

Article

Pore-Scale Imaging of CO₂–Water Displacement: Experimental Insights from Microfluidics

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Abstract

Geological storage of carbon dioxide (CO₂) in deep-sea formations represents a pivotal strategy for mitigating atmospheric CO₂ levels, where storage security and efficacy are fundamentally governed by the pore-scale seepage behavior of CO₂. However, the microscopic displacement mechanisms of CO₂–water two-phase flow under the characteristic high-pressure, low-temperature conditions of the deep sea remain inadequately understood. This study employed a self-developed high-pressure microfluidic experimental platform (0–30 MPa, 4–50 °C) to systematically investigate the CO₂ displacement process in porous media. The effects of injection rate (0.001–5 mL/min) and system pressure (1, 5, and 10 MPa) on displacement patterns, front stability, and final saturation were quantified. The results demonstrate that injection rate is the primary controller of displacement stability: high rates (≥ 0.1 mL/min) induce viscous fingering and lower final saturation, whereas low rates (≤ 0.05 mL/min) promote stable, piston-like displacement. Crucially, elevated pressure exerts a profound stabilizing effect, effectively suppressing fingering instabilities and enhancing final gas saturation (up to 0.544 at 10 MPa). This work elucidates the synergistic regulatory mechanism between injection rate and confining pressure, providing essential pore-scale experimental evidence for optimizing injection parameters to achieve efficient and secure CO₂ storage in deep-sea reservoirs.

Keywords: microfluidics; CO₂ sequestration; two-phase flow; porous media; deep-sea environment; seepage mechanisms



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1. Introduction

Geological storage of carbon dioxide (CO₂) is a critical technological pathway for mitigating climate change (Chen et al., 2023 [1]; Li et al., 2009 [2]; Zhang et al., 2009 [3]). Among the various options, injecting CO₂ into deep-sea sediments has garnered significant attention due to its vast storage potential and unique security advantages (Wang et al., 2023 [4]; Gu et al., 2025 [5]; Tang et al., 2026 [6]). Under the high-pressure, low-temperature conditions of the deep sea, CO₂ can exist in a dense liquid or supercritical state. Its higher density relative to overlying seawater promotes gravitational stability, while the in situ formation of CO₂ hydrate can seal reservoir pores, creating an additional, impermeable caprock (Gizzatov et al., 2021 [7]; Li et al., 2025 [8]; Yu et al., 2025 [9]). This dual-assurance mechanism of “gravitational-hydrate” trapping provides a foundation for long-term, secure storage (House et al., 2006 [10]; Teng & Zhang, 2018 [11]; El-Maghraby et al., 2013 [12];

Suekane et al., 2008 [13]). Furthermore, the deep ocean has historically served as a pivotal carbon sink, with abyssal processes driving fluctuations in atmospheric CO₂ levels (Rafter et al., 2022) [14]. To translate this potential into safe and effective engineering practice, a fundamental understanding of the pore-scale seepage behavior and displacement mechanisms of CO₂ as it invades the native brine within sub-seabed porous media is essential (Jian et al., 2023 [15]).

The CO₂ injection process is fundamentally a problem of immiscible displacement (Lenormand et al., 1988 [16]; Wang et al., 2013 [17]). The displacement pattern—ranging from stable, uniform advancement to unstable viscous fingering—along with the final trapped CO₂ saturation, directly dictates the initial storage efficiency and the subsequent effectiveness of long-term trapping mechanisms like dissolution and mineral trapping (Yamabe et al., 2014 [18]; Cottin et al., 2011 [19]; Zhao et al., 2016 [20]). Core engineering parameters, particularly the injection pressure and injection rate, are the primary variables controlling this microscopic flow behavior (Zhang et al., 2019 [21]; He et al., 2025 [22]; Lu et al., 2022 [23,24]; Zhang et al., 2025 [25]). Therefore, systematically investigating the synergistic effects of pressure and injection rate on CO₂–water two-phase displacement under deep-sea conditions is crucial for optimizing operational strategies and accurately assessing storage integrity and capacity (Shang et al., 2026 [26]; Pan et al., 2023 [27]).

The advent of high-pressure, high-temperature microfluidic technology has revolutionized the in situ, real-time observation of such complex pore-scale processes. This method allows for the precise replication of reservoir conditions in the laboratory and utilizes transparent two-dimensional pore network models to directly visualize fluid dynamics. It has proven highly effective for studying complex multi-phase flows involving CO₂ (Gizzatov et al., 2021 [7]; Zhang et al., 2019 [21]; Bao et al., 2017 [28]; Cottin et al., 2011 [19]; Fan et al., 2025 [29]; Kouhkord et al., 2024 [30]). To address the critical gaps in deep-sea carbon storage, the distinct novelty and advantage of this work lie in the systematic investigation of the synergistic modulation of injection rates (0.001–5 mL/min) and elevated system pressures (1, 5, and 10 MPa) on CO₂–brine displacement patterns, front stability, and final saturation. Unlike previous microfluidic studies that focused primarily on single variables or low-pressure conditions, our work utilizes a self-constructed high-pressure experimental platform to quantitatively demonstrate how elevated pressure fundamentally alters fluid properties to suppress viscous fingering and expand the operational “sweet spot” for efficient injection. Crucially, the core component of this platform features a transparent two-dimensional porous network microfluidic chip (Kim et al., 2012 [31]; Nie et al., 2023 [32]; Lu et al., 2025 [33]; Massimiani et al., 2023 [34]). Fabricated via standard photolithography and soft lithography, the chip possesses a regular and well-defined homogeneous pore-network architecture with a uniform etching depth. It is securely integrated within a customized high-pressure visual cell to ensure absolute structural integrity and allow high-resolution real-time microscopic imaging of the multiphase displacement front (Zhong et al., 2025 [35]). Ultimately, this research aims to reveal the governing principles of injection parameters on pore-scale displacement behavior and elucidate the synergistic optimization mechanisms, thereby providing direct experimental evidence and theoretical support for the engineering design of efficient and secure deep-sea CO₂ storage operations (Hao et al., 2022 [36]; Li et al., 2022 [37]; Wang et al., 2023 [38]; Jia et al., 2022 [39]). The chip is fabricated from PDMS via standard soft lithography, featuring a regular two-dimensional homogeneous pore network with a throat width of approximately 50 µm and an etching depth of approximately 50 µm.

2. Materials and Methods

2.1. Experimental Apparatus and Procedure

This study employs a custom-engineered high-pressure microfluidic platform to conduct a systematic pore-scale analysis of immiscible CO₂–water displacement under simulated deep-sea geological carbon storage conditions. As shown in Figure 1, the platform consists of four functionally synchronized modules: a precision fluid injection system with programmable syringe pumps for constant-rate injection; a high-pressure/high-temperature (HPHT) visualization cell that houses a porous-medium micromodel and maintains stable environmental conditions; a real-time microscopic imaging suite for capturing pore-scale dynamics; and a centralized data acquisition and control unit for parameter logging and system synchronization. This integrated experimental system is designed to precisely replicate in situ reservoir thermodynamics, operating stably within a pressure range of 0–30 MPa and a temperature range of 4–50 °C, thereby enabling investigation of CO₂ seepage behavior in its dense liquid or supercritical state. All experiments were repeated at least three times under each condition to ensure reproducibility, and the results presented are representative of repeated measurements. It should be noted that the 0–30 MPa range represents the maximum technical capacity of the platform; the actual experimental pressures were deliberately selected as 1, 5, and 10 MPa. The aqueous phase used in this study was deionized water.

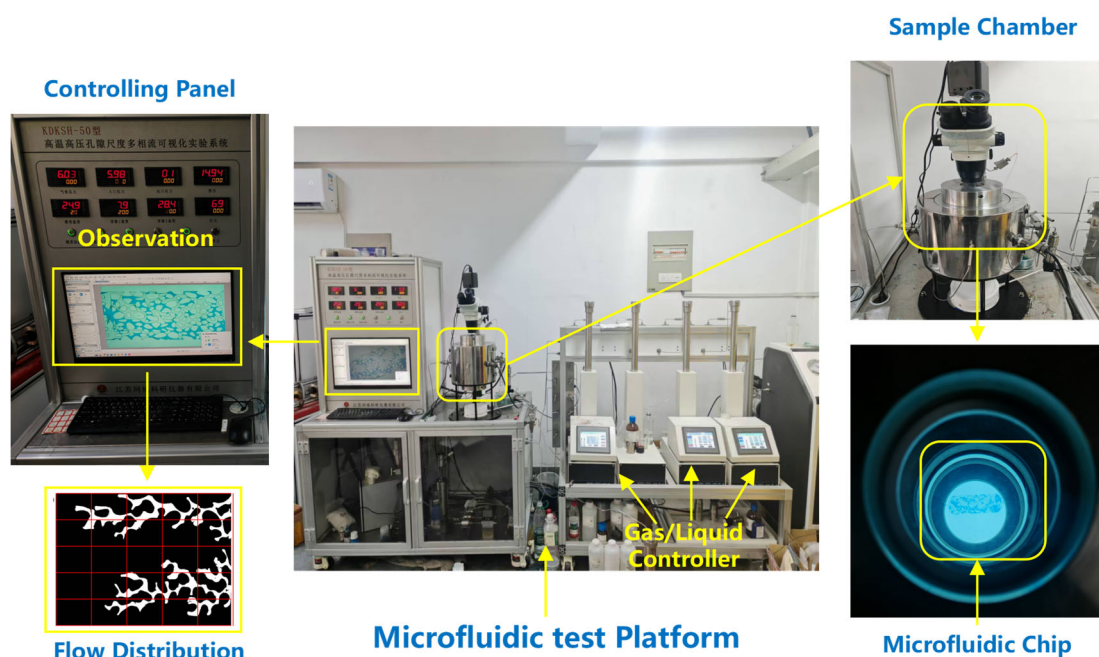


Figure 1. Microfluidic experimental platform.

The experimental pressures of 1, 5, and 10 MPa were selected based on the hydrostatic pressure gradient (~ 0.01 MPa/m), corresponding to approximate seawater depths of 100 m, 500 m, and 1000 m, respectively, which cover typical water depths from continental slopes to abyssal plains. Given that the critical point of CO₂ is 7.38 MPa and 31.1 °C, within our experimental temperature range (4–50 °C), this pressure interval comprehensively encompasses the phase transitions of CO₂—from gaseous (1 MPa) to liquid/dense (5 MPa and 10 MPa at low temperatures) and to supercritical states (10 MPa at elevated temperatures). The physical properties of CO₂, such as density, viscosity, and mobility ratio, exhibit the most dramatic variations near the critical point, and their regulatory effects on displacement mechanisms tend to saturate with further pressure increase; therefore,

the 1–10 MPa setting effectively captures the controlling mechanisms and trends of pressure on displacement behavior while maintaining strong engineering representativeness. Specifically, under each condition: at 1 MPa, CO₂ remains gaseous across all experimental temperatures (4–50 °C); at 5 MPa, it is liquid at 4 °C but remains gaseous at 50 °C, as the pressure is still subcritical; at 10 MPa, it is liquid at 4 °C and becomes supercritical at 50 °C, since both temperature and pressure exceed the critical point. As CO₂ transitions from gaseous to liquid/supercritical states, its density and viscosity increase significantly, interfacial tension decreases substantially, the mobility ratio progressively improves, the displacement front shifts from fingering-dominated to stable and uniformly advancing, and final CO₂ saturation and sweep efficiency are correspondingly enhanced.

The experimental procedure followed a meticulous, multi-step protocol outlined in the workflow of Figure 2. The process commenced with system initialization and calibration, involving the assembly of the closed-loop flow system, rigorous pressure integrity tests, and the calibration of the imaging system for optimal data fidelity. Subsequently, a fabricated porous-media micromodel was integrated into the HPHT cell, and the system was gradually pressurized and brought to the target isothermal condition—such as 1, 5, or 10 MPa—allowing for stabilization to ensure thermal and pressure equilibrium. Upon achieving steady-state conditions, the formal displacement experiment was initiated, wherein CO₂ was injected at a constant, preset rate (ranging from 0.001 to 5 mL/min) to displace the resident brine. Throughout this process, the imaging system continuously recorded the evolution of the CO₂ invasion front, fluid distribution, and any fingering phenomena until CO₂ breakthrough occurred at the outlet. This comprehensive procedure was repeated systematically by varying the system pressure and injection rate to generate a complete dataset for all designated experimental conditions.

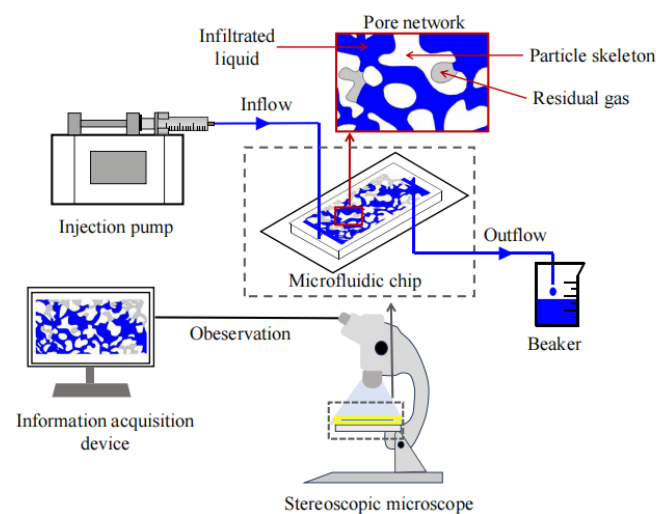


Figure 2. Operation process of the microfluidic experimental platform.

2.2. Data Processing Methods

The raw experimental data, consisting of high-resolution video recordings of the pore-scale displacement process, were subjected to a systematic multi-stage processing pipeline to extract quantitative parameters, as illustrated in Figure 3. First, preprocessing was performed using video editing software to crop the field of view, thereby isolating the core region of the porous network within the microfluidic chip and eliminating edge artifacts. Complete video sequences, spanning from the initial CO₂ influx to eventual breakthrough, were extracted to ensure a full representation of the displacement dynamics. Second, quantitative analysis was conducted using computational algorithms. A custom MATLAB script (Video2Photo, MATLAB R2023b, The MathWorks, Inc., Natick, MA, USA)

was employed to decompose the curated videos into a time series of frame-by-frame screenshots, generating a chronological image sequence that captured the temporal evolution of the fluid phases. Third, to enhance data fidelity, each image frame was processed with specialized algorithms (calcuSg and calcuXtips) for noise reduction and feature extraction. This involved sequential image binarization and Gaussian denoising. Binarization converted grayscale images into a binary format, clearly distinguishing the CO₂ (gas) phase from the aqueous phase. Meanwhile, Gaussian filtering was applied to suppress random signal noise and improve contrast uniformity, thereby significantly enhancing the accuracy of subsequent interface detection and analysis.

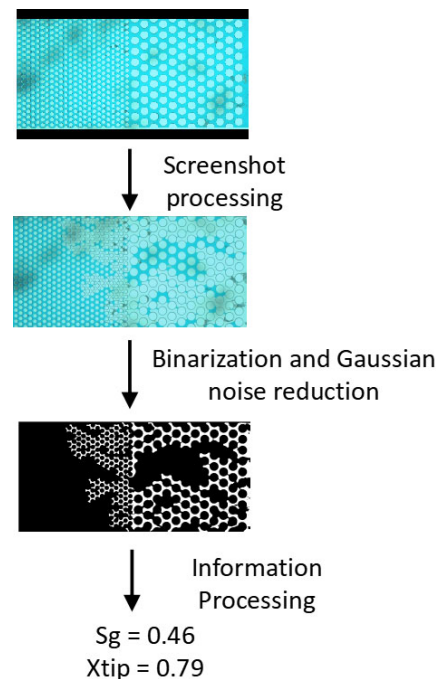


Figure 3. Schematic diagram of the image processing workflow for a microfluidic chip.

Based on the processed binary images, key metrics were quantified, including the real-time gas phase saturation (S_g) and the invasion depth of the CO₂ front. The extracted invasion depth data were imported into analytical software for kinematic analysis, where the average seepage velocity was calculated from the incremental depth over corresponding time intervals. These stage-averaged velocities were compiled into datasets for statistical comparison across different experimental conditions. Finally, to visualize the underlying flow behavior, three primary relationships were plotted: (1) invasion depth versus time, characterizing the advancement kinetics of the CO₂ front; (2) average velocity versus experimental stage, indicating trends in displacement efficiency; and (3) gas saturation versus time, revealing the dynamics of CO₂ accumulation and distribution within the pore network. These visualizations provided the foundational quantitative insights for the mechanistic analysis of how injection rate and pressure govern the displacement process.

3. Results

3.1. Characteristics of Microscopic Displacement and Saturation Evolution Under 1 MPa Pressure

At 1 MPa and across all experimental temperatures (4–50 °C), CO₂ remains in the gaseous state, characterized by low density and low viscosity. As demonstrated in Figure 4, under a low-pressure condition of 1 MPa, the injection flow rate serves as a primary control on the microscopic morphological evolution and saturation dynamics during CO₂ flooding, leading to distinct displacement patterns. Experiments conducted across six flow rates

(ranging from 0.001 to 5 mL/min) reveal a clear transition from capillary-dominated stable displacement to viscosity-dominated unstable fingering.

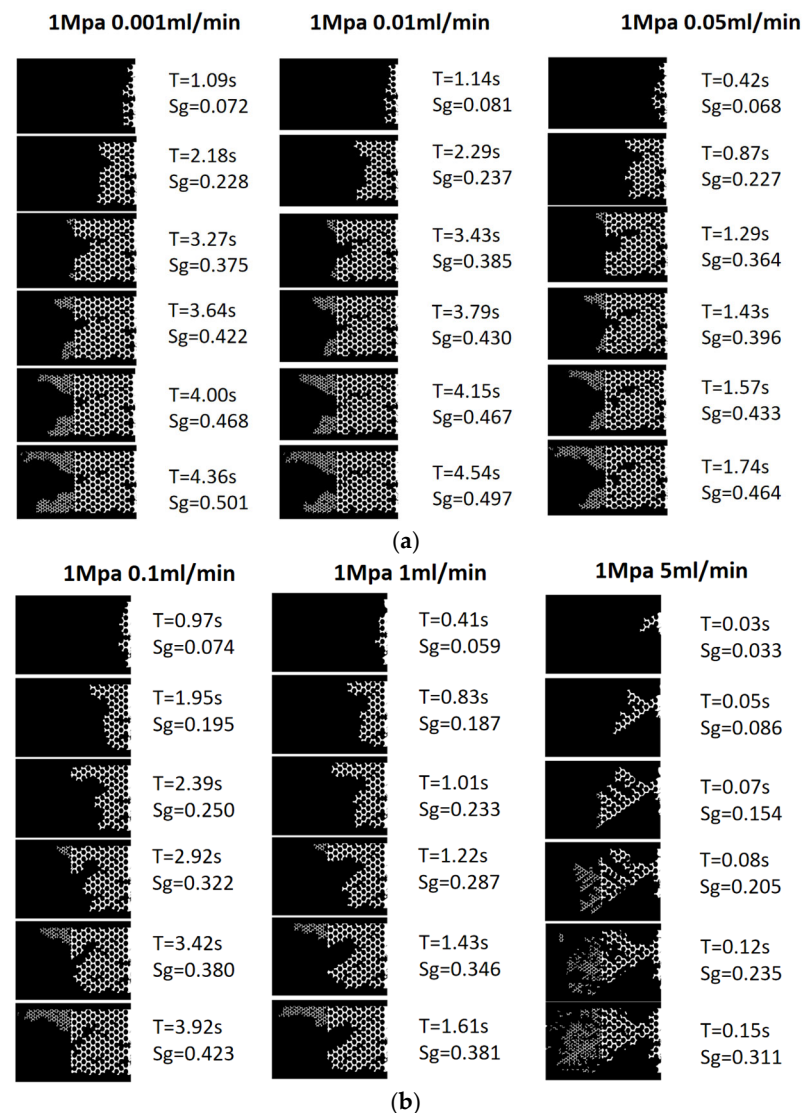


Figure 4. Evolution of microscopic morphologies at different injection rates under a pressure of 1 MPa: (a) low injection rates; (b) medium-to-high injection rates.

In the low flow rate regime (≤ 0.05 mL/min), the displacement exhibits classic piston-like advancement characterized by a smooth and regular frontal interface (Figure 4), with negligible viscous fingering. The temporal evolution of gas saturation (S_g) increases approximately linearly with time. Although a higher flow rate shortens the displacement cycle, it results in a marginal decrease in the ultimate gas saturation, indicating a trade-off between displacement speed and pore-filling efficiency. For instance, the 0.001 mL/min group reached a final S_g of 0.501 at 4.36 s, whereas the 0.05 mL/min group achieved an S_g of 0.464 in a much shorter time of 1.74 s.

In contrast, in the medium-to-high flow rate regime (≥ 0.1 mL/min), the displacement mechanism shifts fundamentally. While higher rates accelerate the process, they severely compromise sweep efficiency and final saturation due to the onset of viscous fingering. As illustrated in Figure 4, the displacement pattern undergoes a progressive transition: the 0.1 mL/min group maintains a relatively smooth interface (transitional state), the 1 mL/min group exhibits early signs of fingering, and the 5 mL/min group shows intense, dendritic

viscous fingering. This unstable behavior is attributed to viscous forces overwhelming capillary forces, causing CO₂ to preferentially invade larger pore throats and bypass significant pore volumes. Consequently, the final saturation drops sharply; for example, the 5 mL/min group reached a low final S_g of only 0.311 at 0.15 s, compared to approximately 0.50 in the low-flow-rate groups.

In summary, at 1 MPa, the displacement pattern is highly rate-dependent. Increasing the flow rate from 0.001 to 5 mL/min drives a transition from a capillary-controlled, stable piston-like flow to a viscosity-controlled, unstable fingering regime. Thus, the flow rate not only controls the displacement velocity but also fundamentally determines the flow pattern and ultimate storage efficiency at this pressure.

3.2. Characteristics of Microscopic Displacement and Saturation Evolution Under a Pressure of 5 MPa

At 5 MPa, CO₂ exists as liquid at low temperatures (4 °C) and as gaseous at elevated temperatures (50 °C), with its density and viscosity significantly higher than at 1 MPa. The displacement characteristics and saturation evolution under a moderate pressure of 5 MPa, as illustrated in Figure 5, demonstrate a significant moderating effect of increased pressure on the flow patterns observed at 1 MPa. The transition from stable to unstable displacement persists with increasing injection rate; however, the onset of instability is delayed, and its severity is markedly reduced.

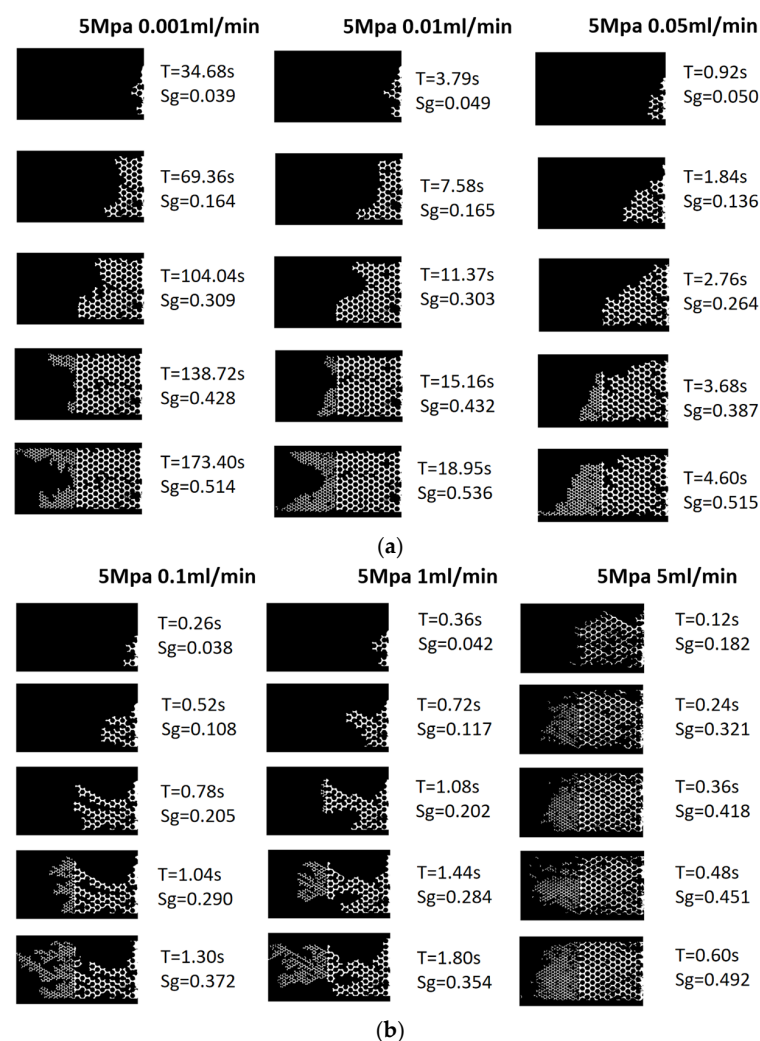


Figure 5. Evolution of microscopic morphologies at different injection rates under a pressure of 5 MPa: (a) low injection rates; (b) medium-to-high injection rates.

At low injection rates (0.001–0.05 mL/min), the displacement process remains predominantly stable and capillary-controlled, similar to the 1 MPa condition but with a notable extension of the displacement duration. The fluid front maintains a regular, piston-like shape, yet the time required to reach a comparable saturation level is longer. For instance, the 0.001 mL/min group took 63.20 s to reach $S_g = 0.505$, compared to 4.36 s at 1 MPa. This indicates that increased pressure, while reinforcing displacement stability, also decelerates frontal advancement at very low flow rates.

The critical distinction at 5 MPa emerges in the medium-to-high flow rate regime (≥ 0.1 mL/min). As shown in Figure 5, the development of viscous fingering is substantially suppressed relative to the 1 MPa case. The displacement interface remains more uniform, and the severe dendritic fingering or isolated water blobs observed at 1 MPa are absent. Even at 1 mL/min, the fluid front retains a relatively regular morphology, exhibiting only slight interfacial fluctuations. Consequently, the final gas saturations achieved are significantly higher. For example, at 0.60 s, the 5 mL/min group attained $S_g = 0.492$, far exceeding the value of 0.311 recorded at 1 MPa.

In summary, the 5 MPa condition introduces a strong stabilizing influence. Although higher injection rates still accelerate the displacement process, the increased pressure effectively mitigates the adverse effects of viscous fingering by enhancing capillary forces and altering fluid properties. This shifts the displacement mechanism from the unstable, fingering-dominated pattern observed at 1 MPa toward a more homogeneous and efficient frontal advancement, resulting in superior displacement uniformity and higher final CO_2 saturation. These results underscore the synergistic regulatory role of pressure and injection rate.

3.3. Microscopic Displacement and Saturation Evolution Characteristics at 10 MPa

At 10 MPa, CO_2 exists as liquid at low temperatures (4 °C) and as supercritical at elevated temperatures (50 °C), characterized by liquid-like density, significantly increased viscosity, and substantially reduced interfacial tension. Under the high-pressure condition of 10 MPa, the displacement behavior exhibits distinct characteristics that further highlight the dominant role of pressure in stabilizing the flow and optimizing efficiency. The experimental results, detailed in Figure 6, are analyzed for low-to-medium and medium-to-high injection rate regimes, revealing how high pressure modulates the interplay between viscous and capillary forces.

For low-to-medium injection rates (0.01 and 0.05 mL/min, Figure 6a), increasing the flow rate exerts a powerful accelerating effect on displacement velocity. The 0.05 mL/min group achieved a comparable saturation ($S_g = 0.481$) in merely 4.30 s, approximately 1/11 of the time required by the 0.01 mL/min group (46.85 s to reach $S_g = 0.544$), demonstrating a non-linear compression of the displacement cycle. Morphologically, both groups exhibit capillary-dominated, piston-like displacement with a regular frontal advance. Only slight fingering or tortuosity is observed at local pore junctions. The fluid interface at 10 MPa is smoother with fewer bifurcations compared to the 5 MPa condition at the same rates, indicating that extreme pressure further consolidates the control of capillary forces, promoting a more uniform and stable process. In terms of saturation evolution, S_g increases approximately linearly with time, and the growth rate is positively correlated with flow rate. Notably, the 0.05 mL/min group achieved a slightly lower final saturation (0.481) than the 0.01 mL/min group (0.544), reflecting a minor trade-off between speed and ultimate pore-filling completeness at high pressure, as faster advancement may leave slightly more residual gas clusters.

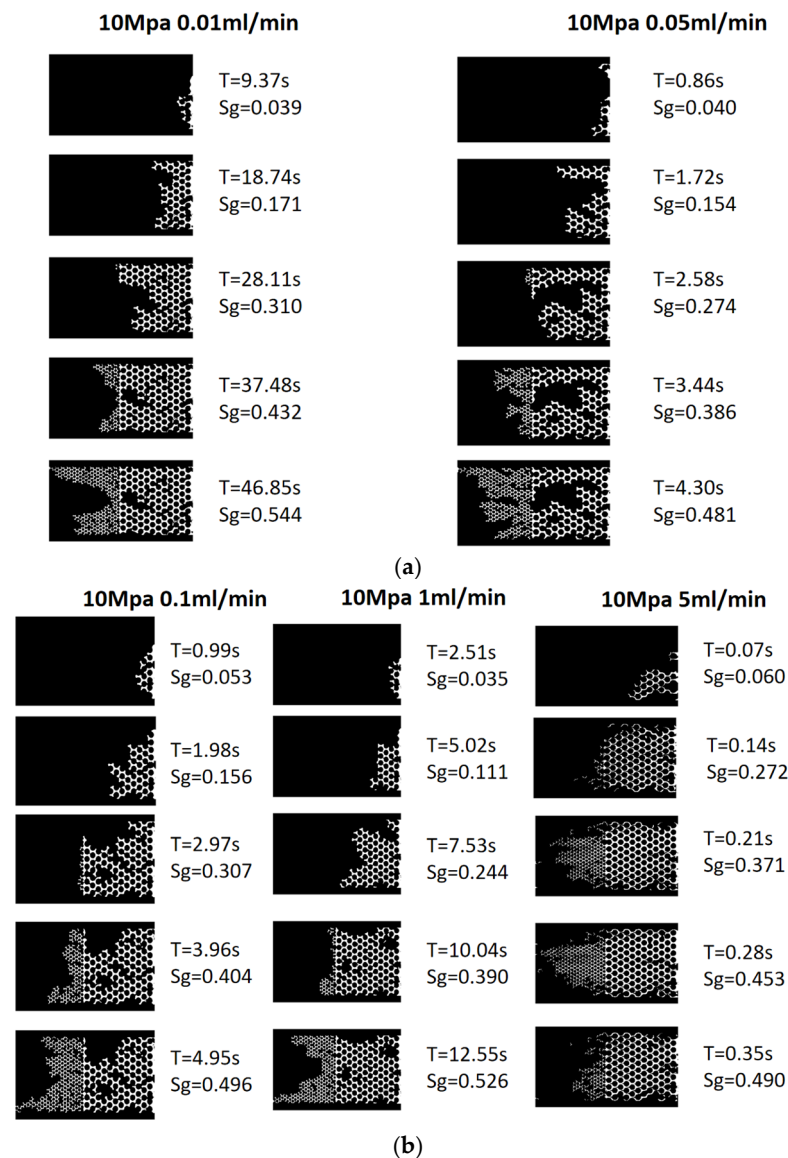


Figure 6. Evolution of microscopic morphologies at different injection rates under a pressure of 10 MPa: (a) low injection rates; (b) medium-to-high injection rates.

For medium-to-high injection rates (0.1, 1, and 5 mL/min, Figure 6b), the effect of flow rate is more pronounced and non-linear. A 50-fold increase in rate (from 0.1 to 5 mL/min) shortened the displacement time to about 1/14. The displacement patterns diverge significantly: the 0.1 mL/min group displays evident viscous fingering with an irregular front; the 1 mL/min group presents a transitional state where viscous and capillary forces compete, resulting in a relatively regular front and the highest ultimate saturation of 0.526; and the 5 mL/min group exhibits near piston-like rapid flushing with a uniform front and only slight local fingering, as the absolutely dominant viscous force enables bulk sweeping that conversely suppresses disordered fingering. The saturation growth rate for the 5 mL/min group is approximately 13 times that of the 0.1 mL/min group. This reveals a clear regime transition under 10 MPa: from capillary-dominated, uniform but slow displacement at low rates, through a competitive regime with significant fingering at medium rates, to viscous-dominated, rapid yet efficient displacement at high rates.

In summary, the 10 MPa environment fundamentally optimizes the displacement mechanism across all flow rates. It strongly suppresses fingering instabilities, enables efficient displacement even at high rates, and ensures high final CO₂ saturations. This

demonstrates the critical role of deep-sea high-pressure conditions in expanding the operational “sweet spot,” allowing for the use of higher, more practical injection rates without compromising storage efficiency.

4. Discussion

4.1. Pore-Scale Displacement Mechanisms and Pattern Characterization

The displacement of resident brine by CO₂ in deep-sea porous media is a core process controlling the initial storage efficiency and security of geological carbon sequestration. This process is governed by the complex interplay of viscous, capillary, and gravitational forces at the pore scale, which dictates the displacement pattern, sweep efficiency, and ultimate trapped phase saturation (Chen et al., 2023 [1]; Yamabe et al., 2014 [18]). The stability of an immiscible displacement front is classically analyzed within the phase diagram defined by the mobility ratio (M) and the capillary number (Ca), delineating the regimes of viscous fingering (VF), capillary fingering (CF), and stable displacement (Lenormand et al., 1988 [16]).

For typical CO₂–brine systems under deep-sea conditions, where CO₂ is less viscous than brine ($M < 1$), the displacement is inherently susceptible to instability, often leading to unfavorable viscous fingering patterns. This instability results in premature breakthrough, low displacement efficiency, and heterogeneous CO₂ distribution, which can compromise storage capacity and security. Recent research has advanced this understanding by introducing quantitative descriptors for characterizing these patterns, such as the fractal dimension (D_f) of the invading fluid cluster and the invading phase saturation at breakthrough (S_{inv}) (Chen et al., 2023 [1]). The specific conditions of deep-sea storage—particularly the high confining pressure—can significantly modulate these dynamics by altering fluid properties (e.g., density, viscosity, interfacial tension) and the effective capillary pressure field (Yamabe et al., 2014 [18]; Zhang et al., 2019 [21]).

As illustrated in Figure 7, the experimental results from this study are contextualized within this established M - Ca phase diagram framework. Under low-pressure conditions (1 MPa), the operational points for various injection rates span from the stable displacement regime at very low Ca to the viscous fingering regime at high Ca . This explains the observed transition from uniform, piston-like advancement at low flow rates to severe, dendritic fingering at high flow rates. Increasing the system pressure to 5 MPa and 10 MPa induces a systematic shift in these operational points toward the stable displacement regime. This shift is primarily attributed to the pressure-mediated increase in CO₂ density and viscosity, which improves the mobility ratio (M), and modification of capillary forces, thereby suppressing the initiation and growth of viscous fingers (Yamabe et al., 2014 [18]). Consequently, even at high injection rates that would typically induce unstable flow at 1 MPa, the displacement under high-pressure conditions exhibits a more uniform front and higher final saturation, as the system is stabilized against viscous instabilities.

This pore-scale mechanistic understanding is corroborated by findings from related studies. For instance, research on CO₂–water–oil three-phase flow has shown that in miscible conditions, supercritical CO₂ can penetrate through water films to contact and mobilize trapped oil, a process governed by diffusive mass transfer and interfacial instability rather than capillary number alone (Zhang et al., 2019 [21]). Similarly, studies on the effects of brine salinity and wettability have demonstrated that these factors can alter interfacial tension and contact angle, thereby affecting the capillary pressure and the competition between viscous and capillary forces, ultimately influencing the displacement pattern and the resulting interfacial contact length crucial for dissolution trapping (Yamabe et al., 2014 [18]). Furthermore, interface-resolved numerical simulations in heterogeneous media have revealed that at high injection rates, viscous forces dominate, leading to complex,

disordered interfaces, while at lower rates, a competition between viscous and capillary fingering can occur, with local porosity variations significantly affecting the flow pattern (Chen et al., 2023 [1]).

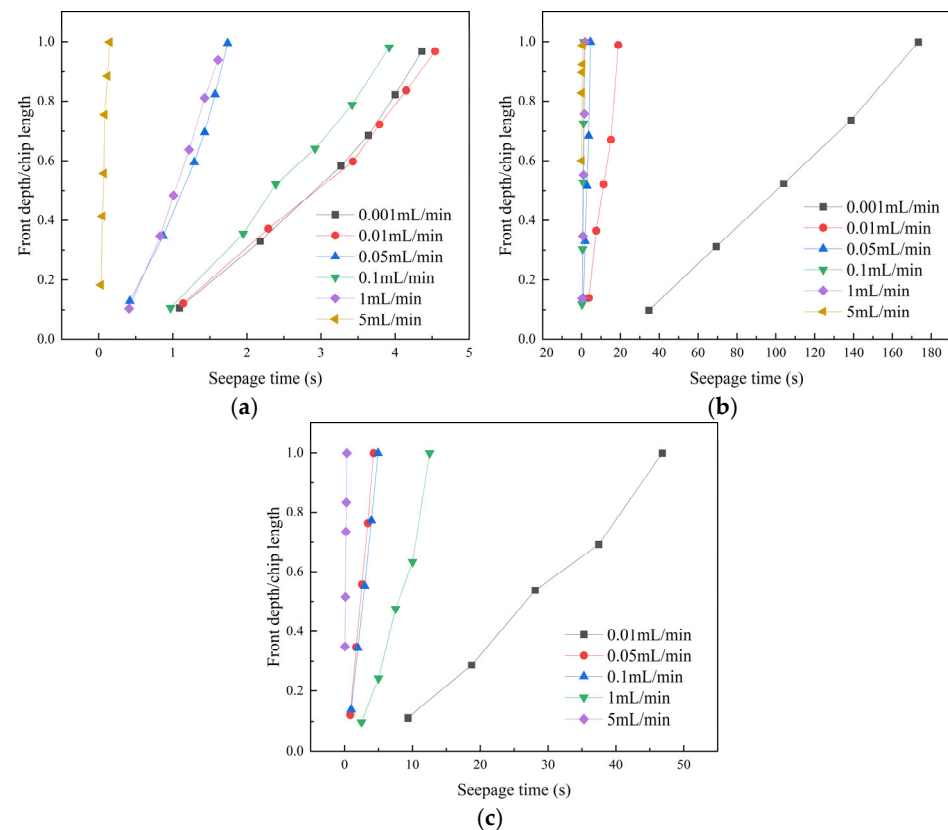


Figure 7. Curves of microfluidic gas–water displacement front depth vs. time under various pressures: (a) 1 MPa, (b) 5 MPa, (c) 10 MPa.

In summary, the displacement pattern observed in our experiments is a direct manifestation of the force balance dictated by the M-Ca condition, which is synergistically regulated by the injection rate (controlling Ca) and the system pressure (affecting both M and capillary pressure). The high-pressure environment of deep-sea reservoirs fundamentally optimizes this balance, expanding the operational “sweet spot” where higher injection rates (for better injectivity) can be used while still maintaining a stable displacement front and high sweep efficiency, a critical prerequisite for effective storage (Chen et al., 2023 [1]).

4.2. Analysis of Average Advancement Rate and Evolution of Displacement Regimes

The evolution of the average advancement rate during the gas–water displacement process, as detailed in Figure 8, provides a dynamic, quantitative perspective to examine the transition between different displacement regimes governed by the interplay of injection rate (directly related to the capillary number, Ca) and system pressure. This analysis interprets these temporal rate changes as direct manifestations of the underlying pore-scale force balance between viscous and capillary forces, which dictates displacement stability and pattern (Chen et al., 2023 [1]; Yamabe et al., 2014 [18]). The velocity profiles offer critical insights into how operational parameters control the competition between efficient, stable drainage and inefficient, unstable channeling.

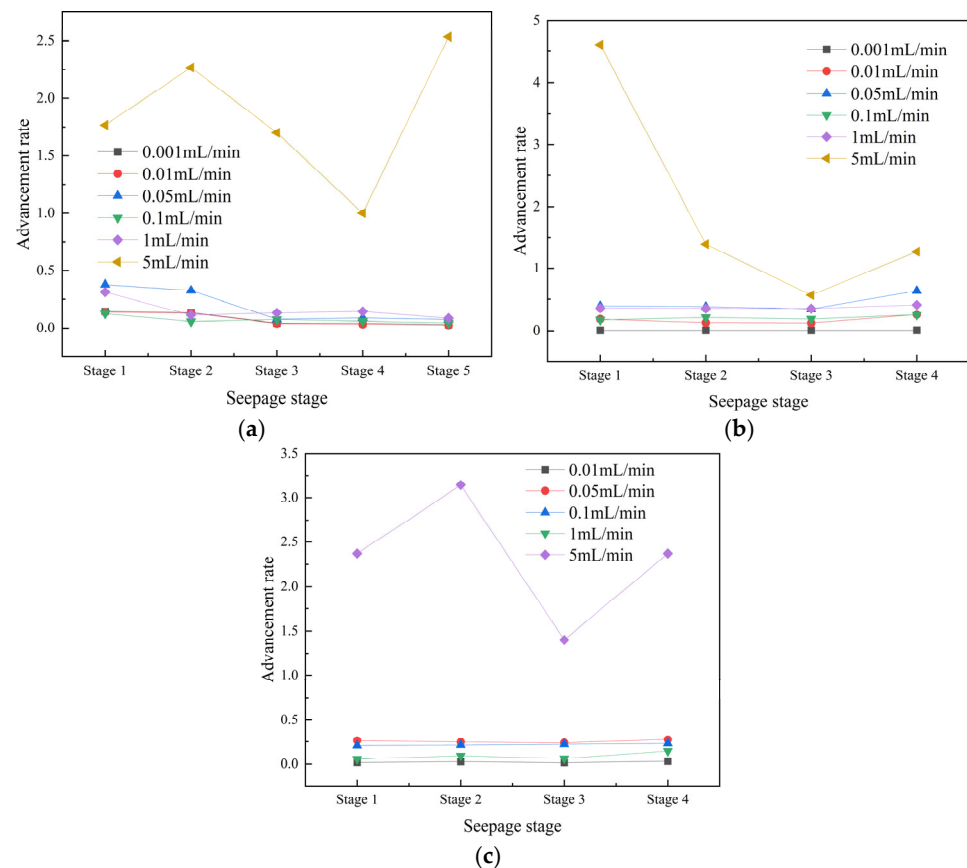


Figure 8. Curves of microfluidic gas–water displacement average rate at different time intervals under various pressures: (a) 1 MPa, (b) 5 MPa, (c) 10 MPa.

Under the low-pressure condition (1 MPa, Figure 8a), the average advancement rate exhibited pronounced stratification and significant stage-wise fluctuations, particularly for high injection rates (e.g., 1 and 5 mL/min). The high-flow-rate groups maintained markedly higher initial velocities but showed sharp peaks followed by rapid declines. This pattern is characteristic of an unstable, viscous-force-dominated (VF) regime where high Ca promotes rapid, finger-like channeling through the path of least resistance. The CO_2 front advanced quickly through larger pores, leading to early breakthrough but poor sweep, after which the velocity dropped sharply as the main channel was established and further expansion stagnated. In contrast, at low injection rates (≤ 0.05 mL/min), where capillary forces dominate (low Ca), the advancement rate was lower but remained remarkably stable over time. This reflects a stable, compact frontal displacement where CO_2 uniformly invaded the pore network, leading to a more gradual and complete filling process, as evidenced by the higher final saturations discussed in Section 4.1.

Elevating the system pressure to 5 MPa (Figure 8b) introduced a profound stabilizing effect. The rate curves for different injection rates began to converge, and the extreme fluctuations observed at 1 MPa were significantly dampened. Notably, the advancement rates for medium to high flow rates (0.1 to 5 mL/min) were lower and their temporal evolution was smoother compared to the 1 MPa case. This can be attributed to the pressure-induced increase in CO_2 density and viscosity, which improves the mobility ratio (M), and the alteration of the capillary pressure field (Yamabe et al., 2014) [18]. These changes suppress the development of viscous instabilities, shifting the system's operational point in the M - Ca phase diagram toward a more stable regime (Yamabe et al., 2014) [18]. Consequently, even at high Ca , the displacement transitioned from chaotic fingering to a more

uniform, cooperative pore-filling process, resulting in a more controlled and sustained advancement rate.

Under the high-pressure condition of 10 MPa (Figure 8c), this homogenizing and stabilizing effect reached its zenith. The rate curves for all injection rates, from very low (0.001 mL/min) to very high (5 mL/min), exhibited remarkably similar and stable temporal profiles. The dramatic stratification and instability observed at 1 MPa were virtually eliminated. This convergence demonstrates that the high intrinsic pressure of the deep-sea environment acts as a master regulator, fundamentally restructuring the seepage mechanism. At this pressure, the modified fluid properties and force balance established a powerful damping effect that suppresses inertial instabilities and viscous fingering, forcing the displacement into a state of stable seepage regulated by the pervasive pressure field. This phenomenon aligns with observations from interface-resolved simulations, which show that increasing the viscosity ratio (akin to the effect of pressure on increasing CO₂ viscosity) can suppress disorder and promote more stable front propagation under certain conditions (Chen et al., 2023) [1]. The resulting stable, homogenized flow front is crucial for maximizing interfacial contact with the brine, enhancing both initial structural trapping and promoting subsequent long-term dissolution trapping mechanisms (Wang et al., 2013) [17].

In summary, the analysis of average advancement rate evolution demonstrates a powerful synergy: injection rate primarily supplies the kinematic energy and determines the inherent instability tendency (via Ca), while system pressure acts as the master stabilizer of the pore-scale force balance. The high-pressure conditions representative of deep-sea geological storage are highly effective in mitigating the adverse effects of high injection rates. By shifting the system into a stable displacement regime within the M-Ca phase diagram, high pressure promotes uniform frontal advancement and homogenized flow dynamics. This allows for the potential use of higher, more practical injection rates (beneficial for project injectivity and economics) without sacrificing the displacement uniformity and high sweep efficiency that are essential for storage security and capacity.

4.3. Temporal Evolution of CO₂ Saturation and Displacement Efficiency

The temporal evolution of CO₂ saturation (S_g), as detailed in Figure 9, served as the definitive metric for quantifying displacement efficiency and the pore-filling process. The final steady-state saturation and the shape of the $S_g(t)$ curve are direct indicators of the displacement pattern—whether it is a stable, uniform drainage that maximizes pore filling or an unstable, fingering-dominated flow that leaves significant portions of the pore space unswept. Specifically, the saturation at breakthrough (S_{inv}) is a key parameter distinguishing between efficient (high S_{inv}) and inefficient (low S_{inv}) displacement patterns (Chen et al., 2023) [1].

As shown in Figure 9a, under low-pressure condition (1 MPa), the $S_g(t)$ curves exhibited a strong dependence on injection rate, demonstrating clear flow rate stratification. High injection rates (e.g., 1 and 5 mL/min) led to a rapid initial increase in S_g but achieved relatively low final plateaus (e.g., ~0.31 for 5 mL/min). This pattern is characteristic of an unstable, viscous-force-dominated (VF) displacement regime, where a high capillary number (Ca) promotes viscous fingering (Lenormand et al., 1988) [16]. The invading CO₂ quickly formed dominant flow channels, bypassing a significant volume of pores and resulting in low S_{inv} , which signifies poor sweep efficiency. In contrast, at low injection rates (≤ 0.05 mL/min), S_g increased more gradually but reached significantly higher final values (~0.50). This behavior signifies a capillary-dominated, stable displacement process where low Ca allows capillary forces to control a compact front, enabling more uniform and efficient drainage of the wetting phase (brine), thereby maximizing the initial residually trapped CO₂ saturation.

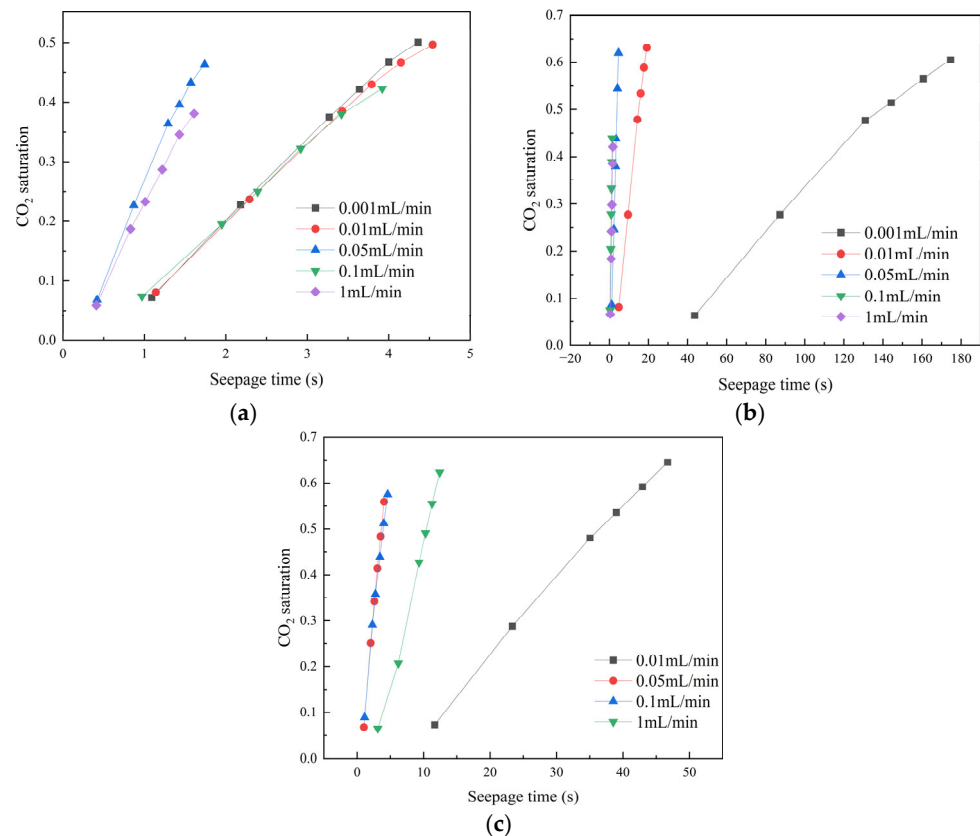


Figure 9. Curves of microfluidic gas–water displacement CO₂ saturation vs. time under various pressures: (a) 1 MPa, (b) 5 MPa, (c) 10 MPa.

A pivotal finding, illustrated in Figure 9b,c, is the profound stabilizing and homogenizing effect of elevated pressure on the displacement outcome. At 5 MPa and, more markedly, at 10 MPa, the $S_g(t)$ curves for different injection rates converged toward similarly high final saturation values (~ 0.50 – 0.55). The pressure increase significantly suppressed the rate-induced stratification observed at 1 MPa. This convergence is attributed to multiple pressure-mediated mechanisms: first, increased pressure elevates the density and viscosity of CO₂, thereby improving the mobility ratio (M) and reducing the destabilizing viscous contrast with brine; second, it modifies the capillary pressure field, which helps suppress the initiation and growth of fingers (Yamabe et al., 2014) [18]. Consequently, even at high injection rates that would otherwise cause severe fingering at 1 MPa, the displacement under high pressure transitioned toward a more stable pattern, resulting in higher final S_g and S_{inv} . This demonstrates that high reservoir pressure, a hallmark of deep-sea environments, is crucial for achieving high initial storage efficiency by ensuring good pore-space utilization across a wide range of operational injection rates, effectively widening the operational “sweet spot.”

Furthermore, the shape of the $S_g(t)$ curves evolved with pressure, offering insights into the changing pore-filling dynamics. At 1 MPa, curves for high-rate injections showed a sharp inflection point followed by a rapid plateau, indicative of fast, channelized breakthrough. This aligns with interface-resolved simulations showing that at high injection rates (high Ca), viscous forces dominate, leading to the formation of disordered, ramified interfaces and rapid but inefficient filling. Under high pressure (10 MPa), the curves became more linear or sigmoidal, with a prolonged filling period before the final plateau. This change reflects a shift in the dominant pore-filling mechanism from unstable frontal advance to a more gradual, percolation-like process involving cooperative pore-filling events, the dynamics of which are stabilized under high confining stress (Yamabe et al., 2014) [18].

The more uniform advancement under high pressure maximizes the interfacial contact area between CO₂ and brine, which is critical for achieving high initial structural trapping and enhances the potential for subsequent long-term dissolution and mineral trapping mechanisms (Wang et al., 2013) [17].

The ability to achieve high final S_g even at moderate-to-high rates under high-pressure conditions is highly advantageous for practical carbon storage. It implies that deep-sea storage projects can potentially utilize higher injection rates—beneficial for operational injectivity and economic viability—without sacrificing storage efficiency, as the ambient confining pressure ensures a stable displacement front and uniform saturation. This synergy between injectivity and efficiency, governed by the pressure–rate interplay, is central to designing robust and scalable sub-seabed carbon sequestration operations (Wang et al., 2013) [17].

In summary, the analysis of CO₂ saturation evolution shows that while injection rate controls the kinetics and inherent instability tendency of the displacement process, system pressure is the master variable determining its ultimate efficiency and stability. The high-pressure conditions inherent to deep-sea reservoirs fundamentally optimize the displacement mechanism, mitigating the adverse effects of high injection rates and ensuring high, uniform CO₂ saturations—a critical prerequisite for effective and secure geological carbon storage.

4.4. Synergistic Regulation of Pressure Effects Across Different Flow Rate Regimes

The analysis of CO₂ saturation evolution, categorized by injection flow rate in Figure 10, elucidates the nuanced synergistic regulatory mechanism between reservoir pressure and injection rate. This cross-plot presentation effectively deconvolves their coupled effects, revealing how pressure distinctly modulates displacement dynamics and ultimate efficiency across the spectrum from capillary-dominated to viscous-force-dominated regimes. This analysis is framed within the classic M-Ca phase diagram, where pressure modifies both the viscosity ratio (M) and the effective capillary forces, thereby shifting the operational point and the resultant displacement pattern (Chen et al., 2023 [1]; Lenormand et al., 1988 [16]; Yamabe et al., 2014 [18]).

In the extremely low flow rate regime (e.g., 0.001 mL/min, Figure 10a), the displacement is intrinsically capillary-dominated (low Ca) at all pressures. The principal effect of increasing pressure is not to change the displacement pattern but to profoundly alter its kinetics and ultimate efficiency. While high pressure (5 and 10 MPa) significantly prolongs the displacement time compared to 1 MPa, it concurrently enables a markedly higher final steady-state saturation. This indicates that elevated pressure enhances capillary forces, facilitating a more refined, complete, and uniform pore-filling process. The extended time-frame under high pressure allows for gradual drainage of smaller pores and more efficient displacement of corner water, which may be bypassed under lower-pressure conditions where capillary forces are weaker. This leads to superior displacement quality and higher residually trapped CO₂ saturation, favorable for initial structural storage security. This observation aligns with findings on the role of capillary forces in stabilizing fronts and improving sweep in related displacement studies (Yamabe et al., 2014) [18].

Within the low-to-medium flow rate range (0.01 and 0.05 mL/min, Figure 10b,c), a transition zone is observed. Here, pressure acts as a powerful homogenizing agent. While the saturation curves at 1 MPa show clear sensitivity to flow rate, elevating the pressure to 5 MPa and 10 MPa effectively narrows the differences in both evolution path and final saturation among experiments. This convergence demonstrates that a high-pressure field can override the destabilizing tendencies introduced by moderate increases in flow rate (Chen et al., 2023) [1]. By increasing CO₂ density and viscosity (thereby improving the

mobility ratio M) and modifying the capillary pressure field, high pressure stabilizes the displacement front. This shifts the system's response away from the unstable fingering branch of the phase diagram and toward a more stable, uniform displacement regime. This effect is crucial for deep-sea storage, as it ensures that a practical range of low-to-medium injection rates can yield similarly high and efficient displacement outcomes, enhancing operational flexibility. This homogenizing effect under pressure is consistent with numerical simulations showing that increased viscosity ratio can suppress flow disorder (Chen et al., 2023) [1].

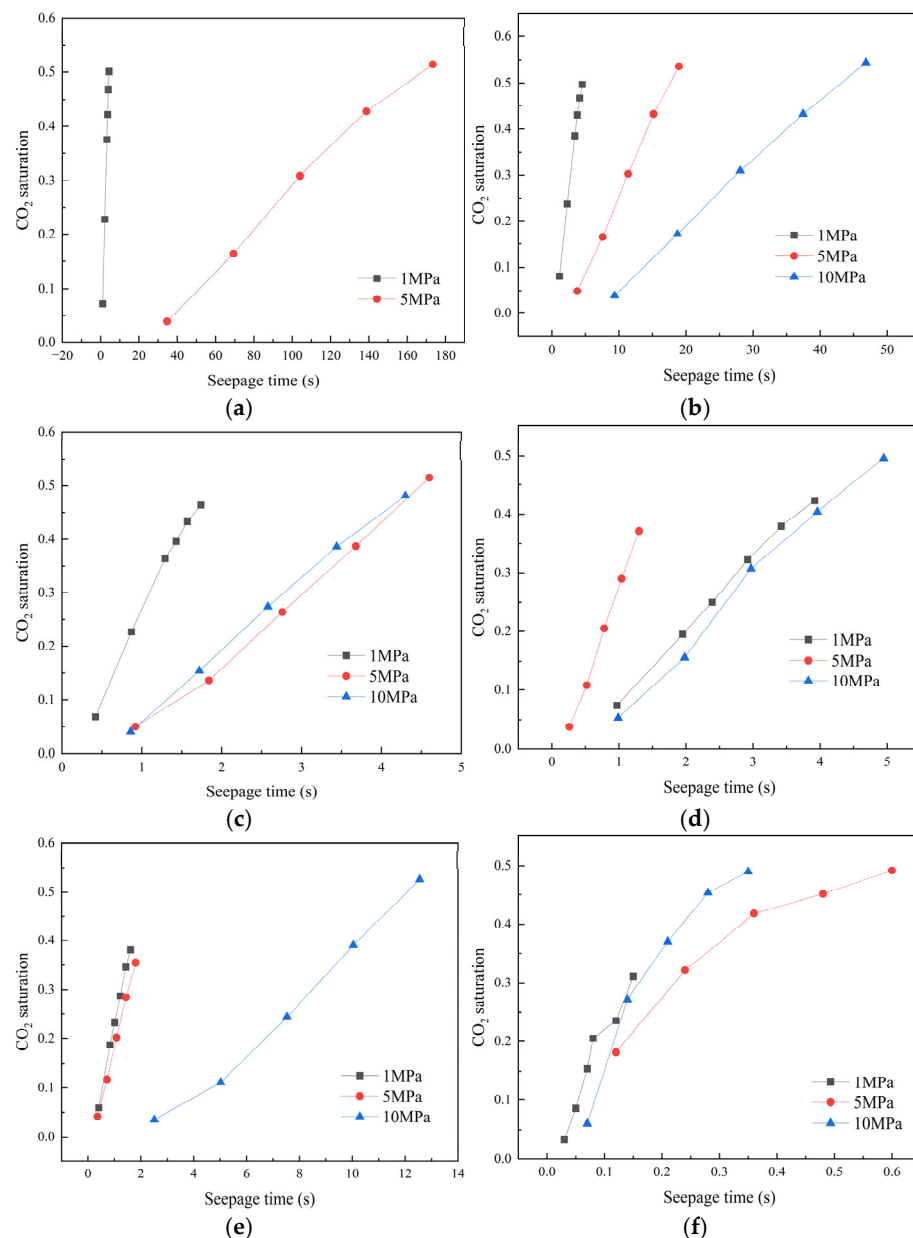


Figure 10. Curves of microfluidic gas–water displacement CO₂ saturation vs. time under various flow rates: (a) 0.001 mL/min, (b) 0.01 mL/min, (c) 0.05 mL/min, (d) 0.1 mL/min, (e) 1 mL/min, (f) 5 mL/min.

In the high flow rate regime (0.1 to 5 mL/min, Figure 10d–f), where viscous forces are significant (Ca is high), the suppressive and optimizing effect of pressure on flow instabilities reaches its zenith. At 1 MPa, the saturation curves for high flow rates exhibit steep, early growth followed by a low plateau—a clear signature of viscous fingering characterized by

low breakthrough saturation (S_{inv}) and inefficient sweep (Chen et al., 2023) [1]. In stark contrast, under high pressures (5 and 10 MPa), the saturation evolution is dramatically transformed: the curves are significantly flattened, the initial growth rate differentials are smoothed, and the final saturations are greatly enhanced. This critical observation confirms that a high-pressure environment fundamentally mitigates the adverse channeling effects of high injection rates (Yamabe et al., 2014) [18]. The pressure increases effective flow resistance within the porous medium and alters the pore-scale force balance, thereby buffering the impact of high-kinetic-energy fluids and transforming the displacement process from rapid, unstable channeling to steady, progressive filling. The resultant higher steady-state saturation and improved uniformity underscore the indispensable role of high confining pressure in enabling the use of practical, higher injection rates without sacrificing storage efficiency—a key consideration for the economic viability of large-scale sequestration projects (Wang et al., 2023) [4]. This finding is particularly relevant in heterogeneous media, where high rates can exacerbate channeling; pressure serves to counteract this, promoting a more uniform sweep even in challenging environments.

In conclusion, the analysis of pressure effects across flow rates, as synthesized in Figure 10, demonstrates a powerful synergy: flow rate primarily determines displacement kinetics and inherent instability tendency (governing Ca), while pressure acts as the master stabilizer and efficiency optimizer (Chen et al., 2023) [1]. The high-pressure conditions of deep-sea reservoirs expand the “sweet spot” of operational parameters, allowing for higher injectivity to meet economic and operational targets while maintaining, or even enhancing, displacement uniformity and final CO_2 saturation. This synergy between injectivity (controlled by rate) and storage efficiency and security (ensured by high pressure) is central to designing robust, scalable, and effective injection strategies for deep-sea carbon storage (Wang et al., 2023) [4].

5. Conclusions

This study systematically investigated the pore-scale seepage characteristics and displacement mechanisms of CO_2 in porous media under simulated deep-sea conditions using high-pressure microfluidic experiments. The effects of injection rate and pressure on displacement patterns, stability, and final saturation were quantitatively analyzed, leading to the following principal conclusions:

1. Injection rate governs the displacement pattern and stability. High injection rates (≥ 0.1 mL/min) substantially increase the initial advancement velocity and shorten breakthrough but induce viscous fingering, leading to unstable displacement and lower final CO_2 saturation due to poor sweep efficiency. Conversely, at low injection rates (≤ 0.05 mL/min), the displacement process is stable and uniform, characterized by piston-like frontal advancement, resulting in more thorough pore-filling and higher ultimate saturation. This defines a critical trade-off between displacement speed and storage efficiency controlled by the capillary number (Ca).
2. System pressure critically regulates migration and final saturation. Elevated pressure exerts a profound stabilizing and optimizing effect. Compared to low-pressure conditions (1 MPa), high-pressure environments (5 and 10 MPa) effectively suppress the development of viscous fingering, promote more uniform frontal advancement, and significantly enhance the final CO_2 saturation. This pressure-mediated stabilization expands the operational range of injection rates that yield efficient displacement, a key advantage for deep-sea storage where high confining pressure is inherent.
3. The temporal evolution of CO_2 saturation follows a non-linear trend. The saturation time profile is generally characterized by a rapid initial increase followed by a gradual approach to a stable plateau. The timing of the growth inflection point

is positively correlated with the injection rate; higher rates lead to an earlier inflection point, indicating faster initial filling but potentially earlier flow channelization and breakthrough.

4. A distinct “fingering effect” is observed and is synergistically controlled by rate and pressure. The severity of viscous fingering exhibits a direct positive correlation with injection rate and an inverse correlation with system pressure. High-pressure conditions fundamentally optimize the CO₂ distribution pattern within the pore network, mitigate the formation of dominant channels, and enhance the residual trapping capacity, thereby improving both storage efficiency and security.

In summary, the findings elucidate a powerful synergistic regulatory mechanism: while the injection rate dictates the displacement kinetics and inherent instability, the system pressure acts as the master stabilizer and efficiency optimizer. The high-pressure conditions representative of deep-sea reservoirs effectively widen the operational “sweet spot,” allowing for the potential use of higher, more practical injection rates to meet injectivity targets without compromising the displacement uniformity and high saturation essential for effective storage. These conclusions provide crucial pore-scale experimental evidence for optimizing injection strategies and assessing storage security in deep-sea carbon sequestration projects.

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