Supporting Information

Analysis and methods for void-free liquid filling of blind microchambers in centrifugal microfluidics

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This file includes:

Note S1 to S2

Figure S1

Tabel S1

Note S1. The influence of channel length on the optimization process of taper ratio

As derived from Equations (7) and (8), the fluid velocity within microchannels can be modulated solely by adjusting the inlet-to-outlet width ratio. To verify this point and test the effects of other geometric parameters, we performed computational simulations on three channel length variants (L = 5, 10 and 15 mm) of a 2:1 contraction ratio design. The numerically simulated velocity profiles within the branch channels are presented in Figure S1, while Table S1 provides a quantitative comparison of the flow acceleration performance across the three microchannel architectures. The results demonstrate that the length of the tapered branch channels does not significantly alter the fluid velocity, thus does not impair the performance of void-free liquid filling.

Note S2. Simulation methodology

All numerical experiments were performed with COMSOL Multiphysics 6.1 (CFD Module). A two–dimensional, transient model was built to resolve the coupled incompressible Navier–Stokes equations and level-set formulation for a water–air system experiencing solid-body rotation.

Geometry and mesh

The computational domain (as shown in Figure 3) consists of two rectangular sub-domains representing water and air, respectively. Characteristic length scales are 10 mm in the streamwise direction and 0.78 mm in height. A physics-controlled, triangular mesh was generated with element sizes varying from 1.3 μm along the interface to 187 μm in the bulk; this yields 8.1×10^4 elements and ensures a cell Reynolds number Re<1 everywhere, satisfying the Péclet–interface criterion $\varepsilon > 1.3\ h_{min}$, esh-independent solutions were verified by halving the global element size, where h_{min} represents the minimum characteristic size of the computational grid, and esh-independent was verified using the grid refinement; testvelocity and pressure fields differed by <1 %.

Governing equations

Fluid motion is governed by:

$$\rho\left(\frac{\partial u}{\partial t} + u \cdot \nabla u\right) =- \nabla p + \mu \nabla^2 u + \rho f_{vol}, \nabla \cdot u$$

where ρ and μ are phase-dependent density and dynamic viscosity obtained from COMSOL's built-in piecewise functions for water (20 °C) and air (1 atm). The free surface is captured with the conservative level-set equation:

$$\frac{\partial \varphi}{\partial t} + u \cdot \nabla \varphi = \gamma \nabla \cdot (\varepsilon \nabla \varphi - \varphi(1-\varphi) \frac{\nabla \varphi}{|\nabla \varphi|}$$

using an interface thickness $\varepsilon = 1.3\ h_{max}$ and re-initialization parameter $\gamma = 1\ m\ s^{-1}$. Volume forces include (i) a centrifugal body force $f_c = \rho \omega^2 (x + 0.1m) e_x$ and (ii) the Coriolis term $f_\Omega = 2\rho \omega u \times e_z$, where the angular velocity is ramped from 0 to 400 rad s⁻¹ over the first 2 s $via\ \omega(t) = \omega_0\ ramp(t)$.

Boundary and initial conditions

All solid walls are set as non-slip boundaries. The downstream boundary is treated as an open outflow with zero normal stress. Initial velocity and pressure are zero, and the level-set field is initialized by a signed-distance function so that φ = 1 in water and φ = 0 in air.

Temporal discretization and solver settings

A fully coupled, variable-order BDF scheme (maximum order = 2) with adaptive time stepping ($CFL \leq 1$) is employed. Velocity and pressure are discretized with equal-order linear Lagrange elements (P1–P1) and stabilized by COMSOL's consistent SUPG/PSPG formulation. Newton iterations are terminated when the residual norm falls below 10^{-6}; each nonlinear step uses a geometric multigrid preconditioner.

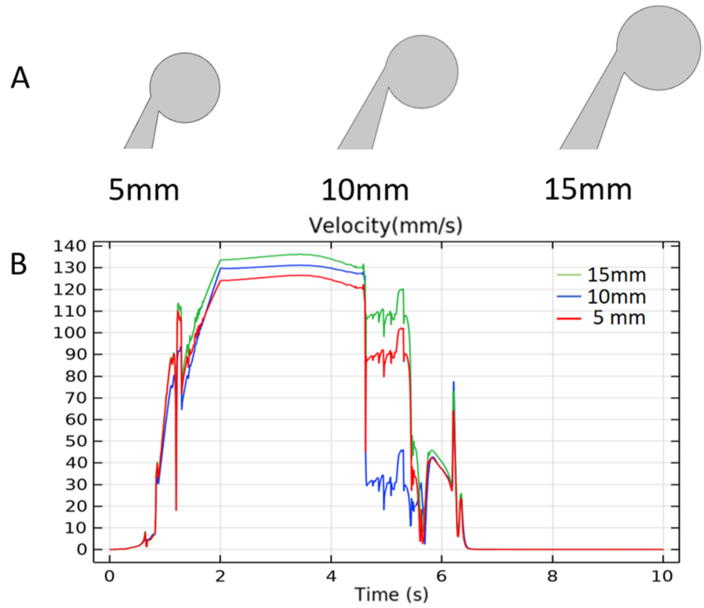

Figure S1. The influence of microchannel length on fluid velocity. A) Modeling of three types of microchannel lengths. B) Fluid velocity curve in microchannels.

Table S1. Performance parameters for three types of microchannel lengths

	5mm	10mm	15mm
Time required to complete filling	5.15 s	4.58 s	5.64 s
Average velocity	116.432 mm/s	117.867 mm/s	120.435 mm/s