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Perspective

Immiscible fluid displacement: From pore doublets to porous media

Zhongzheng Wang

School of Mechanical, Medical and Process Engineering, Queensland University of Technology, QLD 4001, Australia

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Abstract:
Understanding multiphase flow in porous media is essential for diverse engineering applications, from large-scale carbon geosequestration to small-scale fuel cells. Pore-doublet models, despite their geometrical simplicity, offer a powerful framework to study the complex interplay between capillary and viscous forces during multiphase flow. This work revisits some recent advances in the understanding of immiscible fluid displacement processes provided by pore-doublet studies, and highlights their ability to capture key interfacial phenomena such as Haines jumps and to map displacement regimes through phase diagrams. While these models do not capture the full heterogeneity of real porous systems, they often exhibit strong agreement with larger-scale observations. Recent advances in microfluidics fabrication techniques further enhance the capability and efficiency of using pore-doublet models to investigate immiscible displacement processes. Several promising research directions for extending pore-doublet approaches are identified.

1. Introduction

Multiphase flow in porous media is a ubiquitous phenomenon and relevant to many engineering processes, ranging from large-scale carbon geosequestration and underground hydrogen storage (Szulczewski et al., 2012; Heinemann et al., 2021) to microscale applications such as fuel cells and fluid manipulation in microfluidic devices (Wang et al., 2023; Wang et al., 2024). Due to its strong relevance to reducing carbon emission and energy transition, and the presence of rich physical mechanisms at pore scale, understanding fluid flow processes in porous media is practically important, fundamentally interesting, and scientifically challenging.

Given the opaque, disordered, and rough nature of most natural rocks, micromodels (or microfluidic devices) with precise control over pore geometry and surface properties offer an excellent avenue for advancing our understanding of multiphase flow (Datta et al., 2023). Since the pioneering work of Chatzis and Dullien (1983) in the early 1980s, the pore-doublet model — a parallel arrangement of capillary tubes — has offered a simplified yet robust framework for studying the dynamics of fluid-fluid displacement processes. Recent advances using the pore-doublet models have provided critical insights into the interfacial dynamics and preferential flow, enabling improved predictions of fluid movement in heterogeneous porous systems (Fig. 1).

This work first reviews recent advances in the understanding of immiscible fluid displacement using the pore-doublet approach from two key perspectives: (1) interfacial dynamics and Haines jumps, which focus on interfacial motion and pore-scale mechanisms, and (2) phase diagrams for preferential flow, which highlight how findings from pore-doublet systems can inform flow behaviour in large-scale porous media. Finally, several potential future research directions within the context of the pore-doublet model are discussed.

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*Corresponding author.
E-mail address: zhongzheng.wang@qut.edu.au (Z. Wang).

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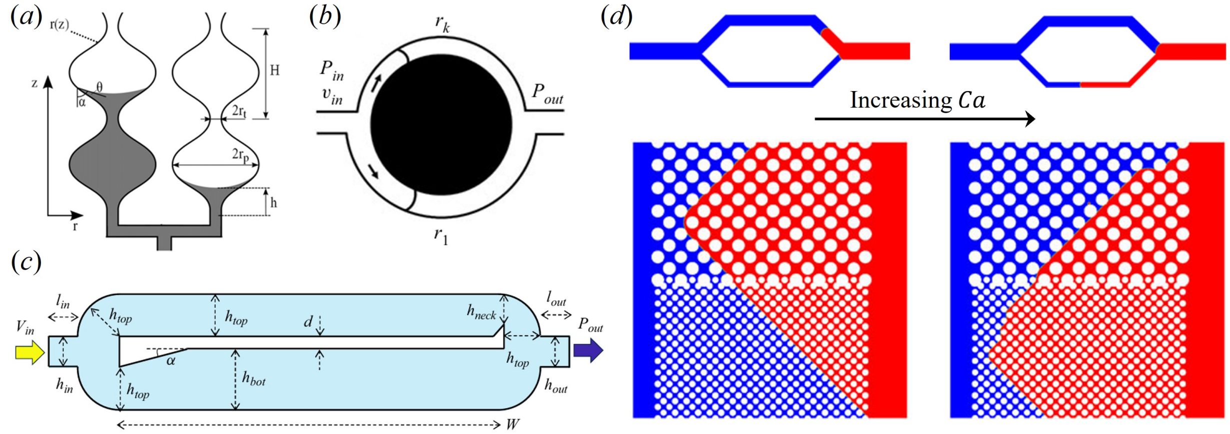

Fig. 1. Pore doublets and porous media. (a) a pore doublet with a pair of interconnected sinusoidal capillaries (Moebius et al., 2012), (b) a pore doublet with two uniform channels with different radii (Liu and Wang, 2022), (c) a dual-channel system with extra barriers (geometrical constrictions) to achieve controlled Haines jumps (Wang et al., 2025) and (d) an example of pore-doublet results having implications on porous media flow during unfavourable displacement processes (Gu et al., 2021).

2. Interfacial dynamics and haines jumps

One interesting aspect of multiphase flow in porous media is the intermittent flow regime, where long intervals of stagnation followed by rapid fluid motion are observed (Måløy et al., 1992; Moura et al., 2020). Pore-doublet investigations in hydraulically coupled sinusoidal capillaries have experimentally revealed the "pinning-jumping" behaviour, known as "Haines jumps/instabilities" (Haines et al., 1930), where the movement of fluid fronts can exhibit rapid interfacial velocities-sometimes exceeding 50 times the mean front velocity (Moebius et al., 2012). These observations highlight potentially significant inertial effects, such that the pore-scale fluid displacement can deviate from the gradual motion assumed by traditional viscous dissipation models, e.g., the conventional Darcy-based models.

Fundamentally, the dynamics of a Haines jump is a manifestation of the competition between viscous and capillary forces at the pore scale. Recent investigations into the slow injection processes in dual-channel systems show that the meniscus movement velocity during Haines jumps can increase, decrease, or remain constant, depending on the viscosity ratio of fluids (Wang et al., 2025). This work subsequently establishes quantitative correlations between interfacial dynamics and the competing forces of capillary and viscous forces, enabling the simultaneous determination of the fluid viscosity and interfacial tension by analysing the meniscus movement velocities.

Despite Haines jumps have been mostly studied in the context of drainage processes (solid being non-wetting to the invading fluid) in rigid porous media, the rapid interface movement accompanied by fast fluid redistribution also appears during imbibition, as demonstrated in regular cellular structure and disordered porous media (Dudukovic et al., 2021; Primkulov et al., 2022). Additionally, by employing microfluidic experiments with single or multiple connected capillaries, Sun and Santamarina (2019) identified several conditions that can be controlled to trigger Haines jumps, including the deformability of solid, compressibility of the fluid and the solid geometry.

3. Phase diagrams for preferential flow

Often, underground geological formations exist in the form of layers, which are associated with contrasting permeabilities that impose challenges in predicting the fluid transport processes. Even in the pore-doublet system with identical daughter channels, non-uniform fluid advancement with strong preferential flow can occur (Al-Housseiny et al., 2014).

Preferential flow in dual-permeability systems (as in the pore doublets or layered porous media with a permeability contrast) has been systematically explored through mathematical and computational models. Simulations using the lattice Boltzmann method show that imbibition favours low-permeability zones at low capillary numbers but shifts to high-permeability zones as capillary numbers increase (Gu et al., 2021). A modified capillary number, incorporating channel width and length, reveals critical thresholds for maximising imbibition efficiency in the capillary number-viscosity ratio diagram.

Expanding on this approach, comprehensive phase diagrams have been developed to capture the combined effects of viscosity ratio, capillary number, wetting conditions, and boundary conditions (Liu and Wang, 2022). The comparison between the phase diagrams of pore doublets and those of porous media suggests that insights from these simplified models can offer a qualitative understanding of flow preferences in more complex, disordered porous systems. More recently, analytical solutions have been derived showing that displacement processes are dominated by capillary number, viscosity ratio, and radius ratio of the pore doublets (Shan et al., 2023). Such findings identified the critical capillary numbers for optimal displacement where the invading fluids in both channels break through simultaneously, providing guidance for improving displacement efficiency in porous media.

Overall, although the findings from pore-doublet models usually cannot be directly generalised to porous media flows, they often exhibit strong qualitative agreement and thus provide a rigorous framework for explaining and understanding the flow behaviour and regimes in heterogeneous porous media.

4. Conclusion and prospect

This work has highlighted how pore-doublet models, despite their simplicity, serve as a powerful framework to unravel the complex physics of immiscible fluid displacement in porous media. Pore-doublet studies have provided valuable insights into how the interplay between fluid properties, flow conditions, and the geometry of pore structure affect multiphase flow.

Recent advances in microfluidic fabrication have enhanced our ability to test and validate pore-doublet model predictions. Looking ahead, there are several promising research directions worth exploring:

(1) Integrating deformable boundaries, non-uniform wettability conditions, or variable injection protocols in pore-doublet multiphase flow, which may better reflect conditions in natural and engineered environments. These factors are particularly relevant to applications such as enhanced oil recovery, carbon geosequestration, and hydrogel-based biomedical devices.

(2) Extending to non-Newtonian fluids (e.g., Carreau fluids), which are increasingly relevant in both biological and industrial contexts, including mucus transport in airways, polymer flooding in subsurface reservoirs, and additive manufacturing.

(3) Bridging the pore-doublet insights with continuum-scale descriptions, which is essential for developing improved upscaling strategies in multiphase flow modelling. In particular, understanding the extent to which the results from pore doublets can be quantitatively generalised to porous media will be critical for better applying the knowledge gained in pore doublet studies.

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Conflict of interest

The author declares no competing interest.

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