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Perspective

Impact of pore-scale corner and film flows on macroscopic transport in porous media

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Abstract:
Capillary pressure-saturation and relative permeability curves are crucial for predicting multiphase fluid flow behavior in porous media, directly influencing the efficiency and reliability of subsurface engineering applications. At low saturations, the wetting-phase flow transitions from bulk displacement to being governed by corner and film flows along pore surfaces. Recent experiments and pore-scale simulations have shown that these microscale flow mechanisms preserve fluid connectivity and continue to influence macroscopic transport behavior, even after bulk flow pathways are no longer active. This work synthesizes current experimental and computational findings, highlighting how the formation and persistence of microscale flow networks made of corner and film flows influence capillary pressure and relative permeability curves, especially by enhancing wetting-phase connectivity at low wetting-phase saturations. Finally, key directions for future research are proposed to further enhance the understanding of how microscale film and corner flows influence macroscopic multiphase flow characteristics.

1. Introduction

Capillary pressure-saturation and relative permeability curves play key roles in every continuum-scale description of multiphase flow in porous media (Pinder and Gray, 2008; Lan et al., 2025). The characteristics of these curves govern the rate and extent of subsurface fluid migration. Accurate capillary pressure-saturation and relative permeability functions therefore underpin the design and risk assessment of a wide spectrum of subsurface technologies, from maximizing hydrocarbon recovery in mature petroleum reservoirs (Wang et al., 2025), to forecasting the storage capacity and security of geological CO_2 sequestration sites (Juanes et al., 2006; Hu et al., 2017), to predicting injectivity and deliverability in large-scale underground hydrogen storage (Yang et al., 2023). Since these curves govern phase pressures, mobilities, and trapping thresholds, even modest inaccuracies can propagate into significant uncertainties in predicted production rates, plume extents, and long term containment.

At low wetting-phase saturations, the dominant flow regime shifts from piston-like advancement through pore centers to film flow along grain surfaces and corner flow within angular pore edges (Tuller and Or, 2001). During drainage, the wetting phase does not become immobile after bulk displacement. Instead, it reconnects through a lattice of thin films, corner filaments, and intermittent liquid bridges (Tuller and Or, 2001). This microscale network forms an auxiliary

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conduit that continues to transport the wetting phase long after bulk flow pathways have closed (Hoogland et al., 2016). At low wetting-phase saturations, once corner and film flow pathways are established, capillary trapped wetting phase clusters can drain through these conduits. This drainage lowers the residual saturation on capillary pressure curves and enhances the wetting-phase relative permeability (Lan et al., 2024).

This perspective synthesizes recent insights into how micron scale corner and film flows reshape macroscopic transport behavior in porous media. It begins by examining how these flow pathways preserve phase connectivity and enhance fluid mobility at low saturations. The analysis then extends to their impact on capillary pressure and relative permeability relationships. Building on these findings, this study concludes by identifying key research directions for incorporating corner and film flows physics into reservoir-scale models.

2. Impact of corner and film flows on fluid transport and connectivity

In porous media, strongly wetting fluids preferentially occupy pore corners due to capillary forces or form films adsorbed on grain surfaces through van der Waals and other surface interactions, with typical film thicknesses ranging from microns to nanometers (Levaché and Bartolo, 2014; Lei et al., 2024). Under strong imbibition conditions, corner and film flows occur rapidly as the wetting fluid advances along pore walls and corners ahead of the main meniscus, forming continuous filaments or films (Zhao et al., 2016; Hu et al., 2018; Cai et al., 2021). In contrast, during drainage, fluid invasion generally proceeds via piston-like displacement at the front, leaving behind residual wetting fluid confined to corners and thin films (Hoogland et al., 2016). Because the porous medium is initially saturated with the wetting fluid, the trailing corner and film flows during drainage are significantly slower than the leading corner and film flows under strong imbibition (Reis et al., 2023; Cai et al., 2025).

Although corner and film flows occupy only a small fraction of the total fluid volume, their impact on fluid connectivity is disproportionately significant. By linking pores that would otherwise become isolated by the invading non-wetting phase, these thin films and corner pathways help preserve the continuity of the wetting phase (Reis et al., 2025). Experimental observations have visually demonstrated that wetting fluids form continuous filaments along pore corners behind the main invasion front, sustaining connectivity even after the non-wetting phase percolates through the system. For example, through X-ray imaging experiments conducted by Hoogland et al. (2016) following the initial piston-like invasion, wetting-phase fluid transport transitions to slow corner and film flows along solid surfaces (Fig. 1(a)). Capillary bridges formed through these films allow connected wetting-fluid clusters to drain farther than disconnected ones (Moura et al., 2019) (Fig. 1(b)). Confocal-microscopy studies further reveal that trapped wetting phases can remain hydraulically connected to the bulk flow via corner-bridge networks (Lan et al., 2024) (Fig. 1(c)).

This persistent network of corner and film flows plays a critical role in enhancing fluid transport at saturations traditionally considered immobile, fundamentally reshaping our understanding of low-saturation flow dynamics. By sustaining connectivity through microscopic pathways, these flows enable continued fluid redistribution even after bulk flow channels have been disrupted, allowing for non-negligible fluxes at low wetting-phase saturations. Incorporating these mechanisms into continuum-scale models substantially improves the accuracy of predictions related to fluid migration and recovery in multiphase flow in porous media.

3. Influence on capillary pressure and relative permeability curves

Capillary pressure and relative permeability curves are fundamental tools widely used to characterize multiphase fluid behavior in porous media. Capillary pressure curves describe the equilibrium pressure required to achieve a given saturation level (Wang and Tokunaga, 2015), while relative permeability curves quantify the ease with which each fluid phase flows when multiple phases are present. As introduced in Section 2, the wetting phase left behind the invasion front can form corner and film flow paths. These conduits reconnect otherwise capillary-trapped wetting phase clusters, permitting their continued drainage, which lowers the residual saturation on the capillary pressure curve and increases the wetting-phase relative permeability. To investigate the impact of corner and film flows on macroscopic capillary pressure and relative permeability curves, the experimental system must observe these flows at the pore scale and simultaneously record/control the capillary pressure at the Darcy scale over a long equilibration period (Lan et al., 2024).

The influence of corner and film flows on capillary pressure curves can be understood in two distinct stages: before and after breakthrough during drainage. Prior to breakthrough, drainage is dominated by bulk flow (Hoogland et al., 2016), and capillary pressure curves exhibit minimal differences with and without the presence of corner or film flows. After breakthrough, however, bulk displacement of the wetting phase is diminished, and continued drainage relies heavily on connectivity maintained through corner and film pathways as capillary pressure increases (Tuller and Or, 2001). These microscale flows enable the wetting phase to continue redistributing, leading to a significant reduction in residual saturation at low saturation levels. Both experimental and computational studies suggest that this reduction is more pronounced in porous media with lower porosity and higher shape factors (i.e., the ratio of system width to length) (Lan et al., 2024).

Relative permeability curves are also shaped by the presence of corner and film flows. For the wetting phase, these microscale flow paths help maintain hydraulic connectivity even after bulk pathways break down, leading to a more gradual decline of relative permeability than predicted by traditional piston-like displacement models. PThe model considering corner and film flows capture this behavior as a distinct "second slope" on wetting-phase relative permeability curve: above the crossover saturation, flow is dominated by bulk pathways, while below this point, a lower but persistent conductivity is sustained by films and corner filaments (Tuller

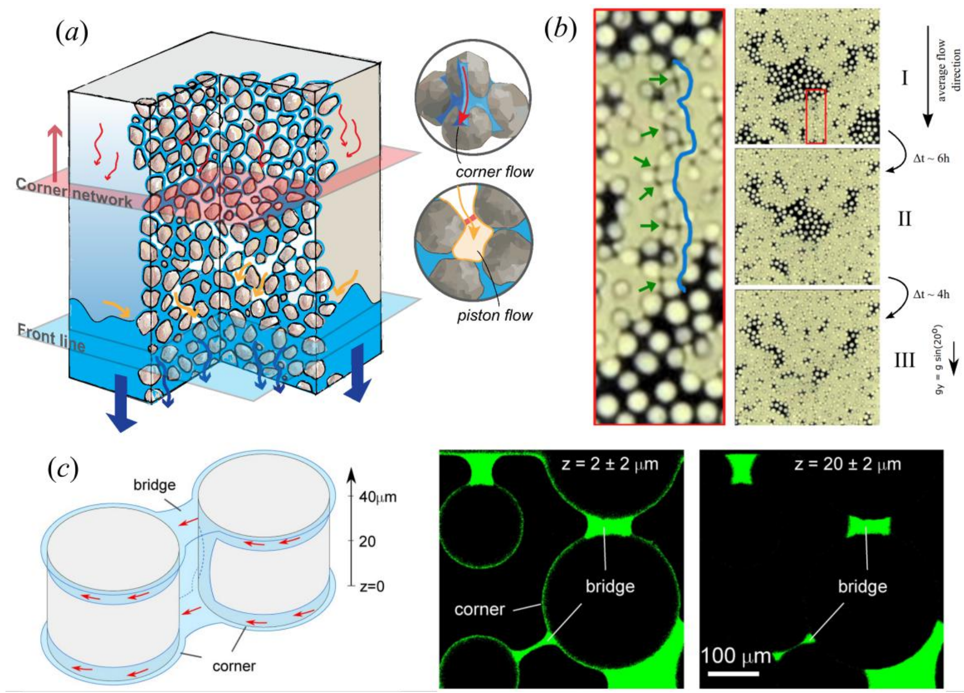

Fig. 1. Corner and film flows in porous media. (a) Schematic of corner and film flow networks that form after piston-like drainage (Hoogland et al., 2016), (b) the draining of trapped wetting-phase clusters through film flow (Moura et al., 2019) and (c) schematic of corner-bridge flow path and the corresponding confocal laser scanning microscope observation (Lan et al., 2024).

and Or, 2001). For the non-wetting phase, the presence of wetting-phase films and corner filaments reduces the effective cross-sectional area available for flow, subtly decreasing its relative permeability. This effect is especially pronounced at intermediate saturations, where wetting films occupy regions critical for non-wetting phase transport (Zhang et al., 2023).

Overall, corner and film flows preserve wetting-phase connectivity at low saturations, reduce residual saturation, and significantly modify the shape and magnitude of both capillary pressure-saturation and relative permeability curves.

4. Conclusion and prospects

This perspective synthesizes recent insights into how microscale corner and film flows influence macroscopic multiphase fluid behavior in porous media. Both experimental and computational studies consistently show that these flow mechanisms maintain wetting-phase connectivity, reduce residual saturation, and significantly alter capillary pressure and relative permeability curves-particularly at low saturations.

Corner and film flows reduce residual saturations by enabling drainage pathways beyond traditional bulk flow mechanisms. These microscale pathways allow previously trapped wetting phases to reconnect and drain, shifting capillary pressure curves toward lower saturations and altering relative permeability behavior by sustaining wetting-phase connectivity even after bulk flow is disrupted.

Looking ahead, several key research directions are critical for advancing our understanding of how microscale fluid interactions govern macroscopic multiphase flow in porous media:

1) Gravity plays a complex role in enhancing or suppressing corner- and film-driven flows, depending on system orientation and fluid density contrasts. While steep vertical pressure gradients can accelerate the drainage of trapped clusters, gravity may also stabilize interfaces and inhibit phase connectivity. Disentangling these competing effects is essential for predicting fluid transport in natural and engineered porous media.
2) Extending insights to three-dimensional porous media is critical. Most current understanding stems from quasi-two-dimensional models, which may underestimate the extent and impact of corner and film flows. In three-dimensional porous media, enhanced geometrical connectivity likely supports more frequent and effective microscale flow pathways. This could amplify their influence on fluid distribution, reduce residual wetting phase saturations, and significantly modify relative permeability behavior. Bridging this dimensional gap is crucial for developing more realistic and predictive models.

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Conflict of interest

The authors declare no competing interest.

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