial NMR test was carried out.
- (4) For #E3, a 7 wt% MnCl₂ aqueous solution was introduced into the fractured core to construct the water-shield analogue. Mn²⁺ is a paramagnetic ion that markedly accelerates the transverse relaxation decay of water-phase hydrogen protons and thereby suppresses the aqueous-phase NMR signal. A previous NMR-based imbibition study in tight reservoirs used 8.0 wt% MnCl₂ in the aqueous phase to distinguish the hydrogen signals of oil and water and to make the measured T_2 response mainly reflect the oil phase [37]. Therefore, the similar concentration of 7 wt% MnCl₂ used in this study was selected to reduce interference from the water signal during NMR measurements. The MnCl₂ solution was used as an NMR-compatible aqueous medium

for constructing the water-shield analogue rather than to reproduce the complete chemical composition of field fracturing fluid.

The imbibition period was set to 24 h to allow the MnCl_2 solution to enter the fracture-adjacent pore space and form an identifiable initial aqueous barrier before CO_2 huff-n-puff. Previous investigations of imbibition water shields have shown that the rapid imbibition stage mainly occurs during the early period and that some NMR T_2 responses and water-shield height distributions become nearly unchanged after approximately 23–24 h, although complete imbibition equilibrium may require a longer time depending on the pore structure and fracture conditions [7]. In addition, MnCl_2 imbibition has previously been used to construct a water-invasion zone in a tight core [36]. Therefore, the 24 h period used here was regarded as a controlled water-shield construction period rather than evidence that complete imbibition equilibrium had been reached.

During water-shield construction, the ISCO pump reading increased from 10.00 to 13.39 mL, corresponding to a delivered volume of 3.39 mL of MnCl_2 solution. The core mass increased from 629.30 to 632.38 g, yielding a net mass increase of 3.08 g (Table 3). Before CO_2 injection, NMR imaging was performed to examine the initial aqueous-phase distribution (Figure 3). Compared with the fractured core without water-shield treatment (Figure 3a), the MnCl_2 -treated core (Figure 3b) exhibited a distinct low-signal region adjacent to the fracture. Because Mn^{2+} suppresses the aqueous-phase NMR signal, this region indicates the spatial distribution of the MnCl_2 solution in the fracture-adjacent pore space. The pump record, gravimetric increase, and pre-injection NMR image therefore jointly confirm that an identifiable initial water-shield analogue had formed before CO_2 huff-n-puff.

Table 3. ISCO pump readings and core-mass changes during water-shield construction for #E3.

Measurement Stage	ISCO Pump Reading (mL)	Core Mass (g)
Before water-shield construction	10.00	629.30
After water-shield construction	13.39	632.38
Net change	3.39	3.08

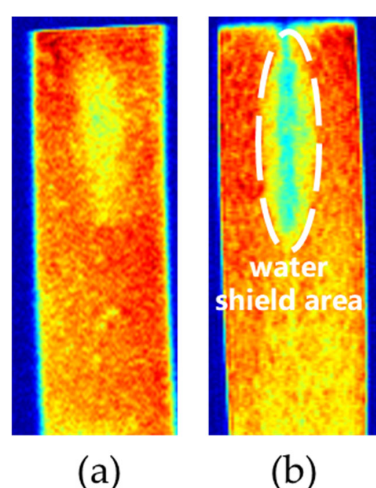


Figure 3. Initial NMR images before CO_2 huff-n-puff: (a) fractured core without a water shield; (b) fractured core after water-shield construction. The colors represent relative NMR signal intensity, increasing from blue/cyan (low intensity) to yellow/red (high intensity). The white dashed lines in (b) delineate the fracture-adjacent low-signal region associated with the MnCl_2 -treated water-shield analogue.

- (5) CO₂ was injected under constant-pressure conditions at reservoir temperature. The system temperature was 75 °C, the confining pressure was 10 MPa, the CO₂ injection pressure was 850 psi, and each soaking period lasted 4 h. The injection pressure was below the measured miscibility pressure of the crude-oil/CO₂ system (22.27 MPa), so the tests were conducted under immiscible conditions.
- (6) After each cycle, pressure data, cumulative NMR T_2 spectra, NMR images, and recovery-degree data calculated from the T_2 signal were recorded for the same core state. Four huff-n-puff cycles were conducted for each case.

In this paper, water-shield breakthrough refers to an inferred transition identified by coupled pressure, T_2 -derived recovery, and NMR-image responses rather than a directly metered outlet-gas breakthrough. The main quantitative indicators are: (i) the abrupt increase in the Cycle-2 relative pressure-decline amplitude of #E3 to 18.4%, about 1.8 times that of #E2; (ii) the highest incremental recovery of #E3 appearing in Cycle 2 (15.34%), followed by a sharp decrease to 7.96% and 4.07% in Cycles 3 and 4; and (iii) localized NMR-image changes concentrated near the fracture instead of a continuously expanding matrix swept region. Therefore, the manuscript uses the cautious term “inferred breakthrough” or “water-shield transition” where direct produced-gas evidence is unavailable.

The formation of the initial water shield was verified before CO₂ injection using the ISCO pump record, the core-mass change, and the pre-injection NMR image. The delivered MnCl₂ solution volume was 3.39 mL, and the core mass increased by 3.08 g, confirming that aqueous solution was introduced into and partly retained by the fractured core. The fracture-adjacent low-signal region in the NMR image further confirmed its spatial distribution. Together, these observations demonstrate that the initial water-shield analogue had been established before the cyclic CO₂ huff-n-puff experiment.

For NMR interpretation, the cumulative T_2 signal was used as a relative oil-signal indicator under the same instrument settings and core state. A T_2 interval below 10 ms was treated as the small-pore-dominated interval, and the interval around and above the main inflection point was treated as the larger-pore-dominated interval. No absolute T_2 -to-pore-radius conversion was made because surface relaxivity was not independently calibrated. The cumulative oil-related T_2 signal was integrated over the measured T_2 range under identical acquisition parameters. Let S_0 denote the integrated oil-related signal before the first CO₂ injection and S_n the signal measured after Cycle n . The incremental T_2 -derived recovery degree of Cycle n was calculated as follows:

$$\Delta R_n = \frac{S_{n-1} - S_n}{S_0} \times 100\%, \quad (1)$$

The cumulative T_2 -derived recovery degree after Cycle n was calculated as follows:

$$R_n = \frac{S_0 - S_n}{S_0} \times 100\% = \sum_{i=1}^n \Delta R_i. \quad (2)$$

Thus, all cycle increments were normalized against the same initial signal S_0 , and the cumulative recovery degree equals the sum of the cycle-specific increments. This method is suitable for relative oil-mobilization quantification under consistent NMR settings and MnCl₂ water-signal suppression, but it is not sufficient alone to demonstrate gas breakthrough.

The relative pressure-decline amplitude was calculated from the measured pressures during the soaking stage. For case i in Cycle n , it was defined as follows:

$$D_{p,i,n} = \frac{P_{s,i,n} - P_{e,i,n}}{P_{s,i,n}} \times 100\%. \quad (3)$$

Here, $P_{s,i,n}$ is the measured pressure immediately after CO₂ injection was stopped and the core was isolated at the beginning of the 4 h soaking period, and $P_{e,i,n}$ is the measured pressure at the end of soaking immediately before production. The measured soaking-start pressure of each cycle, rather than the nominal injection pressure, was used as the normalization reference. Ratios between cases were calculated by dividing their respective relative pressure-decline amplitudes.

Because each experimental condition was tested once, the figures do not include statistical error bars. The discussion therefore focuses on large, internally consistent differences among #E1, #E2, and #E3.

3. Results and Discussion

3.1. Control Effect of Water Shield on Pressure Dynamics of CO₂ Huff-n-Puff

The pressure data were first compared (Figure 4). For the three groups, the injection and production portions of the curves had similar shapes, whereas the main differences occurred during soaking. The soaking-stage pressure response provides information on whether the injected CO₂ contributes mainly to matrix-oil contact or is dissipated through a fast flow path. Because no outlet gas-flow meter was installed, gas channeling is inferred from pressure-decline behavior together with NMR evidence rather than claimed from pressure data alone. The following analysis is therefore organized according to the four huff-n-puff cycles.

In Cycle 1, #E1 and #E2 showed similar pressure-decline behavior, whereas #E3 exhibited a slower decline. Based on the defined soaking-stage calculation, the relative pressure-decline amplitude of #E3 was approximately 10% lower than that of #E2. This response indicates that the initial water shield restricted pressure transmission and CO₂-oil contact near the fracture.

In Cycle 2, the pressure curve of #E3 changed most markedly. Its relative pressure-decline amplitude was 18.4%, approximately 1.8 times that of #E2. This abrupt change is the main quantitative evidence for the inferred transition point of the water shield. After one injection–production cycle, local discontinuities may have developed in the original water film near the fracture. Because fracture conductivity was high, these discontinuities could connect to form preferential gas-flow paths. The rapid pressure decline of #E3 is therefore interpreted as fracture-dominated pressure dissipation rather than direct evidence of greater oil mobilization.

In Cycle 3, the relative pressure-decline amplitudes of #E3 and #E2 became similar, but the two responses cannot be interpreted identically. For #E2, the fracture promoted CO₂ entry into the matrix, and the pressure decline was associated with effective dissolution and diffusion. For #E3, a preferential fracture-dominated pathway had already been inferred after the water-shield transition. Thus, a similar relative pressure-decline amplitude did not imply equivalent matrix-oil mobilization.

In Cycle 4, the relative pressure-decline amplitudes of all three groups were approximately 17%. At this stage, #E1 had developed a larger matrix diffusion range, #E2 had nearly reached a stable fracture-assisted mass-transfer state, and #E3 had reached a stable fracture-dominated pressure-dissipation state. The final cycle therefore shows convergence in the pressure metric but not in the underlying recovery mechanism.

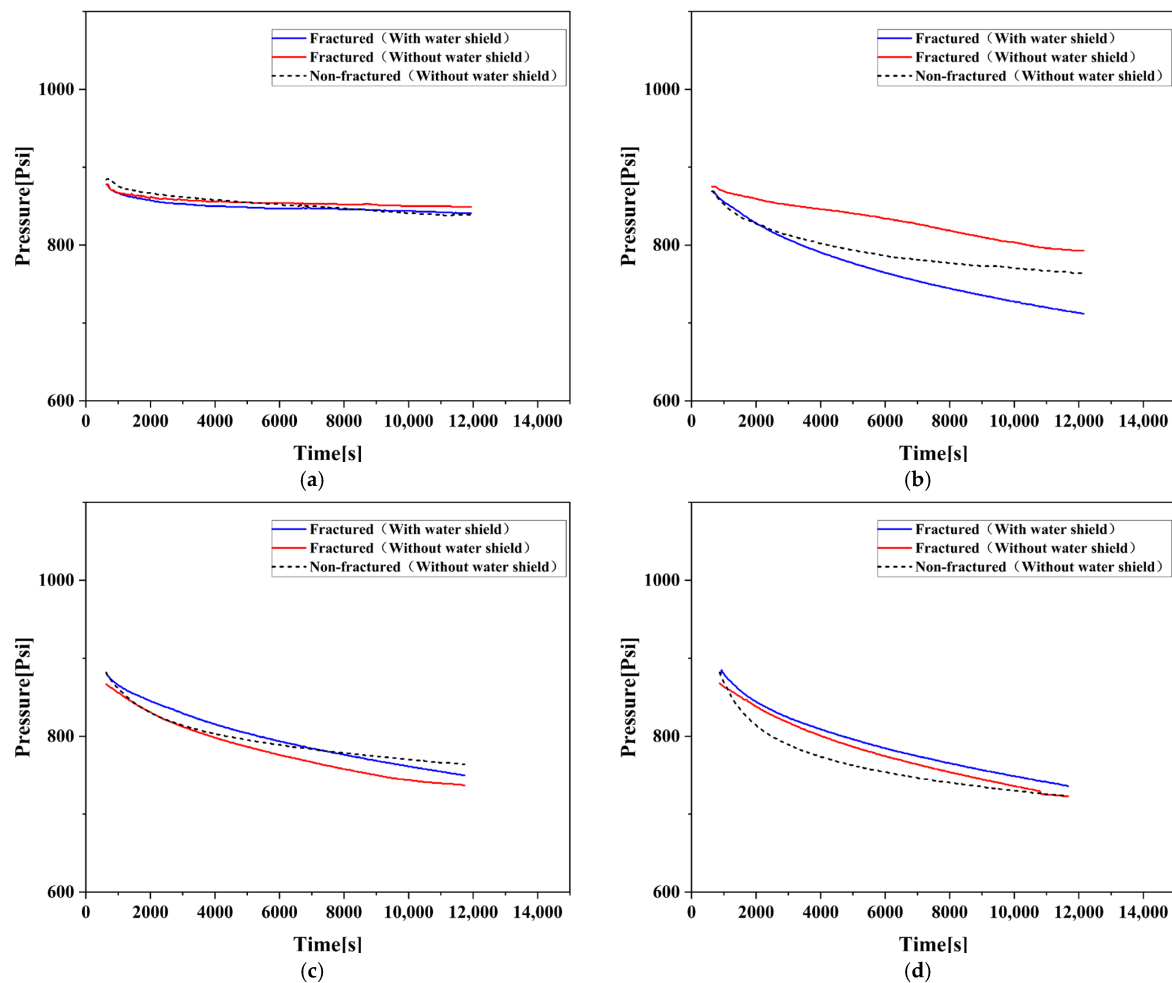


Figure 4. Pressure dynamic curves for #E1, #E2, and #E3 over four CO₂ huff-n-puff cycles. (a) Circle 1; (b) Circle 2; (c) Circle 3; (d) Circle 4.

3.2. Pore-Scale Oil Mobilization Characteristics Revealed by NMR Cumulative T_2 Spectra

The cumulative NMR T_2 spectrum was used to assess relative oil mobilization and pore-scale redistribution, and the T_2 -derived recovery degrees are listed in Table 4. This method is applicable because the aqueous-phase signal was suppressed by MnCl₂ and all cycles were measured under consistent NMR settings. However, cumulative T_2 data alone are insufficient to demonstrate gas breakthrough or water-film rupture; the recovery table is therefore interpreted together with pressure curves and NMR images. Recent online-NMR and spatial-distribution studies likewise demonstrate the value of NMR for resolving cycle-dependent fluid redistribution and effective CO₂-swept regions in tight reservoirs [38,39].

Table 4. Cycle-by-cycle oil recovery degree calculated from cumulative NMR T_2 spectra.

Case	Fracture	Water Shield	Cycle 1 (%)	Cycle 2 (%)	Cycle 3 (%)	Cycle 4 (%)	Cumulative (%)
#E1	No	No	7.27	15.49	11.53	4.92	39.21
#E2	Single fracture	No	8.03	15.82	13.16	4.92	41.93
#E3	Single fracture	Yes	7.24	15.34	7.96	4.07	34.61

For #E1, the cumulative T_2 curve had one main inflection point, and the position was close to 100 ms (Figure 5). The signal below 10 ms was very small, indicating that the oil was mainly stored in large pores before huff-n-puff. With increasing huff-n-puff cycles, the entire curve moved downward, whereas the inflection point did not shift markedly. After four cycles, the reduction in the cumulative oil-related T_2 signal corresponded to a cumulative T_2 -derived recovery degree of 39.21%. This response indicates that, without a fracture or water shield, CO_2 mainly mobilized oil in the larger-pore-dominated interval, whereas oil in the smaller-pore-dominated interval was affected only slightly.

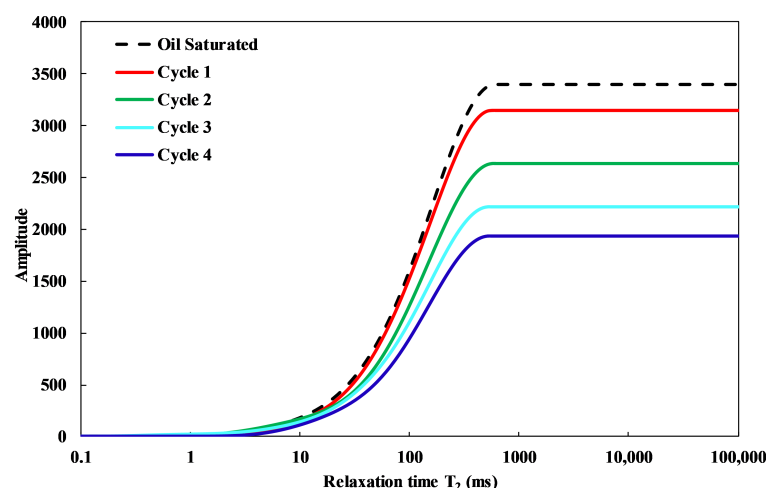


Figure 5. Cumulative NMR T_2 spectra of #E1 (non-fractured core without water shield) after different CO_2 huff-n-puff cycles, showing mainly large-pore-dominated oil mobilization.

For #E2, the cumulative T_2 curve also had an inflection point in the large-pore range, but its downward movement was greater than that of #E1 (Figure 6). The T_2 -derived recovery degrees were 8.03%, 15.82%, 13.16%, and 4.92% from Cycles 1 to 4, giving a final cumulative recovery of 41.93%. Compared with #E1, the single fracture expanded the ranges of effective pressure transmission and CO_2 –oil contact, especially during Cycles 2 and 3.

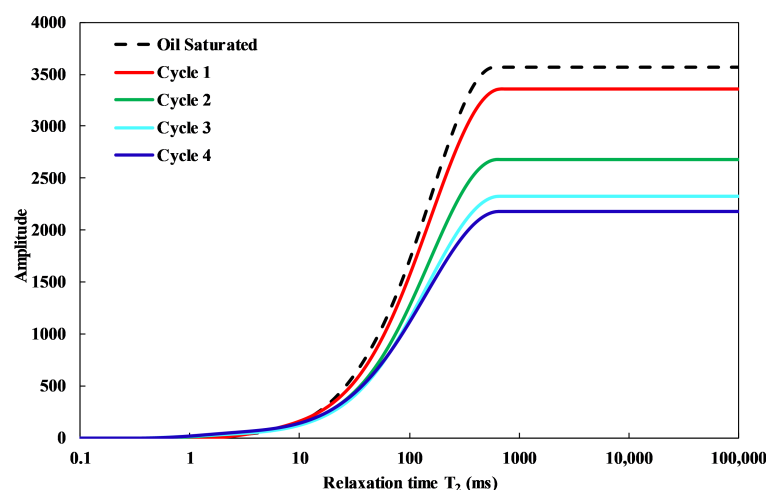


Figure 6. Cumulative NMR T_2 spectra of #E2 (single-fracture core without water shield) after different CO_2 huff-n-puff cycles, showing enhanced oil-signal reduction caused by fracture-assisted pressure propagation.

For #E3, the cumulative T_2 curve showed another feature (Figure 7). It moved downward, but it also retained a left-shifted component in the short- T_2 interval. The T_2 -derived recovery degrees were 7.24%, 15.34%, 7.96%, and 4.07%, and the final cumulative recovery was 34.61%, 7.32 percentage points lower than #E2. This means that the water shield not only reduced total oil mobilization but also changed the pore position of part of the remaining oil.

In Cycle 1 of #E3, the T_2 -derived recovery degree was 7.24%, lower than the 8.03% obtained for #E2. Together with the smaller relative pressure-decline amplitude and the limited change in the NMR image, this result indicates that the initial water shield restricted CO_2 –oil contact and oil mobilization near the fracture. Meanwhile, the signal below 10 ms increased from nearly 0 to approximately 200. Because MnCl_2 suppresses the aqueous-phase signal, this increase is interpreted mainly as oil-signal redistribution toward the short- T_2 interval. A reasonable mechanism is that the water film restricted direct CO_2 contact with oil in larger connected pores while the applied pressure redistributed part of the oil toward smaller connected pores.

In Cycle 2, the water film was inferred to be partly broken, and #E3 reached its maximum cycle recovery of 15.34%, close to #E2 in the same cycle. This does not mean that the water shield had no negative effect. Instead, the coupled evidence indicates a transient transition: the local rupture enabled CO_2 to contact part of the oil-bearing space, but it also initiated a preferential pressure-dissipation path along the fracture.

In Cycles 3 and 4, the cycle recovery of #E3 decreased to 7.96% and 4.07%, whereas #E2 still produced 13.16% and 4.92%. The lower post-transition increments, together with the persistent short- T_2 signal, indicate that part of the oil was trapped in smaller-pore-dominated space or in matrix regions not effectively contacted after fracture-dominated channeling.

The T_2 results show that the water shield changes both the effective pressure-propagation range and the residual oil distribution. At the core scale, it reduces pressure transmission and lowers oil mobilization. At the pore scale, it redistributes part of the oil toward the short- T_2 , smaller-pore-dominated interval. Although the fracture improves pressure transmission, it does not fully remobilize residual oil in these smaller-pore-dominated regions.

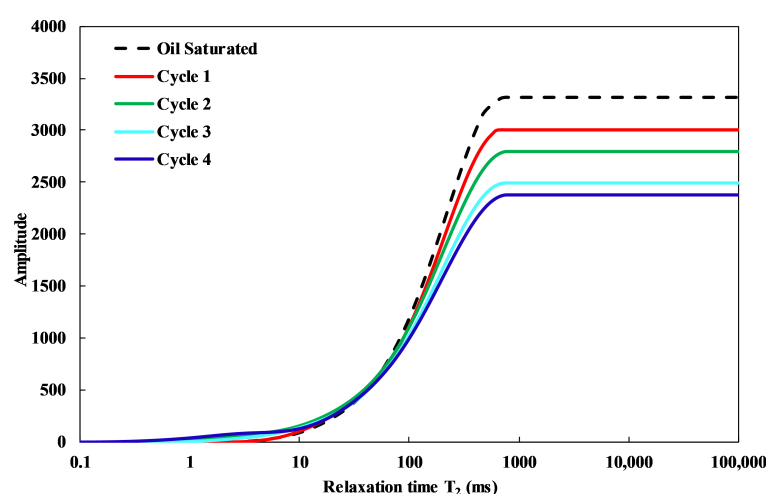


Figure 7. Cumulative NMR T_2 spectra of #E3 (single-fracture core with water shield) after different CO_2 huff-n-puff cycles, showing limited total signal reduction and persistent short- T_2 residual oil signal.

3.3. NMR Imaging as Visual Evidence of Pressure-Driven CO₂ Swept Region

NMR imaging was used as visual evidence in this study (Figure 8). It was mainly used to observe the CO₂ swept region and residual oil distribution after different huff-n-puff cycles. In the images, red represents high residual oil saturation, whereas blue represents low residual oil saturation. The images are interpreted comparatively among cycles and cases; quantitative image segmentation of swept area or residual oil saturation was not performed because the original calibration between color scale and absolute saturation was not established.

After Cycle 2, the swept region of #E1 continued to move into the core. #E2 showed a larger swept region because the fracture improved pressure transmission. #E3 showed lower residual oil saturation mainly around the fracture, whereas the matrix away from the fracture changed little. This response indicates that, after the inferred local water-shield transition, CO₂ entered the core mainly through several weak paths rather than sweeping the matrix uniformly.

After Cycles 3 and 4, the images of #E1 and #E2 showed continued expansion of the swept area, and residual oil saturation decreased progressively. In #E3, the swept area expanded only slightly, with changes remaining concentrated near the fracture. Most of the matrix retained a high oil signal. This image response is consistent with an established fracture-dominated pressure-dissipation pathway.

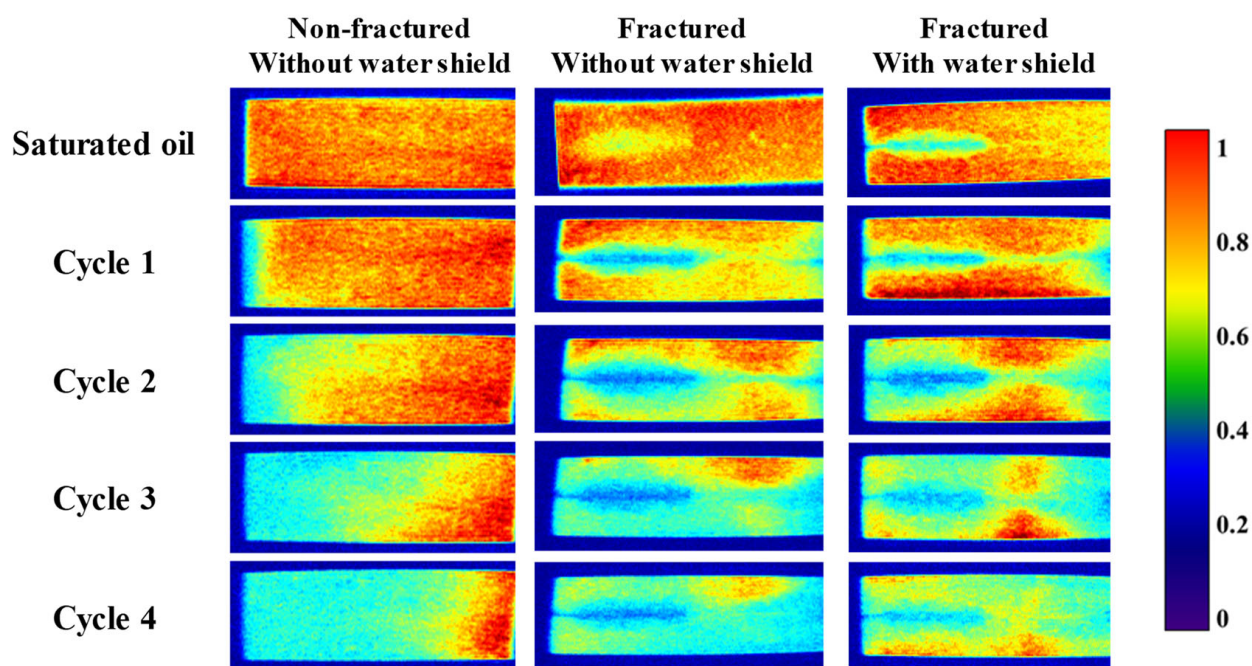


Figure 8. NMR images of the initially oil-saturated samples and the samples after successive CO₂ huff-n-puff cycles. Red indicates higher residual oil saturation and blue indicates lower residual oil saturation under the same imaging condition.

The imaging results provide a comparative visualization of the water-shield effect. In the presence of the water shield, the CO₂-swept region is substantially smaller. The pressure curves, T_2 spectra, and NMR images provide consistent evidence that water-shield evolution first changes pressure transmission and then alters the contact range between CO₂ and matrix oil.

3.4. Dual Effects of Fractures on Pressure Propagation

In the presence of a water shield, the fracture must be considered from two perspectives: it is a pressure-transmission pathway, but it may also become a preferential pressure-dissipation pathway after an inferred local transition.

On the positive side, the fracture reduces flow resistance. Compared with #E1, #E2 increased the final cumulative recovery from 39.21% to 41.93% and maintained higher cycle recovery during the middle cycles. In #E3, the fracture also transmitted pressure to the water film and contributed to the inferred local transition. This process was identified from the coupled changes in the relative pressure-decline amplitude, Cycle-2 recovery response, and fracture-adjacent NMR images.

On the negative side, fracture conductivity is much higher than matrix permeability. Once a local water-shield transition occurs, CO₂ preferentially moves along the fracture instead of entering the matrix slowly. The rapid pressure decline of #E3 in Cycle 2 is consistent with this mechanism. The resulting reduction in effective CO₂-matrix contact leaves part of the injected energy to dissipate along the fracture-dominated pathway.

Therefore, fractures in reservoirs affected by a water shield should not be regarded as exclusively beneficial. A fracture can improve pressure transmission but may also increase channeling risk after a local water-shield transition. In field operations, injection intensity should be controlled to avoid premature disruption of the water shield and fracture-dominated gas loss, while soaking time should be sufficient to promote CO₂-matrix contact before production. For reservoirs with severe retained-water damage, staged pressure control, longer soaking, or pretreatment to reduce near-fracture water blockage may be more suitable than simply increasing injection pressure.

3.5. Dynamic Evolution of the Water Shield During Cyclic CO₂ Huff-n-Puff

Combining the pressure curves, cumulative T_2 spectra, and NMR images reveals a staged mechanism for water-shield-controlled CO₂ huff-n-puff. The water shield initially acts as a fracture-adjacent blocking layer, subsequently undergoes an inferred local transition under cyclic pressure disturbance, and finally creates a preferential pathway for fracture-dominated pressure dissipation. Unlike a static-resistance interpretation of retained water, this framework shows that the water-shield effect evolves over successive cycles. This interpretation is consistent with observations that water invasion reduces CO₂ seepage and oil-contact efficiency [36]. It also supports evaluating pressure-decay responses together with NMR-derived swept-region evidence [26,38,39].

The practical implication is that fractured tight reservoirs containing retained fracturing fluid should not be operated solely by increasing CO₂ injection pressure. Higher pressure may accelerate a local water-shield transition and promote early fracture-dominated gas loss. The impact on oil mobilization is reflected by the T_2 -derived recovery data: the fractured core with a water shield (#E3) reached 34.61% cumulative recovery, 7.32 percentage points lower than the fractured core without a water shield (#E2), and its cycle recovery decreased markedly after the inferred transition. Accordingly, injection pressure, injection volume, and soaking time should be adjusted cycle by cycle using the pressure-decline and T_2 -derived recovery responses rather than held constant for all cycles.

This study has several limitations. First, each case was tested once, so repeatability and uncertainty ranges cannot be reported. Second, the cores were artificial tight-sandstone analogues with a single fracture and did not reproduce natural mineralogical heterogeneity, laminae, multiple-fracture networks, or wettability variation. Third, the MnCl₂ solution was an NMR-compatible analogue of retained water and did not reproduce all components of field fracturing fluid. Fourth, gas-production volume, outlet composition, direct gas-breakthrough time, and quantitative image segmentation were not measured. Future work

should include replicate tests, natural cores, multiple-fracture models, different water saturations and water-shield thicknesses, direct produced-gas monitoring, and calibrated NMR image-segmentation analysis.

4. Conclusions

- (1) The comparative experiments showed that the fracture effect depended on the water-shield condition. The final cumulative T_2 -derived recovery degrees were 39.21%, 41.93%, and 34.61% for #E1, #E2, and #E3, respectively. Without a water shield, the fracture increased the recovery degree by 2.72 percentage points. After water-shield construction, #E3 was 7.32 percentage points lower than #E2, showing that the water shield markedly weakened fracture-assisted CO₂-oil contact.
- (2) The influence of the water shield on pressure transmission changed markedly with the huff-n-puff cycle. In Cycle 1, the relative pressure-decline amplitude of #E3 was approximately 10% lower than that of #E2, accompanied by limited T_2 -signal and NMR-image changes, indicating an early restriction of CO₂-oil contact. In Cycle 2, the relative pressure-decline amplitude increased to 18.4%, approximately 1.8 times that of #E2. The concurrent pressure, T_2 , and fracture-adjacent image responses indicated an inferred local transition of the water shield rather than directly observed gas breakthrough.
- (3) The cycle-resolved T_2 results showed that the inferred local transition only temporarily improved CO₂ access to part of the oil-bearing space and did not produce sustained matrix sweeping. In Cycle 2, the T_2 -derived recovery degrees of #E3 and #E2 were similar, at 15.34% and 15.82%, respectively; in Cycle 3, they were 7.96% and 13.16%. The lower post-transition increments and persistent short- T_2 oil signal in #E3 indicate that part of the oil remained in smaller-pore-dominated regions.
- (4) The NMR images showed that, after Cycle 2, the signal changes in #E3 were concentrated mainly near the fracture, whereas the matrix away from the fracture retained a high oil signal. This spatial response indicates that the fracture gradually changed from a pressure-transmission pathway to a preferential pressure-dissipation pathway after the inferred local transition. Therefore, similar pressure-decline amplitudes do not necessarily represent equivalent matrix-oil mobilization, and pressure responses should be interpreted together with T_2 spectra and spatial NMR images.

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