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The impact of roughness and wettability on imbibition in a fracture

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Understanding the physics of immiscible fluid-fluid displacement in fractures is central to many applications, including hydrocarbon recovery, groundwater contamination by nonaqueous liquids, and geologic CO_2 sequestration. Much of the experimental research on fluid-fluid displacement has focused on smooth fractures and, as a result, the hydrodynamic impact of roughness, especially under unfavorable viscosity contrast and in strong imbibition, remains to be better understood.

Here, we experimentally investigate forced imbibition under unfavorable viscosity contrast (water displacing viscous silicone oil) in a microfluidic fracture, which is a modified Hele-Shaw cell with one plate patterned with a regular honeycomb array of cylindrical posts. This setup allows us to precisely control the fracture aperture, roughness and wettability. We investigate the impact of four parameters: (1) fracture aperture (gap thickness between two plates); (2) roughness amplitude (post height); (3) contact angle of water immersed in silicon oil (θ); and (4) capillary number.

Our experimental system allows us to visualize the fluid displacement patterns that develop on the plane of the fracture, and also—by means of a carefully determined calibration curve—the fluid distribution across the gap. We find three types of invasion paths: (1) water completely fills the channel including both the gap space and roughness crevices, which we term "complete displacement"; (2) water preferentially invades along the roughness as a "thick film", where water covers the rough surface; (3) water preferentially invades within the roughness as a "thin film". Such "thin film"invasion makes the dynamics of imbibition in a rough fracture substantially distinct from that in a smooth cell [1].

These invasion paths together lead to different regimes of imbibition displacements, the transitions between which are explained by the interplay among capillarity and viscous effects in the gap space and the roughness. "Thin film"may occur only when the equilibrium contact angle is below a critical threshold (θ_c), in which the energetic cost of displacement within the roughness is always negative. This is an analogue of the hemi-wicking regime in an unconfined system [2]. However, in a rough confined system, the balance between capillary pressure within the roughness and across the gap space further determines the imbibition configurations at low capillary number: if the roughness capillarity dominates, we observe wicking into roughness; while if gap capillarity dominates, water adopts "complete displacement", but with finger width decreasing to around one pore unit. Further, at high capillary number, liquid entrainment is triggered in the three-phase contact line, with the wetting phase preferentially advancing ahead of the bulk water. If $\theta > \theta_c$, the preferential path is a "thick film", like the forced imbibition pattern on smooth fractures [1], while if $\theta < \theta_c$, the roughness provides an extra preferential "thin film"flow path.

We propose a phase diagram that delineates the different regimes of imbibition dynamics, which explains our experimental data quantitively. In particular, it includes a novel pattern of forced imbibition in a rough fracture controlled by a "thin film"fluid-displacement mechanism—a finding that challenges the current description and modeling of fluid-fluid displacement in fractured media.

Time Block Preference

Time Block C (18:00-21:00 CET)

References

[1] Levaché, B., & Bartolo, D. (2014). Revisiting the Saffman-Taylor experiment: imbibition patterns and liquid-entrainment transitions. Physical Review Letters, 113(4), 044501.

[2] Quéré, D. (2008). Wetting and roughness. Annu. Rev. Mater. Res., 38, 71-99.

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