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Investigating interfacial instability snap-off in a uniform capillary with a sharp wettability contrast

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Understanding two-phase flow in porous media is highly significant in many fields of science and engineering in terms of both theory and practice. Fundamentally, pore-scale immiscible displacement is governed by the wettability of the pore-wall, which in turn, influences the distribution and transport of the fluid phases at the micro- to macro-scale. Whilst two-phase transport mechanisms in strongly-wetting and weakly-wetting systems are well described, there is a general lack of understanding of the fluid invasion protocol in mixed-wet regimes [1], as spatial heterogeneity in surface wettability gives rise to additional complexity in terms of the governing physics of the immiscible fluid flow. Snap-off is a major pore-scale immiscible fluid transport and immobilization mechanism which occurs during imbibition, which causes the entrapment of the non-wetting phase owing to the presence of strong interfacial forces. It is governed by pore geometry and pore surface wettability. Indeed, it is important to recognize the relative influences of each of these factors when attempting to characterize such instabilities. Most research conducted hitherto has studied snap-off under mono-wet conditions; the work of Zhao et al., however, sheds the light on the understanding of snap-off in partial wetting conditions [2]. In addition to these systems, many naturally occurring pore networks exhibit sharp wettability contrasts across their pore walls (e.g. wettability altered mixed-wet carbonate reservoirs). In this work, we propose that such wettability contrasts can give rise to fluid interfacial instabilities capable of producing snap-off-like behavior (i.e. droplet formation) within pore-systems exhibiting invariant geometry (i.e. straight capillary tubes).

To investigate the behavior alluded to above, we perform high-speed microfluidic experiments and complimentary computational fluid dynamics (CFD) simulations. Microfluidic experiments are conducted within uniform (circular) capillaries with a sharp wettability contrast perpendicular to the flow axis, whereby the inlet side of the capillary is superhydrophobic and the outlet portion is hydrophilic. By injecting deionized water into the air saturated capillary, we are able to record the occurrence of a novel instability, whereby the injected fluid phase dislocates at the juncture between the aforementioned wetting regimes. Additionally, finite volume CFD simulations have been performed to probe the nature of this novel interfacial instability over a range of capillary numbers and wettability contrasts. Our results demonstrate that for strong wettability contrasts at low displacement rates (i.e., low capillary numbers), as the interface reaches the boundary between the two distinct wetting regimes, it elongates, enhancing meniscus curvature, which eventually leads to snap-off of the injected fluid phase. This phenomenon has wide-reaching implications towards numerous fields, such as those concerned with bio-fluid dynamics, hydrocarbon recovery, and CO2 sequestration, as well as potential applications within microfluidics / lab-on-chip diagnostics, providing the ability to generate droplets using sharp wettability contrasts in lieu of constrictions in pore or channel geometry.

Participation

In-Person

References

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2. Zhao, B., et al., Forced Wetting Transition and Bubble Pinch-Off in a Capillary Tube. Physical Review Letters, 2018. 120(8): p. 084501

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