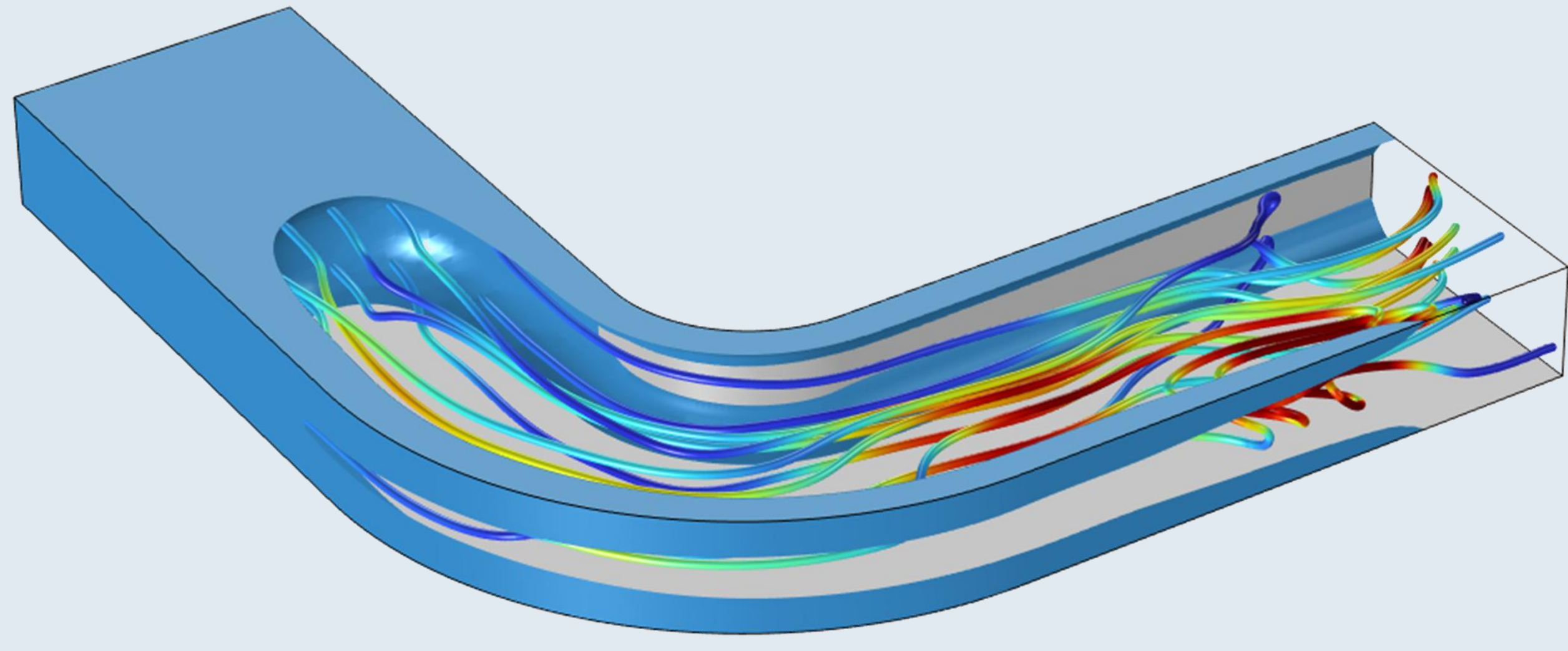


Simulation of Capillary Filling in a Microfluidic Channel



Prediction of interfacial dynamics and dependence on wettability in COMSOL Multiphysics® guides robust, repeatable design of pump-free microfluidic devices for point-of-care diagnostics, lab-on-a-chip systems, and biomedical applications.

Tianyi Hu, Ph.D.
Matthew Hancock, Ph.D.

thu@veryst.com
mhancock@veryst.com

Veryst Engineering
Needham, MA, USA

Abstract

Capillary filling is increasingly utilized in microfluidic devices, where the autonomous movement of liquids driven by surface tension and wetting effects within hydrophilic microchannels enables both pump-free and precise fluid transport. This passive transport mechanism simplifies device architecture while enabling compact, low-cost, and disposable designs. These capabilities make capillary filling desirable for applications in MedTech, surface cleaning in semiconductor manufacturing, and reaction control in chemical production, where reliable, self-driven fluid handling is a key design requirement.

However, achieving robust, repeatable, and controllable capillary filling performance poses significant technical challenges, as the dynamics are highly sensitive to surface wettability, channel architecture, and fluid properties; even minor variations can substantially alter flow rate, reproducibility, and meniscus stability. In this poster, we present advanced simulations of capillary filling of an L-shaped microchannel with water at various wetting conditions. Our results enable engineers to make informed product and process design decisions that enhance efficiency, reliability, and scalability.

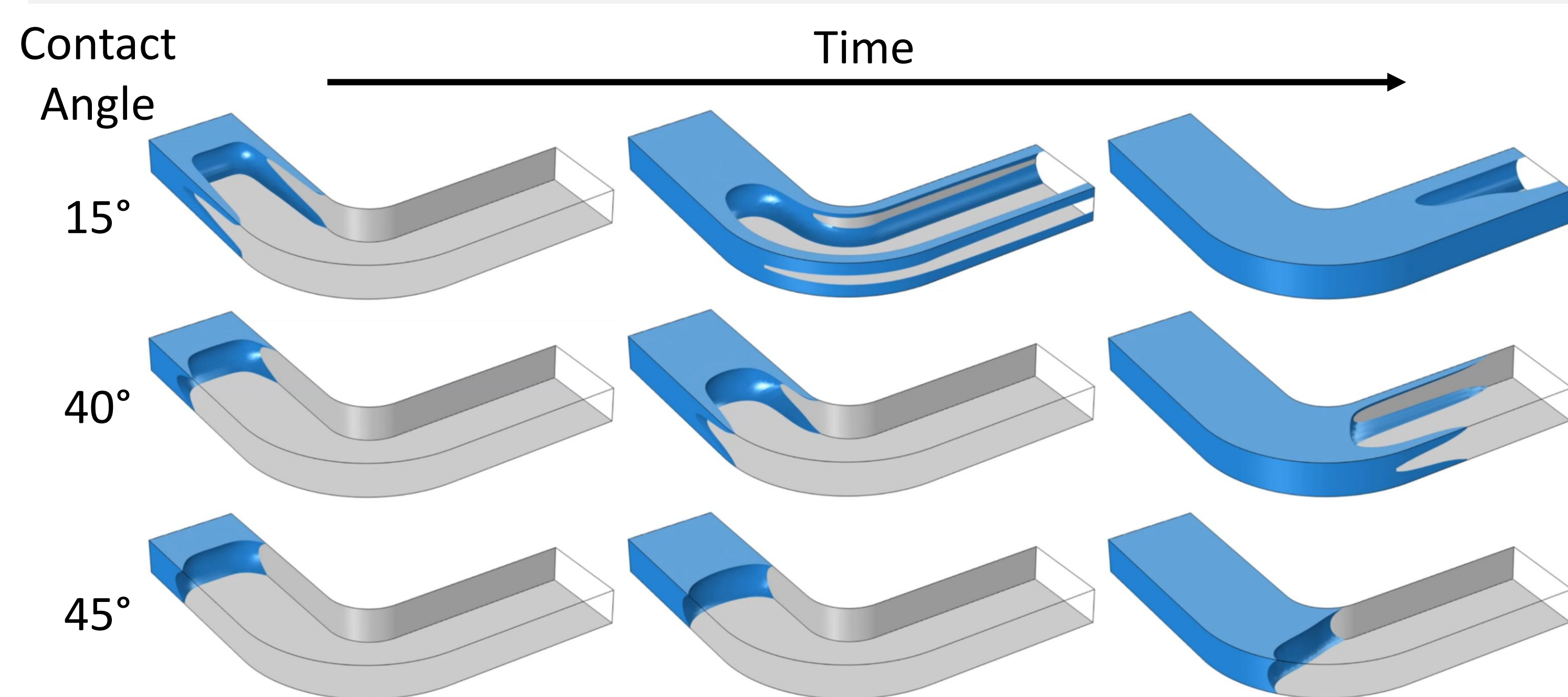


FIGURE 1. Time evolution of capillary filling of L-shaped microchannels with different wettability (quantified by contact angle).

Figure 1 shows the time evolution of capillary filling at contact angles of 15°, 40°, and 45°. For the highly hydrophilic case (15°), the strong wall affinity for water causes the contact line to quickly advance along the walls, forming liquid fingers that stretch well beyond the bulk interface. At 40°, the fingers are shorter, and by 45°, they disappear. A back-of-the-envelope calculation of the free energy balance across a finger cross-section (approximately the shape of an extruded fillet) shows that fingers are energetically beneficial for contact angles below 45° and become more so as the contact angle approaches 0.

Figure 2 shows the inner and outer contact line positions as a function of time. At 15°, the contact line moves at nearly the same velocity along both walls until the channel is filled. At 40°, the contact line initially advances at similar rates along the inner and outer walls, but as the fluid approaches the bend, motion along the inner wall slows slightly while that at the outer wall maintains its speed. At 45°, this asymmetry inverts and becomes more pronounced: upon entering the curved region, motion along the outer wall accelerates while motion along the inner wall decelerates, causing the inner and outer contact lines to reach the end of the channel at approximately the same time. Figure 3 further quantifies this dependence, showing that filling time increases exponentially with contact angle and diverges as θ approaches 90°, where the capillary driving force vanishes and filling ceases.

Methodology & Results

We coupled the Laminar Flow interface with the phase-field method to simulate capillary filling of water through an L-shaped microchannel initially filled with air. The phase-field method tracks the evolving air-water interface, capturing the temporal evolution of the three-phase contact line as it advances along the channel walls. A custom dynamic contact angle boundary condition was implemented to accurately resolve contact line motion. Filling is driven by the capillary driving force, $\gamma \cos \theta$, where γ is the air-water surface tension and θ is the (liquid-side) equilibrium contact angle, varied parametrically from 15° to 85° herein to quantify its influence on the filling dynamics.

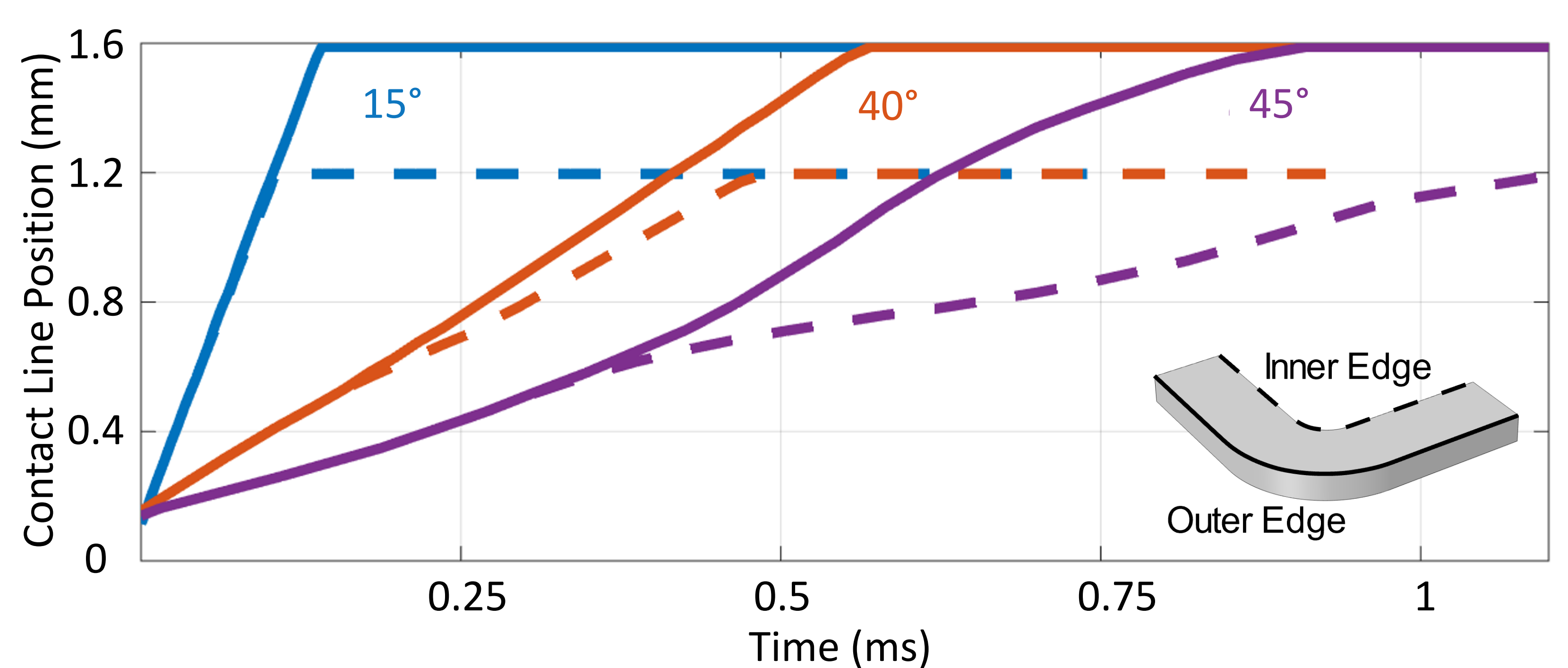


FIGURE 2. Temporal progression of inner and outer contact line positions during filling with different wettability.

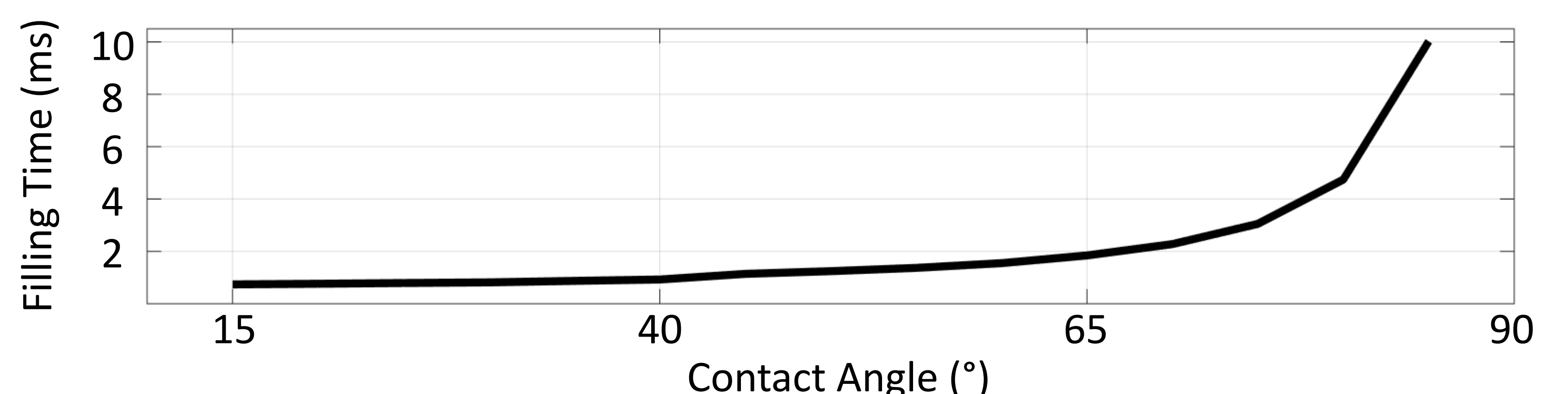


FIGURE 3. Capillary filling time versus contact angle.

