

Experimental study of drop displacement dynamics in microfluidic capillaries

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Introduction

We present results from an ongoing study aimed at estimating the relative magnitude of the net capillary pressure drop across a non-wetting phase (NWP) blob as it is driven through a periodic capillary tube filled with a wetting phase (WP). To this end, we conduct an experimental investigation of NWP plugs and droplets displaced within microfluidic capillaries under varying flow conditions, spanning regimes from capillary-dominated to viscous-dominated flow.

Two types of microfluidic capillary cell models are designed and fabricated in PDMS (polydimethylsiloxane) using the methodology described in Karadimitriou *et al.* (2013). The resulting microfluidic cells are planar (2D) and exhibit a periodic, symmetric geometry. The void space is confined between two parallel horizontal planes of relatively small separation (depth) and is structured to form a symmetric, periodic, orthogonal pattern along the longitudinal vertical plane of symmetry.

Two variants of the unit cell geometry are considered (see Figure 1).

(a) Cell with sinusoidally varying width (“*SinusC*”). This configuration consists of a symmetric conduit with an orthogonal cross-section whose width varies sinusoidally along the longitudinal axis, z . The width is defined as $w(z) = w_0[1 - a \cos(2\pi z/L)]$, where L is the constant periodic length of the cell, a ($0 \leq a < 1$) is the dimensionless amplitude of oscillation, and, w_0 is the mean width of the cell.

(b) Smooth chamber–throat unit cell (“*SmoothC*”). This configuration represents a classical chamber-and-throat geometry with a smooth transition between elements. A typical unit cell consists of two chambers connected by a throat. The chambers are shallow conduits of orthogonal cross-section, while the throat has a constant cross-section. Smooth (sinusoidal) transitions are employed at the throat–chamber junctions.

The origin of the Cartesian coordinate system ($z = 0$) is located midway between two adjacent lattice nodes. The longitudinal profile of the vertical walls is defined piecewise as follows: the throat region, of constant width w_i , extends from $z = -t_{ij}$ to $z = t_{ik}$. Adjacent to the throat, two sinusoidal transition regions extend from $z = -c_{ij}$ to $z = -t_{ij}$ and from $z = t_{ik}$ to $z = c_{ik}$, where the width varies smoothly from $w_{Ti}/2$ to Y_{ij} and from $w_{Ti}/2$ to Y_{ik} respectively, for each half of the cell. Beyond these regions, the chamber sections are defined by circular arcs extending from $z = -c_{ij}$ to $z = -1/2 + D_{cj}\sqrt{2}/4$ and from $z = -c_{ik}$ to $z = 1/2 - D_{ck}\sqrt{2}/4$. The values of the geometric parameters c_{ij}, t_{ij}, Y_{ij} are calculated in terms of the throat width, w_{Ti} , and the chamber diameters, D_{Cj} , by imposing continuity of width and its derivative in the transition between the adjacent curves, i.e. across c_{ij}, t_{ij} .

Materials and implementation protocol

We fabricate a range of capillary cells with varied geometric parameters — $\{w_0, a, L\}$ and $\{w_{Ti}, D_{Cj}\}$ for the *SinusC* and *SmoothC* configurations respectively. The fluids employed, along with their physicochemical properties, are summarized in Table 1.

After saturating the capillary cell with WP, a constant volumetric flow rate is imposed while injecting plugs and droplets of the NWP. These are sufficiently large to maintain contact with the capillary walls as they are displaced by the WP flow. A range of volumetric flow rates is explored in combination with different NWP plug and droplet sizes, enabling the investigation of a broad spectrum of flow conditions spanning 2–3 orders of magnitude in both the capillary number, Ca , and the flow-rate ratio, r .

Results and discussion

By capturing snapshots of the plugs and droplets as they traverse the capillary cells, we analyze the evolution of contact angles and assess the influence of capillary geometry and flow conditions. In particular, we identify conditions under which meniscus curvature reversal occurs, marking a transition between drainage- and imbibition-type flow regimes.

In addition, we measure the pressure drop induced at the inlet and outlet ports of the capillary tube. These measurements are compared against:

- theoretical predictions based on a combined Hele-Shaw flow analysis for viscous pressure losses and Young–Laplace formulations for capillary resistance; and
- numerical simulations of immiscible flow using a coupled Level-Set and Stokes flow model implemented in COMSOL Multiphysics® (Mouravas *et al.*, 2026).

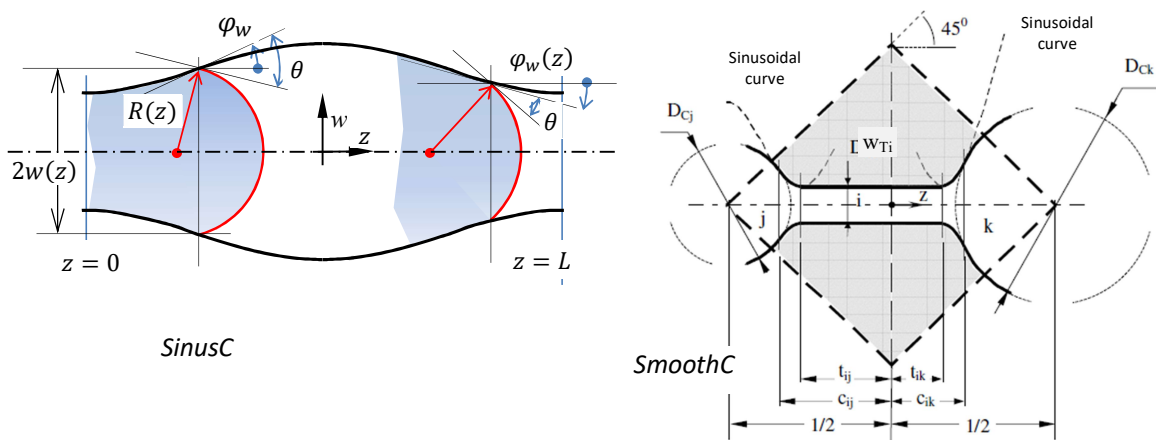


Figure 1. Geometric layout of the two types of planar microfluidic capillary cells with orthogonal cross-sections, used in the experimental study: (left) sinusoidal varying width cell (SinusC); (right) Smooth chamber–throat cell (SmoothC)

Table 1. Physicochemical properties and wettability of the pair of fluids used in the study results

Fluids & physicochemical properties	Density $\tilde{\rho}$ [kg/m ³]	Dyn. viscosity $\tilde{\mu}$ [mPas]	Interf. tension $\tilde{\gamma}_{nw}$ [N/m]	Contact angle	
				Advancing, θ_A [deg]	Receding, θ_R [deg]
Fluorinert™ FC-770 (WP)	1793	1.359	55×10^{-3}	54 ± 5	45 ± 5
Deionized Water + Dye (NWP)	1000	1.00			

Conclusions

The analysis demonstrates that, when contact angle hysteresis is accounted for, the net capillary pressure drop can significantly exceed the viscous pressure drop over a wide range of NWP/WP/porous medium system parameters and flow conditions, particularly at low capillary numbers and low flow-rate ratios. These findings highlight the importance of explicitly incorporating hysteresis-related capillary effects into capillary tube models of two-phase flow in pore networks. Doing so enables a more rigorous, mechanism-based description of flow behavior across an extended range of flow regimes (Valavanides, 2018).

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References

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