Droplet migration in a Hele–Shaw microchannel: Effect of the lubrication film on the droplet dynamics

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Introduction

Droplet-based microfluidics is a promising tool for performing biochemical or chemical assays. Droplets are unit systems of controlled volume and content, within which mixing, reacting and/or transferring can be achieved. Therefore, a comprehensive understanding of droplet migration in confined microchannels is essential to many microfluidics applications. Rectangular confined channels with the width significantly larger than the height are commonly used in microfluidics devices. In such cases, the confinement of the droplet is only in the vertical direction and the droplet is exposed to a two-dimensional Poiseuille flow (as in a Hele–Shaw cell).

Simulation Method & Setup

The one-fluid approach is employed to resolve the two-phase flow, where the phases corresponding to the droplet and the ambient fluid are treated as one fluid with material properties that change abruptly across the interface. The volume fraction is introduced to distinguish the two different phases. The incompressible, variable-density, Navier-Stokes equations with surface tension and the advection equation for the volume-fraction evolution are given as

$$\rho(\partial_t \mathbf{u} + \mathbf{u}\cdot\nabla\mathbf{u}) = -\nabla p + \nabla\cdot(2\mu\mathbf{D}) + \sigma\kappa\delta_s\mathbf{n} \qquad (1)$$

$$\nabla\cdot\mathbf{u} = 0 \quad (2) \qquad\qquad \partial_t C + \mathbf{u}\cdot\nabla C = 0 \qquad (3)$$

The governing equations are solved by the open-source code *Gerris* using a finite-volume approach and the Volume-of-Fluid method on an adaptive mesh.

$r=\rho_f/\rho_d$	$m=\mu_f/\mu_d$	$Re_f=\rho_f H U_f/\mu_f$	R/H	$Ca_f=\mu_f U_f/\sigma_f$
0.75	0.74	1.35	0.5~2	6.2×10^{-3}~9.9×10^{-2}

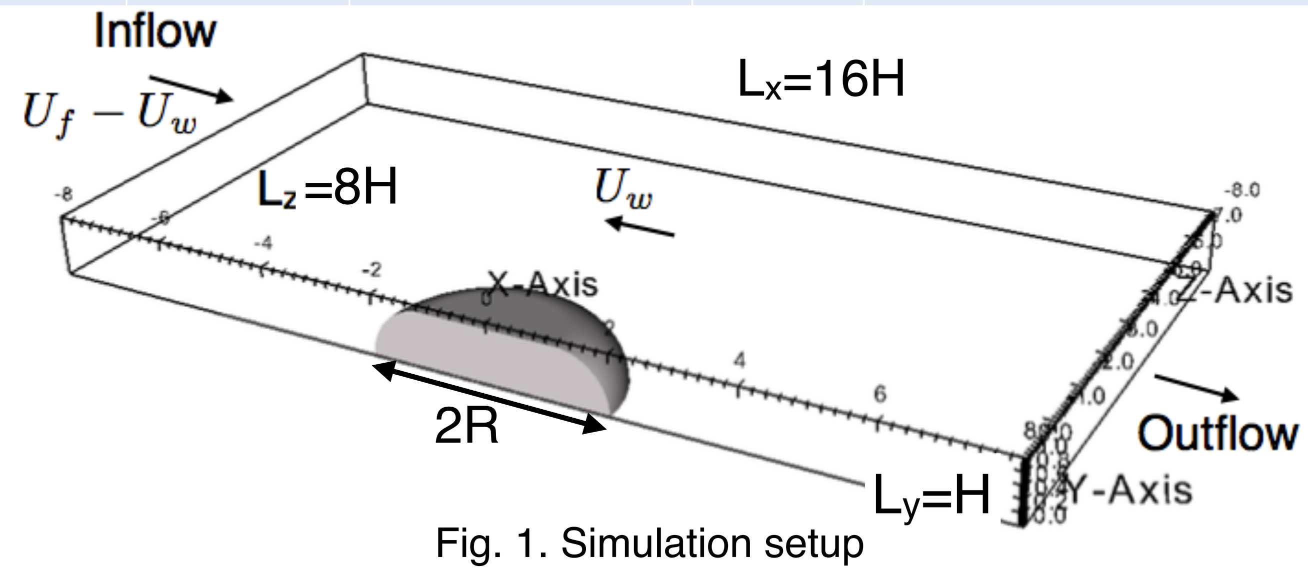

Fig. 1. Simulation setup

2D Validation

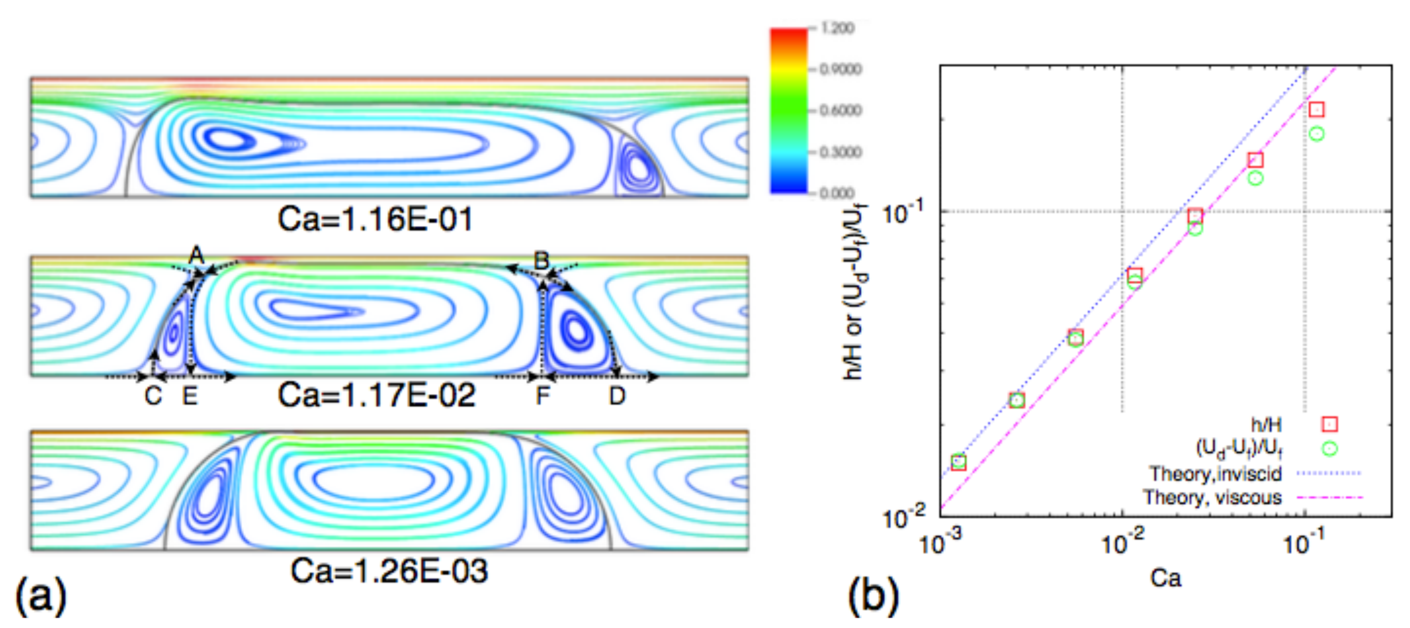

Fig. 2. Simulation results of a planar droplet a 2D channel.(a) Droplet shape and the streamlines in the droplet reference frame.(b) Relative droplet velocity and film thickness as functions of the capillary number compared to extended Bretherton theory

Droplet Velocity

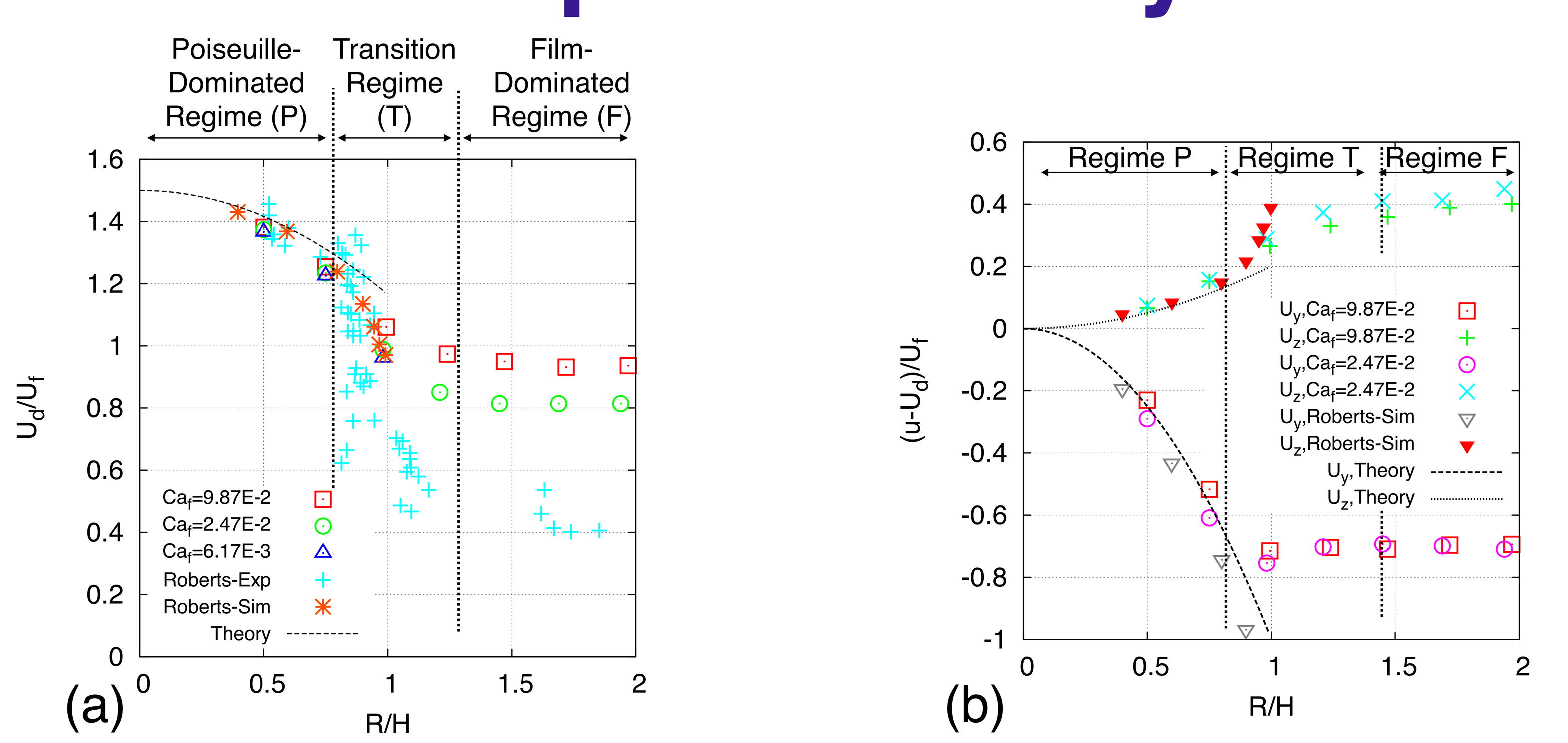

Fig. 3. (a) Mean droplet velocity U_d and (b) relative u-velocities at the top and the side of the droplet (U_y and U_z) as a function of droplet radius and capillary number.

3D Flow Structure

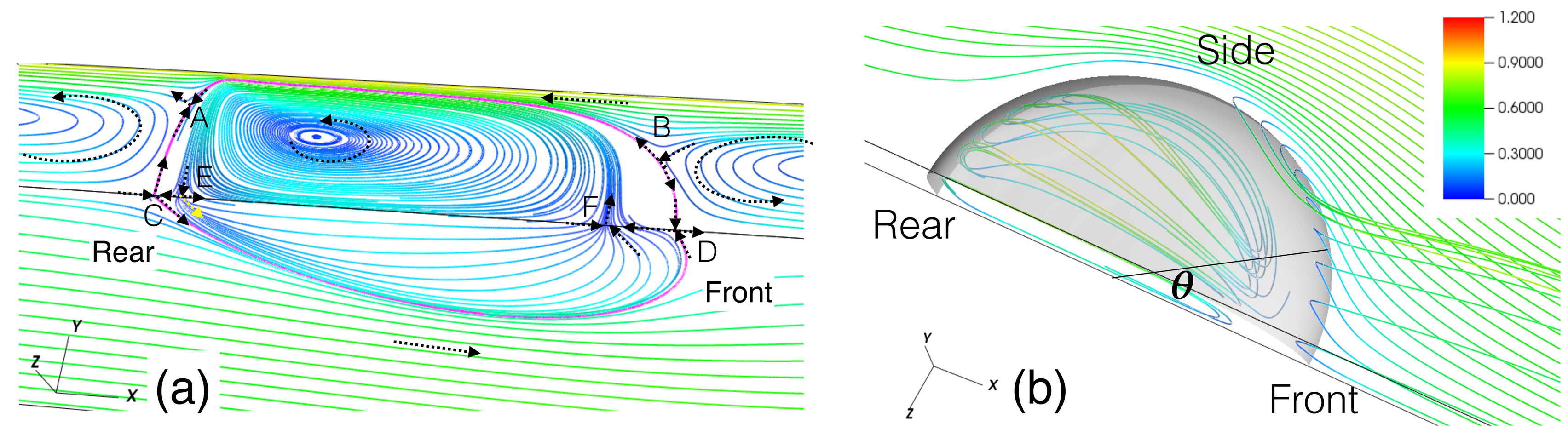

Fig. 4. Streamlines for Ca_f=9.9×10^{-2} andR/H=2 in the droplet reference frame. (a) On the symmetric planes z=0 and y=0 and (b) Flow pattern inside and outside of the droplet. The color of the streamlines denotes the corresponding relative velocity magnitude.

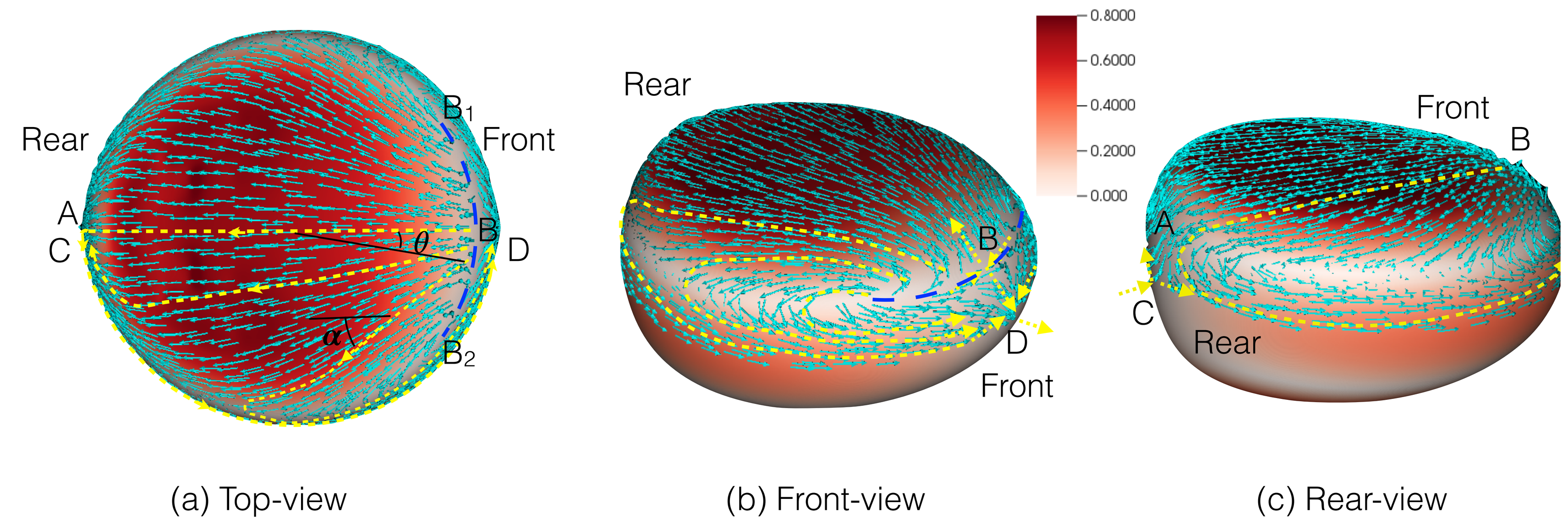

Fig. 5. (a) Top- (b) front- and (c) rear-views of relative velocity in the droplet reference frame {u – U_d, v, w} on the droplet interface for Ca_f=9.9×10^{-2} and R/H = 2. The color denotes the magnitude of the relative velocity.

Film Configuration & Dynamics

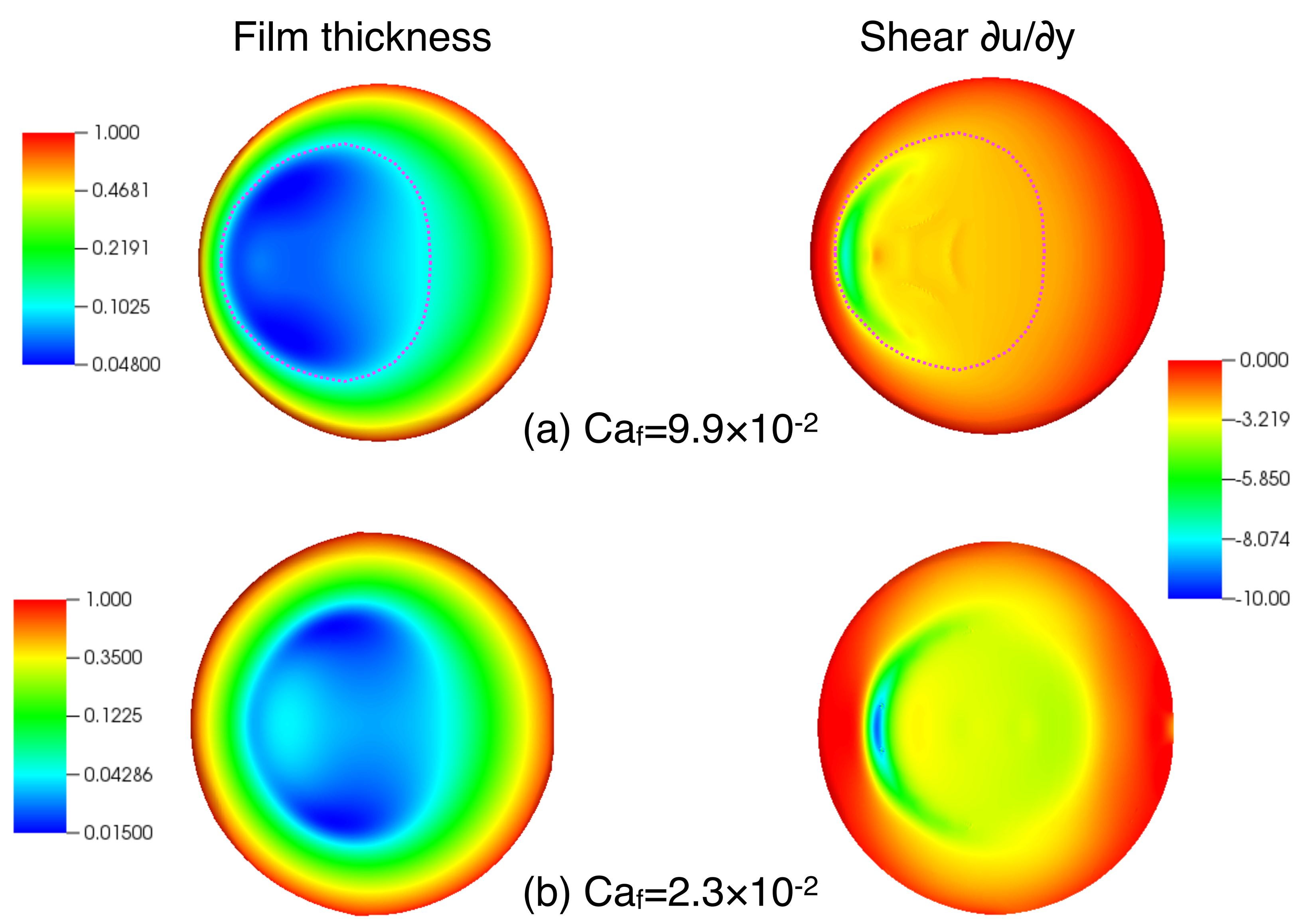

Fig. 5. (a) Top- (b) front- and (c) rear-views of relative velocity in the droplet reference frame {u – U_d, v, w} on the droplet interface for Ca_f = 9.87 × 10^{-2} and R/H = 2. The color denotes the magnitude of the relative velocity.

Summary & Discussions

The migration of a droplet in a Hele–Shaw microchannel has been investigated by 3D direct numerical simulations. Parametric studies were performed by varying the droplet horizontal radius and the capillary number. For droplets with an horizontal radius R larger than the half-height of the channel H, the droplet overfills the channel and a lubrication film is formed between the droplet and the wall. The ratio R/H has a significant impact on the droplet velocity and controls three regimes: the Poiseuille-dominated regime, the film-dominated regime, and the transition regime. Excluding moving contact lines and the Marangoni effects, the droplet velocity (for large R/H) in the present simulations is observed to be lower than the average inflow velocity, consistent with experimental observations and in disagreement with the Taylor–Saffman prediction. The strong shear induced by the lubrication film and the three-dimensional flow structure seem to both contribute to the low mobility of the droplet.

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