

Article

Research on Interfacial Instability Control During CO₂ Displacement of Non-Newtonian Fluids

Yu-Ting Wu ^{1,2,3,†}, Sung-Ki Lyu ^{4,†} , Zhen Qin ^{1,3,5,*} , Jie Zhang ¹ and Hua Qiao ³

¹ School of Mechanical Engineering, Nantong Institute of Technology, Nantong 226002, China; zhangjie@ntit.edu.cn (J.Z.)

² School of Transportation and Vehicle Engineering, Shandong University of Technology, Zibo 255000, China

³ Zhejiang Shuanghuan Driveline Co., Ltd., Hangzhou 310023, China; qiaohua@gearsnet.com

⁴ School of Mechanical and Aerospace Engineering, Gyeongsang National University, Jinju-si 52828, Republic of Korea; sklyu@gnu.ac.kr

⁵ School of Mechanical Engineering, Shandong University of Technology, Zibo 255049, China

* Correspondence: qin@sdut.edu.cn

† These authors contributed equally to this work.

Abstract

Viscous fingering is an interfacial instability that occurs when multiple fluids displace each other. This research focuses on the interface instability during immiscible displacement of shear-thinning fluids by CO₂. By controlling velocity and applying heat to the upper and lower walls, the influence of velocity and temperature on viscous fingering during CO₂ displacement is investigated. Moreover, by modifying the geometric conditions of the classical Hele-Shaw cells (HSCs), a novel analytical framework for viscous fingering is proposed. The primary methodology involves implementing a minute depth gradient distribution within the HSC, coupled with the Volume of Fluid (VOF) multiphase model, which systematically reveals the dynamic suppression mechanism of shear-thinning effects on viscous finger bifurcation. The results indicate that temperature elevation leads to increased sweep efficiency, reduced residual non-Newtonian fluid in the displaced zone, and enhanced displacement efficiency. Furthermore, increased velocity leads to reduced sweep efficiency. However, at lower velocities, displacement efficiency remains relatively low due to limited sweep coverage. The direction and magnitude of the depth gradient significantly govern the morphology and extension length of viscous fingering. Both positive and negative depth gradients promote fingering development on their respective sides, as the gradient establishes anisotropic permeability that prioritizes flow pathways in specific orientations, thereby intensifying finger propagation.

Keywords: viscous fingering; non-Newtonian fluid; carbon dioxide; interface control; CFD; VOF



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1. Introduction

Concerning the Hele-Shaw (two closely spaced parallel plates), observations have shown that during displacement processes like water flooding to displace oil, the less viscous displacing fluid forces the more viscous crude oil to move, forming dendritic intrusion channels. This diversion effect, resulting from viscosity mismatch, is collectively referred to as viscous fingering [1–3]. This effect manifests extensively across natural and engineered systems, including groundwater infiltration in subsurface aquifers [4], reservoir displacement processes in petroleum production [5], curtain coating defects in

industrial applications [6], and transdermal drug diffusion in biomedical contexts [7]. The dual-edged nature of this phenomenon has garnered cross-disciplinary attention. For beneficial applications in materials design, it enables precise modulation of dendritic fractal architectures [8]—facilitating the fabrication of catalyst supports with high specific surface area in nanoporous materials [9], structural coloration surfaces for bio-inspired functional coatings [10], and materials endowed with unique photonic/electronic responsiveness in microfluidic devices [11]. Conversely, for negative suppression in petroleum extraction, viscous fingering induces premature breakthrough of displacing fluids, reducing crude oil recovery rates by 10–30% [12–14]; in microchemical systems, this phenomenon induces reactant mixing inhomogeneity and microchannel clogging, effects that become markedly accentuated in shear-thinning non-Newtonian fluids—such as polymer solutions and blood—within hemodynamic or rheological contexts [15–17]. Consequently, achieving active control over interfacial stability across diverse scenarios—such as fostering beneficial fingering in materials synthesis while suppressing detrimental instabilities in petroleum extraction—emerges as a pivotal frontier for enhancing technical efficacy.

A substantial body of international scholarship has conducted multifaceted in-depth investigations into the viscous fingering phenomenon. Chuoke et al. derived the critical velocity for viscous fingering initiation from planar interface instability using perturbation theory [18]. Subsequently, numerous researchers have conducted extensive theoretical and experimental investigations centered on this foundational framework. S. A. Abdul Hamid et al. investigated the fingering phenomenon during invading water penetration into polymer slugs in secondary polymer flooding through a coupled approach integrating numerical simulations and analytical methods [19]. This study establishes an approximate method for predicting the dynamic process of polymer slug volume growth caused by water fingering under no-adsorption conditions. This method derives a concise analytical expression that can be used to estimate the minimum slug size required to prevent water fingering from compromising slug integrity before polymer breakthrough. Alan et al. used numerical simulation to predict the incremental oil recovery and water cut reduction characteristics caused by polymer injection [20]. Furthermore, the physical mechanism of this phenomenon has been revealed and a predictive framework established through the latest modeling approach. Salmo et al. verified the novel immiscible viscous fingering modeling approach through experimental studies [21]. The experiment obtained spatiotemporal images of two-dimensional immiscible fingering evolution through X-ray scanning technique, convincingly demonstrating the effectiveness of the novel approach. As a core parameter in unsteady-state immiscible displacement simulation, the fractional flow curve (f_w) function exhibits systematic variations closely related to the viscosity ratio (μ_o/μ_w), with such variations possessing well-defined physical significance. Currently, numerous researchers have conducted extensive experimental and theoretical studies focusing on Newtonian displaced fluids [22–26], investigating the effects of various parameters—including fluid properties, flow inertia, channel geometry, permeability, and capillary pressure—on viscous fingering.

Compared with Newtonian fluids, non-Newtonian fluids flowing in HSCs have received relatively less attention. However, it is noteworthy that fluid rheology plays a pivotal role in the evolution of viscous fingers. Viscous fingering is a flow instability caused by viscosity contrast between two liquids, where even minute perturbations can induce significant alterations in the motion of the contact line. Yang et al. constructed a pore network model to simulate non-Newtonian fluid two-phase flow [27], and identified a transition mechanism from capillary fingering to viscous fingering during the displacement process. For Ellis fluids, the stronger the shear-thinning effect, the more readily the injected fluid invades small-radius pore throats, thereby suppressing viscous fingering development, enhancing displacement efficiency, and significantly reducing the scale of the transition

zone. Ahmadikhamsi et al. employed a radial HSC experimental setup to investigate viscous fingering phenomena in non-Newtonian fluids induced by the displacement of oil phases using Carbopol®940 polymer solutions (with/without SDS surfactant) [28]. The experiments revealed that, contrary to conventional Saffman–Taylor instability characteristics, the injection rate of polymer solutions significantly affects the morphological evolution of viscous fingers. The study demonstrates that surfactant addition not only alters system properties by reducing interfacial tension, but also decreases solution viscosity, thereby collectively enhancing capillary number effects. Shokri et al. investigated thermal viscous fingering instabilities during the displacement of Newtonian fluids by shear-thinning non-Newtonian fluids in heterogeneous porous media [29]. The results indicate that a decrease in the thermal retardation coefficient intensifies flow instabilities, numerical simulations quantitatively characterized perturbation mechanisms of stratified heterogeneity on the coupled evolution of temperature and concentration fields, identifying switching thresholds for fingering patterns under synergistic effects of heat-mass transfer and rheological properties. Logvinov et al. discovered that the fluid diffusion rate exhibits strong dependence on the power law index n [30]. Mafei et al. elucidated the regulatory mechanism of depth gradients on interfacial stability by introducing minute depth gradients or modifying the geometric configuration of the HSC top plate, thereby validating the efficacy of depth gradient manipulation in controlling viscous fingering behavior during air-driven displacement of non-Newtonian fluids [31]. In studies focusing on the displacement of non-Newtonian fluids, the influence of factors such as the properties of the non-Newtonian fluid, the HSC configuration, and the pore structure on the viscous fingering phenomenon was investigated. While displacing phases such as water and air are predominantly selected as conventional media in the studies, research specifically addressing the displacement of non-Newtonian fluids by CO₂ has rarely been explored.

In summary, this study will utilize numerical simulation methods to investigate and optimize the CO₂ displacement shear-thinning fluid process within a three-dimensional HSC. The temperature of the upper and lower walls and the CO₂ displacement velocity will be used as variables to elucidate the effects on viscous fingering in the three-dimensional model. In addition, the HSC will be geometrically modified by introducing varying depth gradients to modulate the fingering behavior.

2. Numerical Method

In an HSC system, the governing equations are typically formulated using the depth-averaged Darcy's law. This implies that the depth-averaged velocity of each fluid phase along the depth direction can be expressed by Equation (1).

$$\mathbf{u}_j = -\frac{h^2}{12\mu_j} \nabla p_j \quad (1)$$

where p_j and $\mathbf{u}_j$ are the phase j depth-averaged pressure and velocity vectors, respectively.

Due to the overall low level of fluid motion velocity, the flow state can be considered incompressible. Consequently, the continuity equation can be transformed into:

$$\nabla \cdot \mathbf{u}_j = 0 \quad (2)$$

where $\mathbf{u}$ represents the velocity vector. The corresponding momentum equation (or equation of motion) can be expressed as:

$$\rho \left[\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} \right] = \nabla \cdot \left(-p\mathbf{I} + \mu \left[\nabla \mathbf{u} + (\nabla \mathbf{u})^T \right] \right) + \mathbf{F}_{st} \quad (3)$$

In the formula, p represents pressure, ρ represents density, μ represents dynamic viscosity, I represents unit vector, t represents time, and F_{st} represents surface tension.

In this study, ANSYS Fluent 2021 R1 (commercial software) is utilized to conduct the numerical simulations. To capture the two-phase interface and characterize the morphological features of viscous fingering, the VOF method, based on a fixed Eulerian computational grid, is employed to track the free boundary. This method assumes that the fluids involved in the advected fluxes are immiscible and defined within the computational cells. Furthermore, the VOF method adopts a single coupled pressure equation and a single momentum equation system for each dimension. For multiphase flow modeling, this method formulates a shared velocity field based on the mass-weighted averaged mass and momentum transport equations. These equations, neglecting interphase mass transfer, can be defined as:

$$\frac{\partial}{\partial t}(r_\alpha \rho_\alpha) + \nabla \cdot (r_\alpha \rho_\alpha \vec{U}_\alpha) = 0 \quad (4)$$

$$\begin{aligned} \frac{\partial}{\partial t}(r_\alpha \rho_\alpha \vec{U}_\alpha) + \nabla \cdot (r_\alpha \rho_\alpha \vec{U}_\alpha \otimes \vec{U}_\alpha) = & \nabla \cdot \left(r_\alpha \mu_\alpha \left(\nabla \vec{U}_\alpha + \left(\nabla \vec{U}_\alpha \right)^T \right) \right) \\ & - r_\alpha \nabla p + r_\alpha \rho_\alpha \vec{g} + \vec{F}_{st} \end{aligned} \quad (5)$$

where the subscript α refers to the gas (g) and liquid (l) phases such that $r_l + r_g = 1$. In addition, $\vec{U}_\alpha$ represents the velocity field of phase α , r_α —volume fraction, ρ_α —density, p —pressure, μ_α —viscosity, $\vec{g}$ —gravity and $\vec{F}_{st}$ represents the surface tension.

In this study, the parameters of the underlying 3D rectangular HSC are as follows: the length is 100 mm, the width is 20 mm, and the gap (depth, d) between the upper and lower plates is 1 mm. The specific configuration is illustrated in Figure 1. Furthermore, a series of variations in its depth gradient were conducted. During the entire simulation process, high-quality structured grids were employed, with the total number of cells approximately 1.4 million. Furthermore, to enhance simulation accuracy, mesh refinement was performed in the boundary layer region (as shown in Figure 2b). When there were more than 1.4 million elements in the meshed computational domain, the grid independent test, as shown in Figure 2b, revealed that the velocity at the out-flow did not depend on grid size. As a result, we took into account the 1,432,856 element count in the computational, domain.

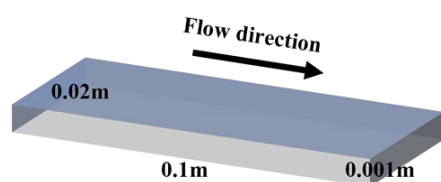


Figure 1. Three-dimensional model of the HSC.

In terms of boundary condition settings, CO_2 displaces the non-Newtonian fluid at a constant velocity of 0.02 m/s which is uniformly distributed at inlet, while the outlet adopts an ambient atmospheric average static pressure outlet condition, where the relative pressure P_{rel} is 0 Pa. In addition, the entire displacement time is 3.5 s. In the calculation settings, a second-order upwind scheme is adopted to balance accuracy and stability, avoiding excessive dissipation of the first-order scheme or oscillation of the QUICK scheme under strong gradients. For pressure velocity coupling, the PISO algorithm is used, which converges faster than the SIMPLE algorithm and is particularly suitable for transient situations. To solve the interface smearing problem in the VOF method, the time step is 0.002 s, ensuring that the interface movement does not exceed 1 or 2 grid cells within

each time step. The displaced phase is a non-Newtonian fluid, with primary consideration given to the impact of its shear-thinning behavior on the viscous fingering phenomenon. During the numerical simulation process, a power-law non-Newtonian fluid model was implemented in the calculations.

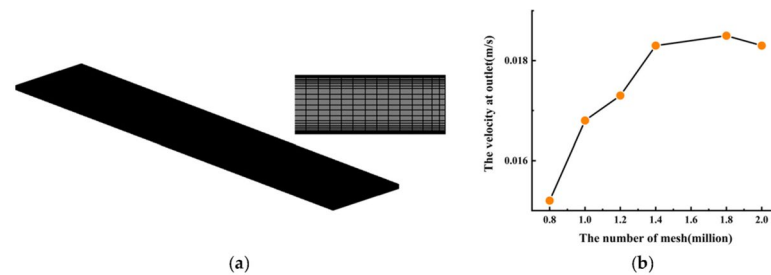


Figure 2. Grids of the computational domain (a) and verification of mesh independence (b).

$$\mu = \mu_0 \gamma^{n-1} \quad (6)$$

where γ is the shear rate, and n is the power law exponent. The fluid is classified into shear thickening for $n > 1$, shear thinning for $n < 1$, and the fluid recovers the Newtonian behavior at $n = 1$. For shear thinning fluids, the smaller the value of n , the more significant the shear thinning effect. In this study, we consider medium shear thinning fluid where $n = 0.4$ as the research object.

3. The Effects of Wall Temperature on Viscous Fingering During Displacement Processes

In the process of CO₂ displacing non-Newtonian fluids, to investigate the underlying mechanism of temperature on the viscous fingering phenomenon, three temperature conditions, $T_1 = 300$ K, $T_2 = 305$ K, and $T_3 = 320$ K, were selected for simulation studies. The computational domain and boundary conditions are illustrated in Figure 3. At the initial moment, the entire fluid domain is occupied by the non-Newtonian fluid (Fluid 1), which is maintained at an ambient temperature of 298.15 K; subsequently, ambient-temperature (298.15 K) CO₂ (Fluid 2) begins to enter the domain. In the numerical setup, the upper and lower walls were configured with no-slip boundary conditions, which is the same processing method with Singh [32]. Their temperatures were actively maintained at specified values T_1 , T_2 , and T_3 respectively to achieve continuous fluid heating.

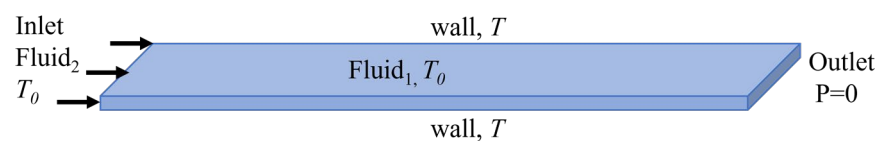


Figure 3. Computational model configuration implementing wall heating technology (with temperature control points).

During the computational process, the energy equation must be solved due to the involvement of thermal diffusion and convection. The viscosity of the non-Newtonian fluid was redefined by selecting the ‘shear rate and temperature-dependent’ model. Under this model, the viscosity is governed by the constitutive equation given in Equation (8). It can be observed that viscosity exhibits an inverse relationship with temperature, specifically, as temperature increases, viscosity tends to decline.

$$\mu = \eta(\dot{\gamma})H(T) \quad (7)$$

where $H(T)$ is the temperature dependence, known as the Arrhenius law.

$$H(T) = \exp \left[\alpha \left(\frac{1}{T - T_0} - \frac{1}{T_\alpha - T_0} \right) \right] \quad (8)$$

where α is the ratio of the activation energy to the thermodynamic constant and T_α is a reference temperature for which $H(T) = 1$. T_0 , which is the temperature shift, is set to 0 by default and corresponds to the lowest temperature that is thermodynamically acceptable. Therefore T_α and T_0 are absolute temperatures.

From Figure 4, it is distinctly observed that regardless of temperature magnitude, symmetric fingering structures develop in the CO₂ displacement front at $t = 1$ s, with cavitation bubble nuclei emerging near the fingering roots. However, with increasing temperature, the fingering propagation distance decreases, the fingering root thickens, and the intermediate cavitation zone progressively contracts. At $t = 1.5$ s in the displacement process, under the 300 K and 305 K conditions, degenerative thinning occurs in the upper fingering structure. In contrast, at 320 K, both fingering branches develop well-maintained profiles with enhanced interfacial stability between the displacing and displaced phases. From Figure 5, it is quantitatively determined that at $t = 1$ s with a temperature of 300 K, the fingering propagation distance is measured as 0.043 m. When the temperature is increased to 320 K, this distance shortens to 0.035 m. Similarly, at $t = 1.5$ s under 300 K, the inferior fingering branch propagates to 0.076 m, whereas at 320 K the superior fingering extension reaches 0.064 m. This quantitatively confirms that elevated temperature reduces the maximum fingering penetration distance by approximately 19.8%, corresponding to enhanced stabilization of displacement fronts.

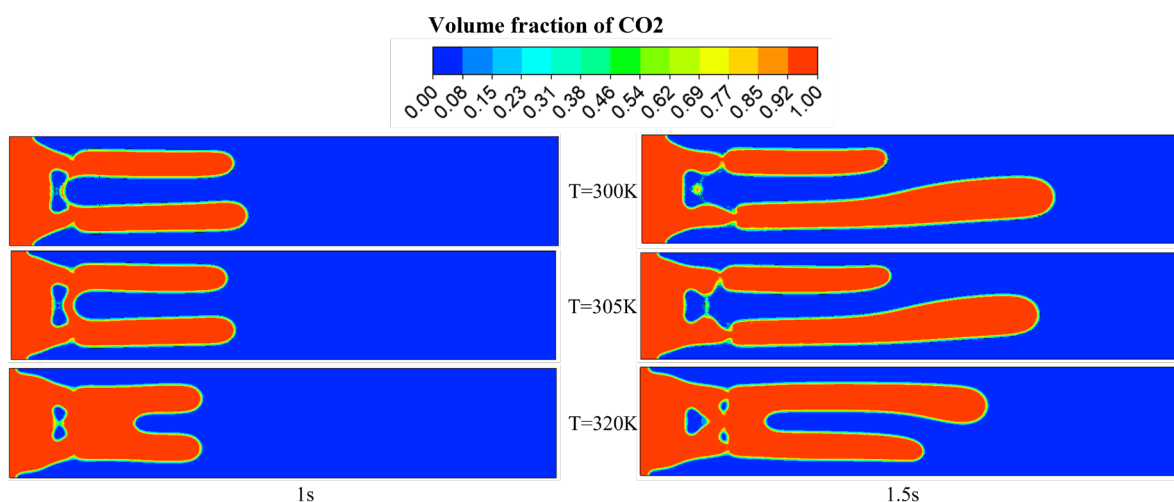


Figure 4. Morphological contours of viscous fingering at $t = 1$ s (left) and $t = 1.5$ s (right) under distinct temperature conditions.

Figure 6 defines sweep efficiency φ : the ratio of the CO₂-swept area A_v (area enclosed by the black contour line) to the reference area A_0 (green-shaded area demarcated by the maximum penetration front of fingering structures).

$$\varphi = A_v / A_0 \quad (9)$$

φ increases with rising temperature. This indicates a reduction in residual non-Newtonian fluid within the displaced zone and a corresponding enhancement in displacement efficiency. Due to the increase in temperature, the kinetic energy of molecular thermal motion is enhanced, breaking the existing weak interactions, resulting in a macroscopic decrease in viscosity, which helps CO₂ to be better absorbed in the reservoir. In

addition, an increase in temperature will accelerate the diffusion of molecules at the interface, making it easier for displacement phase molecules to diffuse into the displaced phase, expanding the displacement range and improving displacement efficiency. This holds significant implications for enhancing hydrocarbon recovery in oil and gas reservoirs, as expanded sweep coverage enables the mobilization and displacement of previously immobile fluid phases trapped in pore networks.

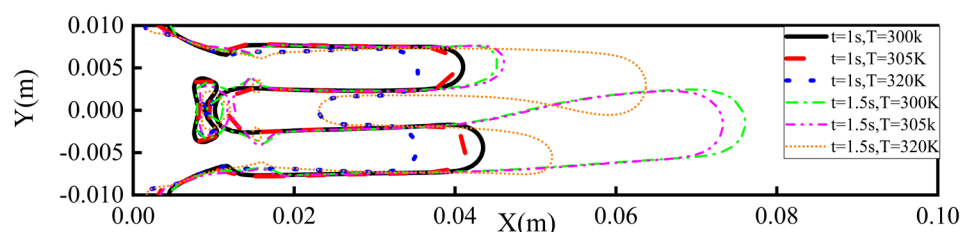


Figure 5. Spatial-temporal evolution of viscous fingering front positions under varying temperature conditions at distinct time instants.

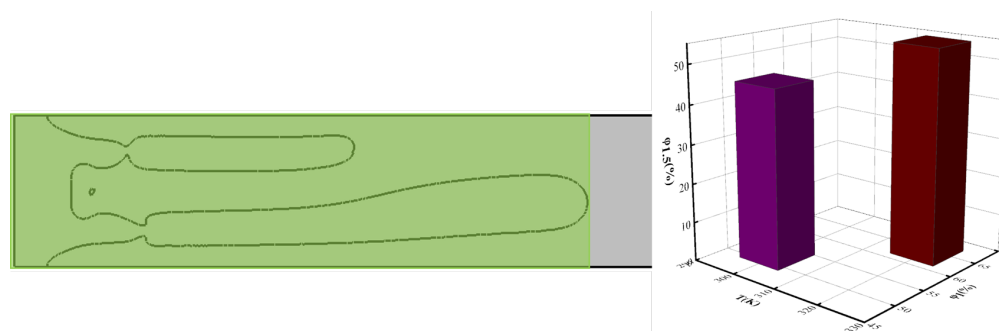


Figure 6. Quantitative mapping of sweep region and corresponding sweep efficiency ϕ evolution during CO₂ displacement with increasing temperature.

It can be concluded that at both $t = 1$ s and $t = 1.5$ s, the sweep efficiency

4. Effects of CO₂ Displacement Velocity on Viscous Fingering Instabilities

To investigate the effects of CO₂ displacement velocity on viscous fingering, three representative velocity magnitudes, 0.01 m/s, 0.02 m/s, and 0.04 m/s were selected for systematic analysis. From Figure 7, the viscous fingering patterns at a unified time instant of $t = 0.8$ s are analyzed. At the displacement velocity of 0.01 m/s, the phase interface exhibits relatively regular and smoothed morphology, with a concentrated distribution of air volume fraction, demonstrating stable advancement of the displacement front. This stability phenomenon due to under low-velocity conditions, the fluid interaction between CO₂ and shear-thinning fluids exhibits relatively weak coupling. Consequently, viscous forces dominate the flow dynamics, effectively constraining interfacial deformation and suppressing diffusive mixing between the immiscible phases. When the displacement velocity increases to 0.02 m/s, the interfacial morphology becomes significantly more complex, manifesting dichotomous symmetric fingering branches. Cavitation inception emerges near the fingering roots, accompanied by an expanded spatial distribution of the air volume fraction field. This phenomenon originates from increased inertial forces at higher velocities, which progressively overcome the viscous resistance of the displaced fluid. Consequently, CO₂ more readily penetrates the non-Newtonian phase, disrupting the interfacial stability maintained at low velocities and triggering nonlinear amplification of fingering instabilities. Under the high-velocity condition of 0.04 m/s, the displacement interface transitions into a turbulent-like state. The inferior fingering branch exhibits near-complete detachment from its route structure, while the air volume fraction distribution becomes spatially expanded and fragmented across broader regions of

the flow domain. This intensified flow behavior arises because inertial forces substantially dominate over viscous resistance at elevated velocities. Consequently, CO₂ rapidly penetrates and convectively disperses within the shear-thinning fluid matrix, culminating in complex displacement morphologies characterized by turbulent-like interfacial dynamics. Furthermore, with increasing displacement velocity, the fingering penetration distance exhibits significant augmentation. At 0.04 m/s, the maximum finger extension reaches 0.078 m, exceeding the value observed at 0.01 m/s by a factor of approximately 9.75 (as quantified in Figure 8). At elevated velocities, despite achieving greater penetration distances, the dispersed flow patterns of CO₂ result in extensive spatial bypassing of the shear-thinning fluid. This leads to heightened entrapment of residual non-Newtonian phase within un-swept pore networks, ultimately diminishing macroscopic displacement efficiency. Consequently, the sweep efficiency ϕ under varying velocity conditions was analyzed (as validated in Figure 9). A monotonic decline in ϕ is observed with increasing velocity magnitude. At the velocity of 0.01 m/s, ϕ peaks at 83%, representing the optimal displacement coverage scenario. However, at lower velocities, the constrained sweep coverage combined with sluggish advancement of the displacement front results in diminished volumetric displacement rates per unit time, leading to suboptimal displacement efficiency on a temporal basis. As displacement velocity increases, the sweep coverage expands and the displacement front advances at accelerated rates. This synergistic effect substantially enhances the volumetric displacement flux per unit time, leading to measurable improvements in displacement efficiency. Despite the expanded spatial coverage observed at elevated velocities, runaway fingering instabilities induce severe flow channeling. This results in heterogeneous displacement patterns characterized by diminished sweep efficiency ϕ and elevated retention of residual non-Newtonian fluid within unswept zones. Therefore, in diverse engineering applications, a holistic optimization approach must be adopted to balance sweep efficiency (ϕ) against displacement efficiency. This necessitates strategic selection of operational parameters—particularly displacement velocity and temperature—to maximize hydrocarbon recovery while minimizing residual trapping.

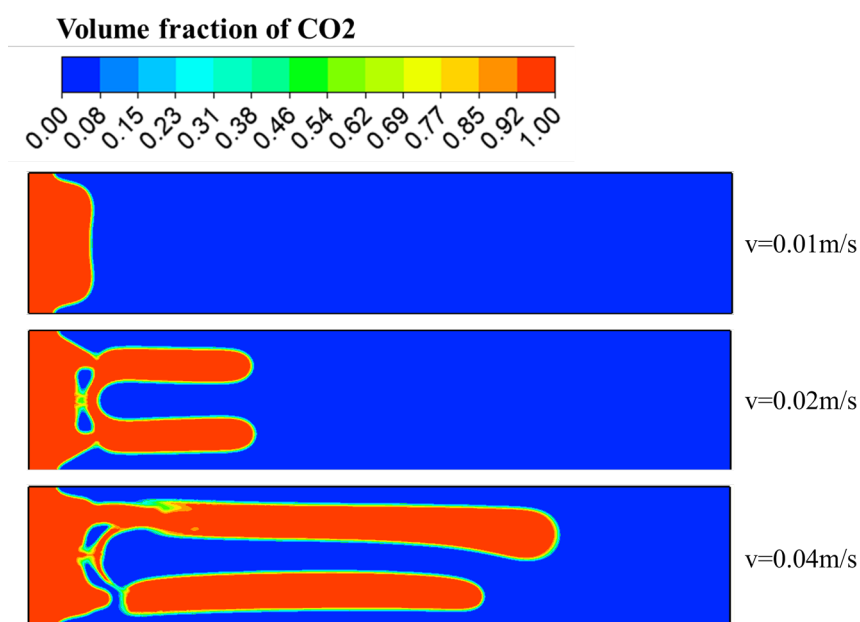


Figure 7. Morphological contours of viscous fingering patterns under distinct velocity magnitudes at $t = 0.8$ s.

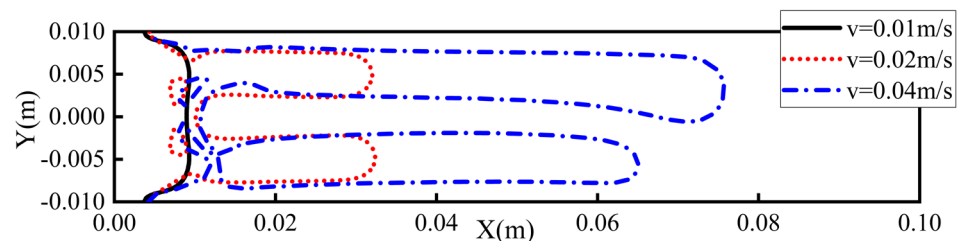


Figure 8. Spatiotemporal evolution and quantitative comparison of viscous fingering front positions across distinct velocity magnitudes (0.01 m/s, 0.02 m/s, 0.04 m/s) at $t = 0.8$ s.

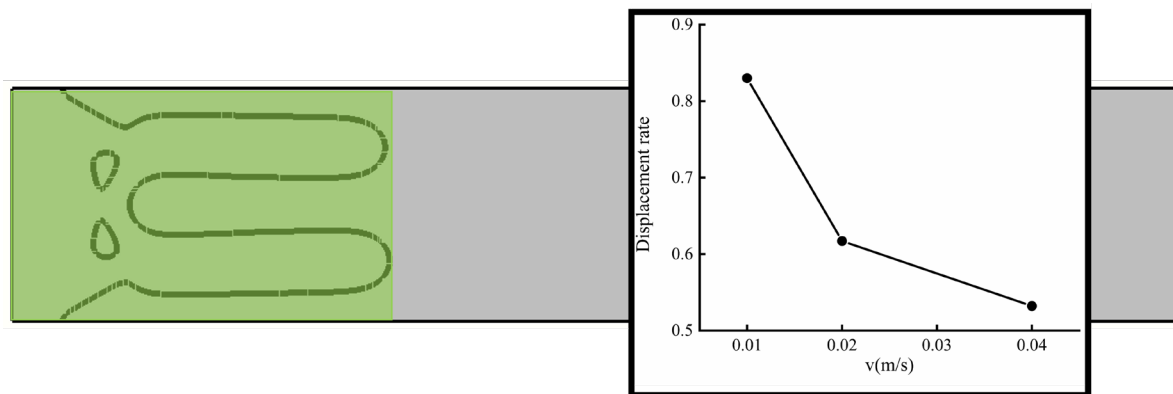


Figure 9. Quantitative comparison of sweep efficiency (φ) across distinct velocity magnitudes (0.01 m/s, 0.02 m/s, 0.04 m/s) at $t = 0.8$ s.

5. Effects of Depth Gradient on Viscous Fingering Instabilities in Modified HSC

It is well-established that once the physical properties of fluids are fixed, the parameter space available for flow manipulation becomes severely constrained. To overcome this limitation, a microscale depth gradient was incorporated into the HSC configuration—providing a novel geometric dimension to modulate classical viscous fingering dynamics. In this modified configuration, the HSC adopts a tapered geometric profile along the direction of fluid displacement. The investigation encompasses two distinct tapered configurations: positive and negative depth gradients (Figure 10). Both configurations exhibit a constant depth gradient magnitude along the primary flow direction.

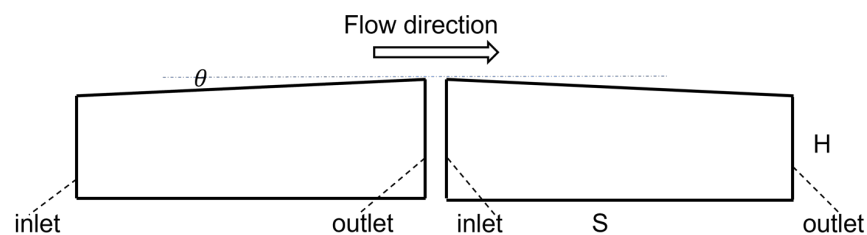


Figure 10. Introducing depth gradient in an HSC: positive gradient (left) and negative gradient (right).

The flow dynamics at $t = 1$ s were analyzed across distinct depth gradient configurations. From Figure 11, it is observed that in the absence of a depth gradient, the displacement of the shear-thinning fluid manifests dichotomous symmetric fingering branches. The interfacial progression exhibits relative uniformity with a stabilized displacement front, while cavitation inception emerges proximal to the bifurcation zone of fingering roots. Quantitatively, this configuration yields the shortest penetration distance (0.078 m at $t = 1$ s), as rigorously quantified in Figure 12. Under positive depth gradient conditions, the displacement of the shear-thinning fluid generates asymmetric fingering structures between

the upper and lower domains. The superior fingering branch exhibits enhanced development compared to its inferior counterpart, with moderate cavitation confined to micro-scale nuclei near the fingering roots. Furthermore, as the positive depth gradient intensifies from 0.5° to 1.0° , the superior fingering branch maintains morphological stability without significant alterations, while the inferior branch undergoes progressive degeneration. Conversely, under negative depth gradient conditions, the inferior fingering branch demonstrates superior development relative to its superior counterpart, accompanied by pronounced cavitation phenomena localized at the fingering roots. Through quantitative comparison in Figure 12, it is demonstrated that as the depth gradient intensifies from -0.5° to -1.0° , the fingering propagation distance exhibits a monotonic increase. At the depth gradient of -1.0° , viscous fingering achieves its maximum penetration length of approximately 0.053 m, representing the farthest displacement extent observed in the study. This phenomenon arises from the flow constriction induced by the negative depth gradient, which hydrodynamically focuses CO_2 into a dominant fingering channel. This confinement generates a high-speed narrow band flow, resulting in localized velocity amplification—as quantitatively visualized in Figure 13. In contrast, the fingering propagation distance under positive depth gradient conditions is less than that achieved with negative gradients yet exceeds the displacement extent observed in the absence of any depth gradient. Consequently, both the direction and magnitude of the depth gradient exert profound influences on viscous fingering morphology and extension dynamics, as governed by the following mechanistic principles, both positive and negative depth gradients selectively enhance the development of laterally preferential fingering branches, whereas the absence of depth gradient yields a symmetric dual-branch pattern with balanced interfacial progression. This phenomenon fundamentally stems from alterations in flow field distribution induced by depth variations along the flow path. The presence of a depth gradient establishes preferential flow pathways in specific spatial orientations, thereby amplifying fingering instabilities through localized flow intensification.

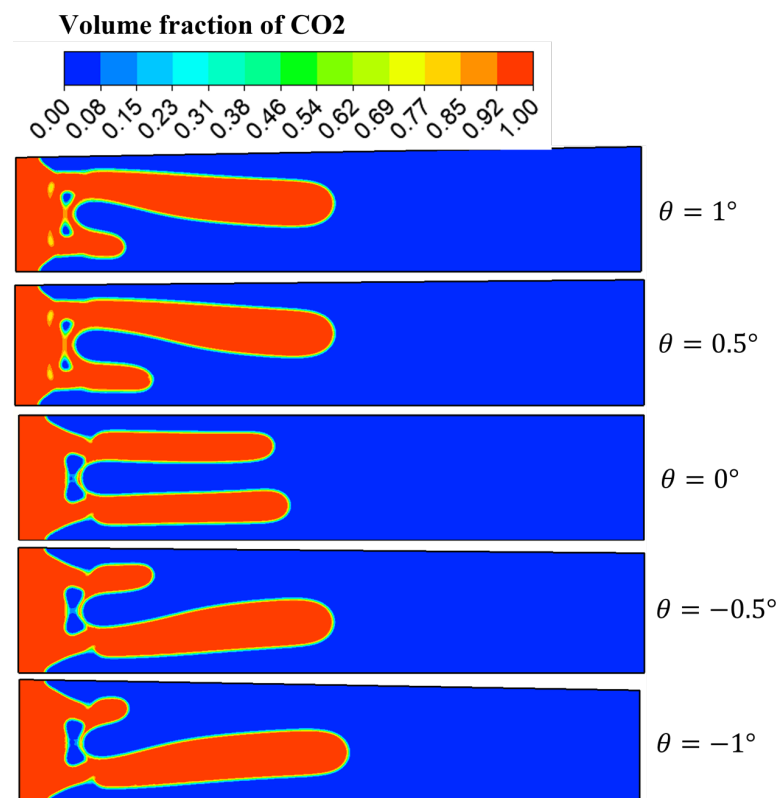


Figure 11. Contour maps of fluid phase distribution for shear-thinning fluids under distinct depth gradient configurations.

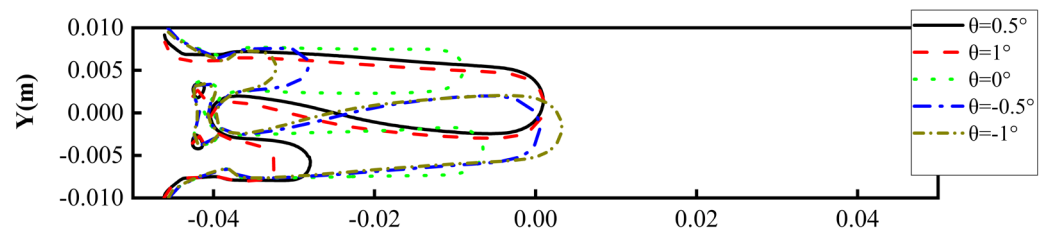


Figure 12. Quantitative comparison of viscous fingering front positions across distinct depth gradients at $t = 1$ s.

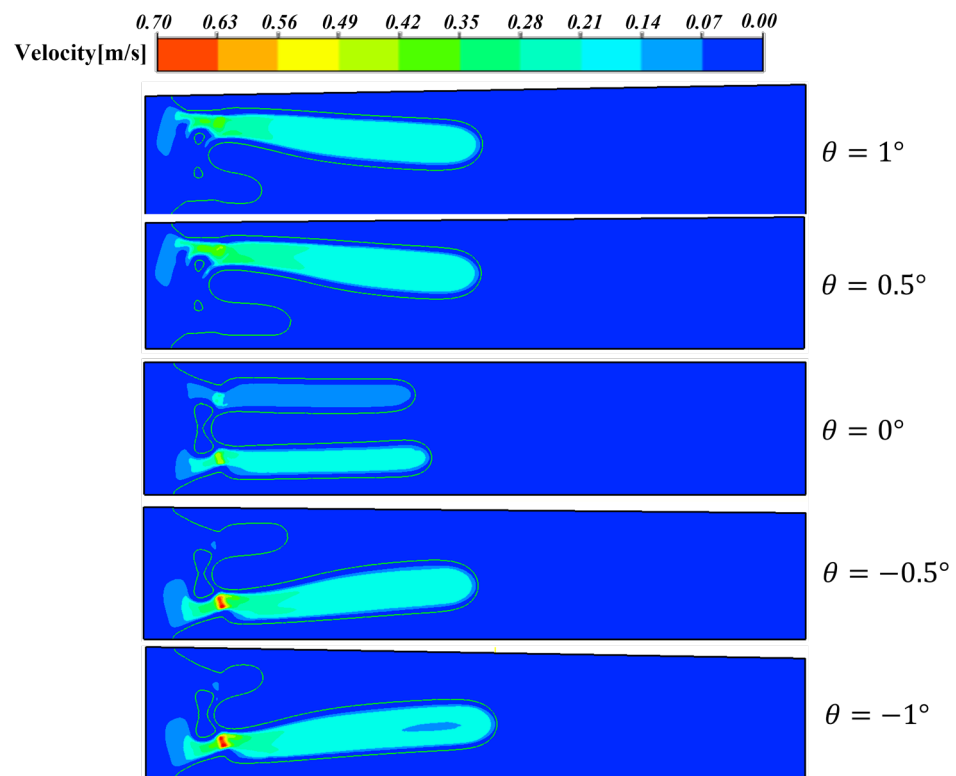


Figure 13. Visualization of velocity field distributions under distinct depth gradient configurations at $t = 1$ s.

From the velocity contour maps in Figure 13, it is quantitatively evident that asymmetric velocity distributions persist between dual fingering branches across all depth gradient configurations, including the baseline case with zero gradient. Particularly under depth gradient conditions, the velocity magnitude within degenerated fingering branches approaches quasi-stagnant flow regimes. From Figure 14, it is quantitatively demonstrated that as the depth gradient transitions from negative to positive values (-1° to $+1^\circ$), the maximum velocity within fingering structures undergoes progressive attenuation. This reduction stems from the geometric transition of the flow conduit from convergent (narrowing) to divergent (widening) profiles, which fundamentally decelerates flow velocities through hydrodynamic expansion effects. Although the flow velocity under positive depth gradient conditions is minimized, the geometric expansion of the flow conduit significantly reduces viscous resistance. This facilitates focused advancement of CO_2 along the dominant fingering channel, ultimately achieving greater penetration distance compared to scenarios devoid of depth gradients. Therefore, depth gradients fundamentally modulate viscous fingering morphology and propagation dynamics by altering the geometric confinement of flow conduits, thereby inducing strategic redistribution of velocity fields. In engineering applications, deliberate modulation of depth gradients within flow conduits enables

strategic control over displacement behaviors, thereby facilitating targeted suppression or triggering of interfacial instabilities as required by operational objectives.

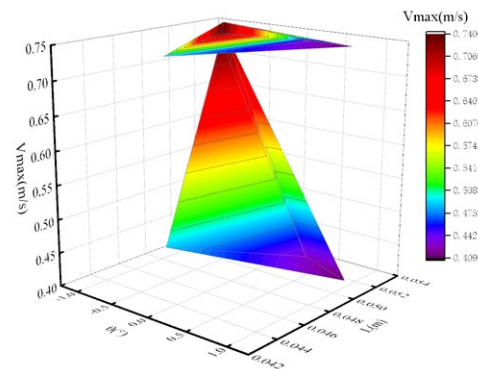


Figure 14. Quantitative analysis of fingering penetration distance and maximum intra-fingering velocity under distinct depth gradients.

6. Conclusions

In this study, a numerical simulation methodology was employed to investigate the process of CO₂ displacing shear-thinning fluids within a three-dimensional HSC. Distinct investigations were systematically conducted to quantify the effects of velocity magnitude and temperature conditions on the displacement dynamics. Furthermore, to achieve targeted modulation of viscous fingering processes, the three-dimensional HSC was engineered with modified geometric configurations incorporating variable depth gradients. The principal findings are summarized as follows:

- (1) Through comparative analysis of displacement behaviors at 300 K, 305 K, and 320 K, it is consistently observed that symmetrically bifurcated fingering structures develop across all temperature conditions, accompanied by cavitation nucleation phenomena localized at the fingering roots. However, with increasing temperature, the fingering propagation distance decreases, the root thickness of the fingering structures increases, and the intermediate cavitation zone progressively contracts. Furthermore, the sweep efficiency φ exhibits a positive correlation with increasing temperature, indicating a reduction in residual non-Newtonian fluid within the displaced zones and a consequent enhancement in displacement efficiency. Due to the increase in temperature, the kinetic energy of molecular thermal motion is enhanced, breaking the existing weak interactions, resulting in a macroscopic decrease in viscosity, which helps CO₂ to be better absorbed in the reservoir. In addition, an increase in temperature will accelerate the diffusion of molecules at the interface, making it easier for displacement phase molecules to diffuse into the displaced phase, expanding the displacement range and improving displacement efficiency. This holds profound strategic significance for enhancing hydrocarbon recovery in both oil and gas reservoirs. The thermally expanded sweep coverage enables efficient mobilization and displacement of previously inaccessible fluid phases trapped in complex pore networks, thereby unlocking substantial volumes of challenging reserves.
- (2) To investigate the influence of velocity on fingering, three representative velocities of 0.01 m/s, 0.02 m/s, and 0.04 m/s were selected. At the velocity of 0.01 m/s, the displacement interface is relatively smooth, showing a relatively stable advancing pattern of the displacement front. When the velocity increases, the displacement interface becomes more disordered, and the distribution of the air volume fraction becomes more scattered. This phenomenon arises from a fundamental shift in hydrodynamic dominance: at lower velocities, viscous forces govern flow behavior, while increasing velocity progressively amplifies inertial effects. The dynamic interplay between these

competing forces dictates the evolution of interfacial morphology, sweep coverage, and displacement efficiency. Moreover, under low-velocity conditions, while sweep efficiency ϕ reaches its peak value, the sluggish advancement of the displacement front results in diminished volumetric displacement rates per unit time, leading to suboptimal displacement efficiency on a temporal basis. When the velocity increases, the sweep coverage expands; however, due to excessive viscous fingering, this results in a non-uniform displacement process, lower sweep efficiency, and a higher residual volume of non-Newtonian fluid. Therefore, in various engineering applications, both sweep efficiency and displacement efficiency should be comprehensively considered to determine (or achieve) an appropriate overall recovery efficiency.

- (3) In the variant study of the classical HSC model, four depth gradients, -0.5° , -1° , $+0.5^\circ$ and $+1^\circ$, were introduced. It was found that both the direction and magnitude of the depth gradient significantly influence the morphology and extension length of viscous fingering. Both positive and negative depth gradients promote the development of fingering on one side. In the absence of a gradient, the two fingers develop relatively uniformly. This phenomenon fundamentally stems from flow field redistribution induced by depth variations along the flow conduit. The presence of a depth gradient establishes preferential flow pathways in specific spatial orientations, thereby amplifying fingering instabilities through localized flow intensification. Furthermore, as the depth gradient changes from negative to positive, that is from -1° to $+1^\circ$, the maximum velocity within the fingers gradually decreases. This occurs because the increasing gradient magnitude transforms the flow channel from a narrowing configuration to a widening one, thereby causing a reduction in velocity. Therefore, depth gradients fundamentally modulate the morphology and propagation of viscous fingering by dynamically altering the geometric confinement of flow conduits, thereby strategically reconfiguring the spatial distribution of velocity fields. In engineering applications, deliberate modulation of depth gradients within flow conduits enables strategic control over displacement dynamics, facilitating targeted suppression or triggering of interfacial instabilities as required by operational objectives.

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References

1. Homsy, M.G. Viscous Fingering in Porous Media. *Annu. Rev. Fluid Mech.* **1987**, *19*, 271–311. [[CrossRef](#)]
2. Bensimon, D.; Kadanoff, L.P.; Liang, S.; Shraiman, B.I.; Tang, C. Viscous flows in two dimensions. *Rev. Mod. Phys.* **1986**, *58*, 977. [[CrossRef](#)]

3. Ganesh, A.; Douarche, C.; Auradou, H. Active Saffman-Taylor Viscous Fingering. *Phys. Rev. Lett.* **2025**, *134*, 128301. [[CrossRef](#)] [[PubMed](#)]
4. Fahad, M.; Hussain, F.; Rahman, S.S.; Cinar, Y. Experimental investigation of upscaling relative permeability for two phase flow in fractured porous media. *J. Pet. Sci. Eng.* **2017**, *149*, 367–382. [[CrossRef](#)]
5. Arab, D.; Kantzas, A.; Bryant, S.L. Water flooding of oil reservoirs: Effect of oil viscosity and injection velocity on the interplay between capillary and viscous forces. *J. Pet. Sci. Eng.* **2020**, *186*, 106691. [[CrossRef](#)]
6. Lyu, S.; Hwang, W. Selective superhydrophilic/phobic coating using capillary pressure for positive-displacement nanoliter dispensing. *Surf. Coat. Technol.* **2015**, *277*, 258–261. [[CrossRef](#)]
7. Ji, S.; Li, H.; Wang, G.; Lu, T.; Ma, W.; Wang, J.; Zhu, H.; Xu, H. Rheological behaviors of a novel exopolysaccharide produced by *Sphingomonas* WG and the potential application in enhanced oil recovery. *Int. J. Biol. Macromol.* **2020**, *162*, 1816–1824. [[CrossRef](#)]
8. Chen, X.; Li, Y.; Liu, Z.; Trivedi, J.; Tang, Y.; Sui, M. Visualized investigation of the immiscible displacement: Influencing factors, improved method, and EOR effect. *Fuel* **2023**, *331*, 125841. [[CrossRef](#)]
9. Chen, Z.; Schmid, R.; Wang, X.; Fu, M.; Han, Z.; Fan, Q.; Scheer, E.; Huang, M.; Nielaba, P.; Cölfen, H. Growth strategy for solution-phase growth of two-dimensional nanomaterials via a unified model. *Nat. Synth.* **2023**, *2*, 670–677. [[CrossRef](#)]
10. Abu Jarad, N.; IWeitz, J.; Didar, T. Advancements in Surface Modification Strategies of Blood-contacting Biomaterials to Improve Biocompatibility and Tissue Integration. *ChemRxiv* **2023**. [[CrossRef](#)]
11. Zhang, Z.; Wei, B.; Hu, Y.; Yang, D.; Ma, D.; Huang, S. Extraordinary sensitive mechanochromic hydrogels for visually detecting ultrasmall pressure. *Cell Rep. Phys. Sci.* **2023**, *4*, 101387. [[CrossRef](#)]
12. Kargozarfard, Z.; Riazi, M.; Ayatollahi, S. Viscous fingering and its effect on areal sweep efficiency during waterflooding: An experimental study. *Pet. Sci.* **2019**, *16*, 105–116. [[CrossRef](#)]
13. Gorell, B.S.; Homsy, M.G. A Theory of the Optimal Policy of Oil Recovery by Secondary Displacement Processes. *SIAM J. Appl. Math.* **2006**, *43*, 79–98. [[CrossRef](#)]
14. Orr, F.M.; Taber, J.J. Use of Carbon Dioxide in Enhanced Oil Recovery. *Science* **1984**, *224*, 563–569. [[CrossRef](#)]
15. Regaieg, M.; McDougall, S.; Bondino, I.; Hamon, G. Finger Thickening during Extra-Heavy Oil Waterflooding: Simulation and Interpretation Using Pore-Scale Modelling. *PLoS ONE* **2017**, *12*, e0169727. [[CrossRef](#)]
16. Raut, S.; Raihan, M.K.; Song, Y.; Xuan, X. Fluid shear thinning effects on particle focusing in a spiral microchannel. *Phys. Fluids* **2024**, *36*, 112036. [[CrossRef](#)]
17. Yadali Jamaloei, B.; Babolmorad, R.; Kharrat, R. Visualization and analysis of viscous fingering in alcohol-assisted surfactant waterflooding of heavy oil in a two-dimensional sandstone micromodel. *Fuel* **2016**, *184*, 169–179. [[CrossRef](#)]
18. Chuoke, R.L.; Van Der Meurs, P.; Van Der Poel, C. The instability of slow, immiscible, viscous liquid-liquid displacement in permeable media. *Trans. AIME* **1959**, *216*, 188–194. [[CrossRef](#)]
19. Hamid, A.A.S.; Muggeridge, H.A. Analytical solution of polymer slug injection with viscous fingering. *Comput. Geosci.* **2018**, *22*, 711–723. [[CrossRef](#)]
20. Beteta, A.; Sorbie, K.S.; Skauge, A. Immiscible Viscous Fingering: The Simulation of Tertiary Polymer Displacements of Viscous Oils in 2D Slab Floods. *Polymers* **2022**, *14*, 4159. [[CrossRef](#)] [[PubMed](#)]
21. Salmo, I.C.; Sorbie, K.S.; Skauge, A.; Alzaabi, M.A. Immiscible Viscous Fingering: Modelling Unstable Water–Oil Displacement Experiments in Porous Media. *Transp. Porous Media* **2022**, *145*, 291–322. [[CrossRef](#)]
22. Sajjad, H.R.; Dani, O.; Ying, L.; Lai, C.Y.; Lu, N.B.; Datta, S.S.; Stone, H.A.; Shokri, N. Suppressing viscous fingering in structured porous media. *Proc. Natl. Acad. Sci. USA* **2018**, *115*, 4833–4838. [[CrossRef](#)]
23. Zhao, B.; Mohanty, K.K. Effect of wettability on immiscible viscous fingering in porous media. *J. Pet. Sci. Eng.* **2019**, *174*, 738–746. [[CrossRef](#)]
24. Esmaeilpour, M.; Gholami Korzani, M. Analyzing Impacts of Interfacial Instabilities on the Sweeping Power of Newtonian Fluids to Immiscibly Displace Power-Law Materials. *Processes* **2021**, *9*, 742. [[CrossRef](#)]
25. Redapangu, R.P.; Vanka, S.; Sahu, C.K. Multiphase lattice Boltzmann simulations of buoyancy-induced flow of two immiscible fluids with different viscosities. *Eur. J. Mech./B Fluids* **2012**, *34*, 105–114. [[CrossRef](#)]
26. Bakharev, F.; Campoli, L.; Enin, A.; Matveenko, S.; Petrova, Y.; Tikhomirov, S.; Yakovlev, A. Numerical Investigation of Viscous Fingering Phenomenon for Raw Field Data. *Transp. Porous Media* **2020**, *132*, 443–464. [[CrossRef](#)]
27. Yang, X.; Tang, Y.; Li, M.; Li, C.; Wang, M.; Li, X.; Zhao, J. Effect of shear-thinning of non-Newtonian fluid on the crossover from capillary fingering to viscous fingering in porous media. *Phys. Lett. A* **2022**, *449*, 128364. [[CrossRef](#)]
28. Ahmadikhamsi, S.; Golfier, F.; Oltean, C.; Lefèvre, E.; Bahrani, S.A. Impact of surfactant addition on non-Newtonian fluid behavior during viscous fingering in Hele-Shaw cell. *Phys. Fluids* **2020**, *32*, 012103. [[CrossRef](#)]
29. Shokri, H.; Kayhani, H.M.; Norouzi, M. On the miscible thermo-viscous fingering instability of non-Newtonian fluids in heterogeneous porous media. *Rheol. Acta* **2019**, *58*, 755–769. [[CrossRef](#)]
30. Logvinov, A.O. Radial Viscous Fingering in Case of Poorly Miscible Fluids. *Transp. Porous Media* **2018**, *124*, 495–508. [[CrossRef](#)]

31. Mafi, M.; Qin, Z.; Wu, Y.; Lyu, S.-K.; Ma, C. Research on the Interfacial Instability of Non-Newtonian Fluid Displacement Using Flow Geometry. *Coatings* **2023**, *13*, 1848. [[CrossRef](#)]
32. Singh, A.; Pandey, K.M.; Singh, Y. CFD analysis of viscous fingering in Hele-Shaw cell for air-glycerin system. *Mater. Today Proc.* **2021**, *45*, 6381–6385. [[CrossRef](#)]

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