

## Reduced net capillary pressure drop analysis for NWP blobs driven within periodic capillary tubes

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### Introduction

We present results from an ongoing study (Papachristou *et al.*, 2026) aimed at estimating the relative magnitude of the net capillary pressure drop across a non-wetting phase (NWP) blob driven through a periodic capillary tube filled with a wetting phase (WP). The NWP blob is assumed to be sufficiently large to remain in contact with the tube walls.

A lubrication-approximation flow analysis is implemented to estimate viscous flow resistance arising from bulk viscosity. To account for inherent hysteresis effects, different contact angles are assigned to the advancing and receding N/W menisci. Based on this framework, we derive analytical expressions for the reduced capillary pressure drop, defined as the capillary pressure drop relative to the viscous pressure drop.

Within this context, we evaluate the relative contribution of capillary and viscous mechanisms to the overall flow resistance across a broad range of flow conditions spanning 2-3 orders of magnitude in the capillary number,  $Ca$ , and the flowrate ratio,  $r$ .

Assuming fixed advancing and receding contact angles during displacement of the NWP along the capillary tube, we also explore the geometric parameter space of sinusoidal capillary tubes to identify conditions under which meniscus curvature reversal occurs, leading to a transition between drainage- and imbibition-type flow behavior.

### Results and discussion

The calculations indicate that, when contact angle hysteresis is considered, the net capillary pressure drop can significantly exceed the viscous pressure drop over an extended domain of the NWP/WP/PM system parameters (mainly viscosity ratio, fluid wettability and pore geometry). This behavior is particularly pronounced when NWP drops are displaced at flow conditions described by low  $Ca$  and low  $r$  values.

The predictions of the simplified analytical model are validated against:

- numerical immiscible flow simulations based on a coupled Level-Set and Stokes flow model, and implemented using the commercial software COMSOL<sup>TM</sup> Multiphysics,
- lattice-Boltzmann (LB) simulations using a constant flux PI controller recently developed by Lee *et al* (2026), and
- microfluidic experiments conducted in specially fabricated PDMS (Poly-Di-Methyl-Siloxane) micromodels (Mouravas *et al.*, 2026).

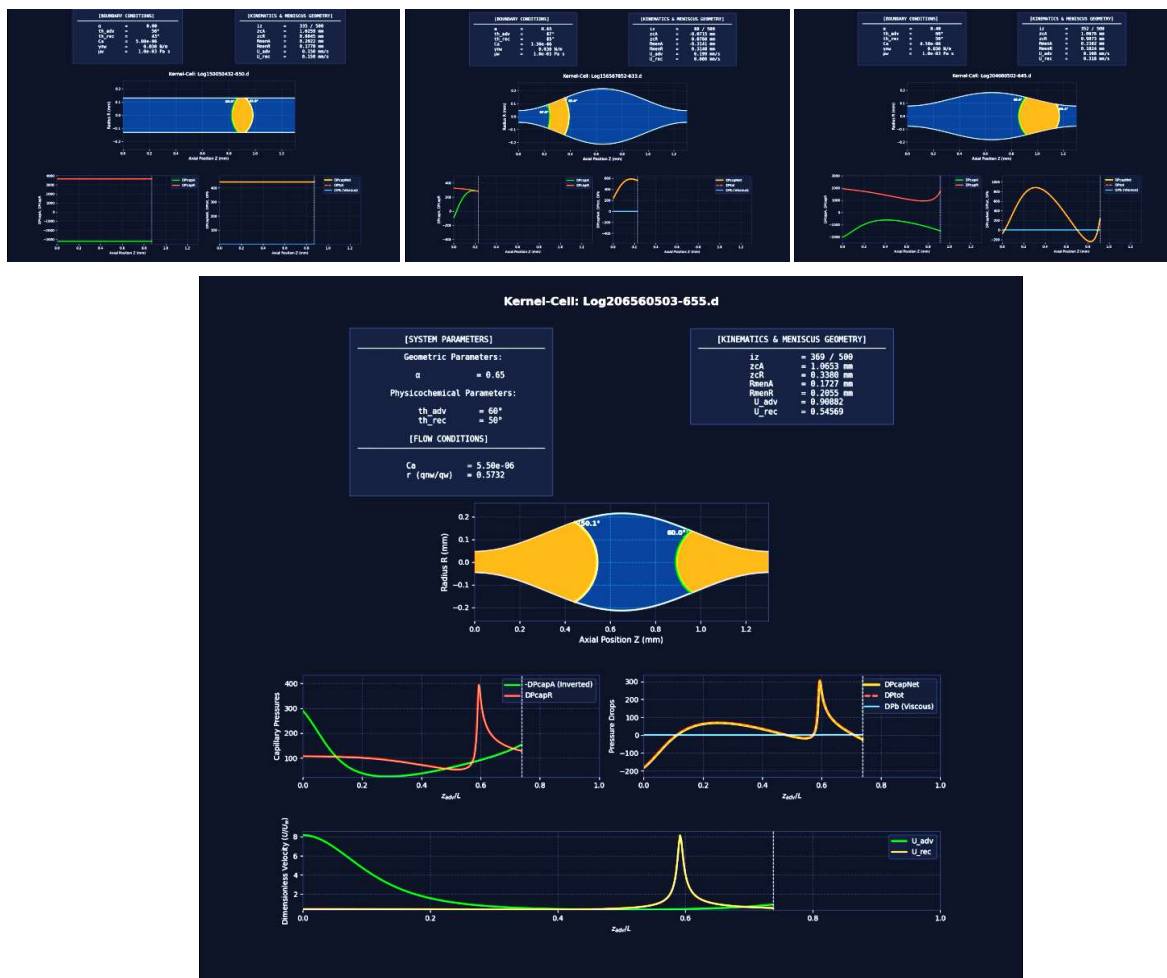
These comparisons demonstrate good qualitative agreement and confirm the importance of hysteresis-induced capillary effects in determining the overall pressure drop.

### Conclusions

The analysis shows that, when contact angle hysteresis is taken into account, the net capillary pressure drop can substantially exceed the viscous pressure drop across a wide range of NWP/WP/PM system parameters and flow conditions, particularly at low capillary numbers and flow-rate ratios.

These findings suggest that capillarity effects associated with hysteresis should be explicitly incorporated in capillary tube models of two-phase flow in pore networks, in order to provide a more rigorous, mechanism-based description across an extended range of flow regimes (Valavanides, 2018).

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**Figure 1.** Indicative calculations from a systematic parametric study showing the relative effect of the capillary resistances (hysteresis): (top) different configurations of the capillary tube geometry and wettability; (bottom) video snapshot details of the analysis. (<https://users.uniwa.gr/marval/HydroLab/dropsinpores.html>)

## References

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