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Conditions Allowing Steady Multiphase Flow in Microfluidic Devices

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Microfluidic devices allow direct observation of interfacial phenomena and multiphase flow in porous media. However, they have difficulty representing steady multiphase flow without fluctuating occupancy of locations in the network. The ability of two phases to form steady, intertwined flow pathways is an essential property of 3D pore networks (Sahimi, 1994; King and Masihi, 2019); fluctuating pore occupancy occurs at elevated capillary number (Gao et al., 2020). A two-dimensional network can represent this only if the flow paths of the two phases cross at some locations in the network (Fisher, 1961). Crossing is possible in a microfluidic network if wetting phase can form a bridge across the top and bottom of a gap between grains at a pore throat while nonwetting phase flows through the throat, as illustrated in the graphical abstract, left figure.
We review conditions for existence of quasi-static flow pathways in conventional microfluidic geometries. We examine whether paths can cross in several different throat geometries (Cox et al., 2023) using the Surface Evolver software (Brakke, 1992). For relatively long straight or curved throats, the most common geometry in microfluidic networks used to study flow in geological formations (see graphical abstract, center and right figures), the capillary pressure for bridging is the same as that for snap-off. As a result, phases displace each other in turn in the network, even at the very lowest capillary number.
Concave throats, as between cylindrical barriers, can support bridges over a substantial range of capillary pressure. The range of capillary pressures at which bridging is stable increases as throats become more strongly concave (i.e., pillar radius decreases) and for narrower throats. Steady two-phase flow would be possible in networks of pores with throats of this geometry.
For networks of this geometry, we estimate the range of fractional flows of wetting and nonwetting phase that could be sustained (Obbens, 2022). To get past pore bodies occupied with nonwetting phase, wetting phase is restricted to the corners at the top and bottom of the pillars, shown in the graphical abstract, left figure. We input flow geometries determined by the Surface Evolver into the COMSOL numerical flow solver to estimate relative permeabilities of both phases for a given network realization. We choose assumptions that favor the flow of the wetting phase: for instance, penetration of the nonwetting phase just to the point where it connects across the network. The results show that the relative permeability of the wetting phase is roughly 1/10 of that of the nonwetting phase. Given the assumptions made, this is a generous estimate. If viscosities of the two phases were roughly equal, the maximum fractional flow of wetting phase would be 0.1. For gas-water studies, where the viscosity ratio can be 50:1, the maximum fractional flow of water would be 0.2%. Imposing a fractional flow above this would guarantee fluctuating pore occupancy in the network.

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