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Experimental and numerical studies of two-phase microfluidic flows

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INTRODUCTION

Flow of immiscible fluids is important in microfluidics for applications such as generation of emulsions and vesicles, drug delivery capsules, cell encapsulation and chemical reactions. The behaviour of these flows differs from large scale flows, primarily, due to dominance of surface forces such as viscosity and interfacial or surface tension over volume forces such as gravity and inertia. This can be illustrated by the scaling law[1]:

$$\frac{surface\ forces}{volume\ forces} \propto \frac{L^2}{L^3} = L^{-1} \xrightarrow[L \to 0]{} \infty \qquad \text{Equation 1}$$

whereby the variation of physical quantities is expressed with the length scale of the system, L. Generation of emulsions in micro-sized channels exploits the balance between these forces. In particular, the balance between the interfacial and the viscous forces is most significant. Hence, the Capillary number (Ca) is used in the characterisation of emulsification microsystems. Other important dimensionless numbers, as per Pi-theorem, in two-phase (biphasic) microfluidic systems are shown in **Table 1**.

Table 1: Important dimensionless numbers and scaling laws for two-phase microfluidic flows[1,2]

Dimensionless number	Equation	Significance (force ratio)	Scaling law
Bond (Bo)	$\rho g L^2/\sigma$	gravitational/interfacial	L^2
Capillary (Ca)	$\mu V/\sigma$	viscous/interfacial	L
Ohnesorge (Oh)	$\mu/\sqrt{\rho\sigma L}$	viscous/interfacial	$L^{-1/2}$
Peclet (Pe)	VL/D	convection/diffusion	L^2
Reynolds (Re)	$\rho VL/\mu$	inertial/viscous	L^2
Weber (We)	$\rho V^2 L/\sigma$	inertial/interfacial	L^3
D-diffusion coefficient, ρ-density, L-length scale, σ-interfacial tension, μ-viscosity, V-flow velocity			

AIM

To study the formation of water-in-oil (w/o) droplets in T-junction microchannels using experiments and computational fluidic dynamics (CFD).

DROPLET GERNERATION IN MICROFLUIDIC T-JUNCTION

The experiments were carried in rectangular 200μm x 75μm T-junction microchannel made from transparent polydymethyl siloxane (PDMS) material using soft lithography techniques. The fluids were fed into the microchannel using syringe pumps. The deionised water (density = 1000 kg/m^3; viscosity = 0.001 Pa.s) was fed on the side arm and the mineral oil (density = 840 kg/m^3; viscosity = 0.026 Pa.s) was fed in the main arm, as illustrated in **Figure 1**. Sorbitan monolaurate (Span 20) surfactant (1% v/v) of was dissolved in the oil phase, resulting in the interfacial tension of ~ 0.003 N/m. The flow was imaged with a digital camera at 1200 frames per second under a microscope using a 10x magnification objective lens.

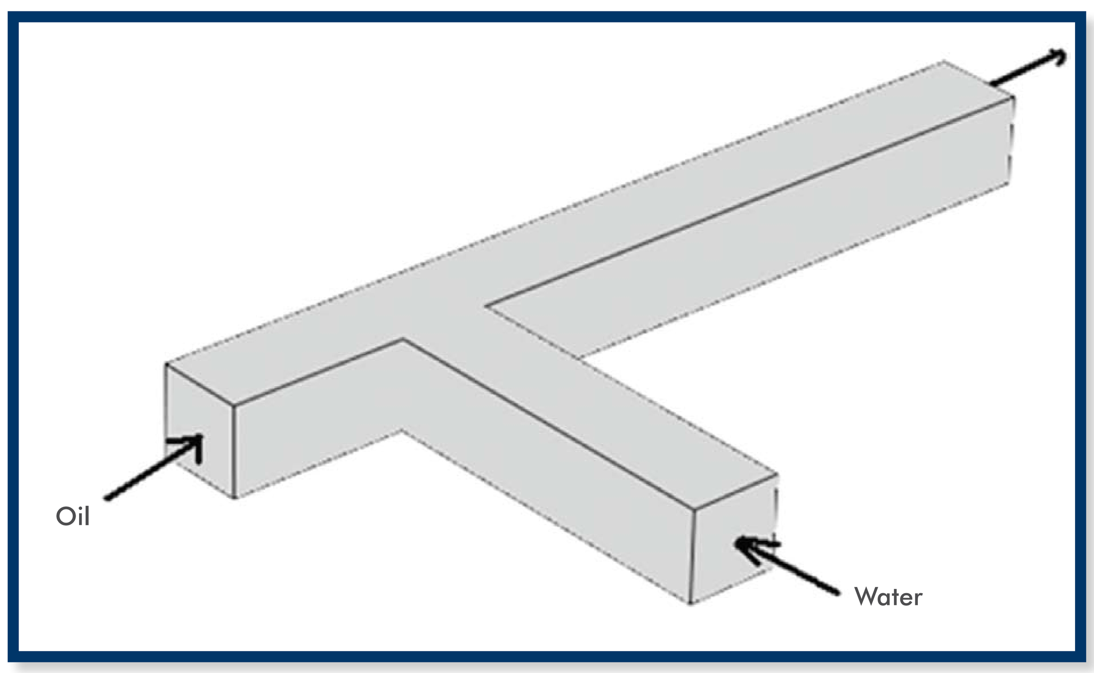

Figure 1: Illustration of the fluids entry into the microfluidic T-junction

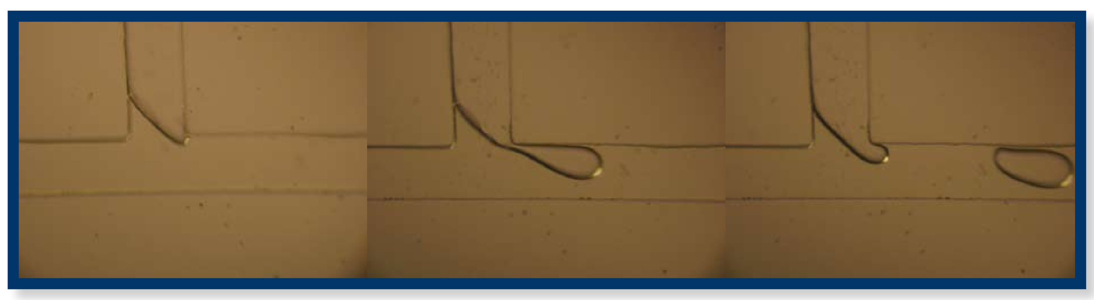

Figure 2: Snapshots showing sequence of w/o droplet breakup in a 200 μm wide microfluidic T-junction

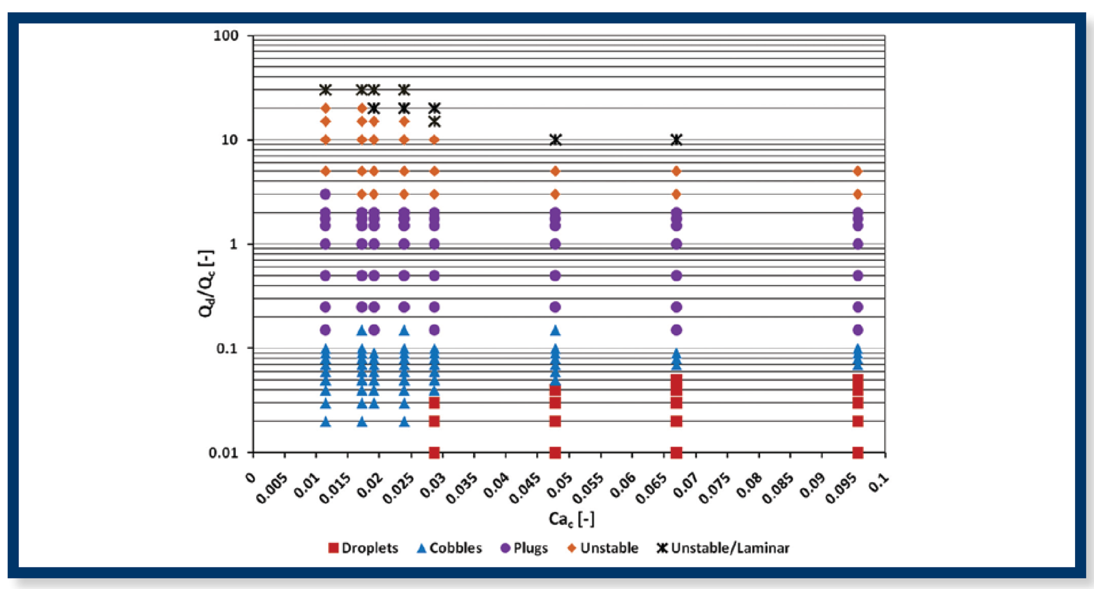

Figure 3: Variation of flow patterns in a T-junction microchannels as a function the capillary number of the oil phase (Ca_o)

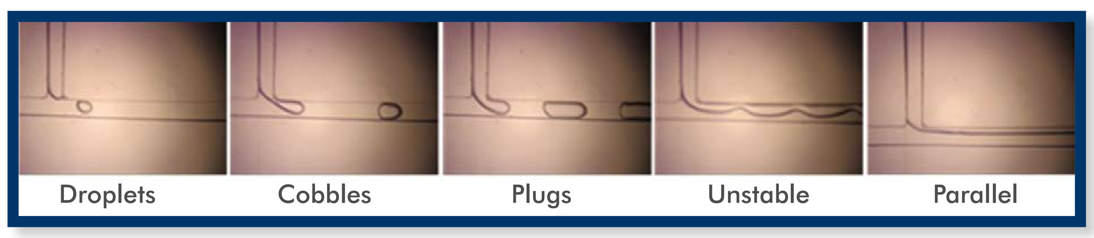

Figure 4: Various flow patterns in a T-junction microchannels

MODELLING AND SIMULATION

The CFD modelling and simulation was achieved using COMSOL Multiphysics software program, whose numerical scheme is based on a finite element method (FEM)[3]. The fluid-fluid interface model was based on the conservative level set method (LSM) by Olsson and Kreiss[4]. The fluid-fluid interface is, implicitly, represented by φ, where φ equals to 0 on one phase and equals to 1 on another. At the interface φ equals to 0.5.

The Navier-Stokes equations

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u}\right) - \nabla\cdot\left[\mu\left(\nabla\mathbf{u} + \nabla\mathbf{u}^T\right)\right] + \nabla p = \mathbf{F} \qquad \text{Equation 2}$$

$$\nabla\cdot\mathbf{u} = 0 \qquad \text{Equation 3}$$

and the level set equation

$$\frac{\partial\varphi}{\partial t} + \mathbf{u}\cdot\nabla\varphi = \gamma\nabla\cdot\left[\varepsilon\nabla\varphi - \varphi(1-\varphi)\cdot\mathbf{n}\right] \qquad \text{Equation 4}$$

are coupled and solved simultaneously, where $\mathbf{F} = \sigma\kappa\delta\,\mathbf{n}$, $\kappa = \nabla\cdot\mathbf{n}$,

$\delta = 6\left|\nabla\varphi\right|\left|\varphi(\varphi-1)\right|$, $\mathbf{n} = \frac{\nabla\varphi}{\left|\nabla\varphi\right|}$ and σ is the interfacial tension.

The γ parameter controls the interface thickness and was assumed to be equal to the mesh size. Interface is reinitialised using the ε parameter which is approximated to the maximum velocity of the flow.

A smeared out Heavisides function was used to calculate density (ρ) and viscosity (μ) based on the respective fluids.

$$\rho = \rho_o + \left(\rho_o - \rho_w\right)\varphi \qquad \text{Equation 5}$$

$$\mu = \mu_o + \left(\mu_o - \mu_w\right)\varphi \qquad \text{Equation 6}$$

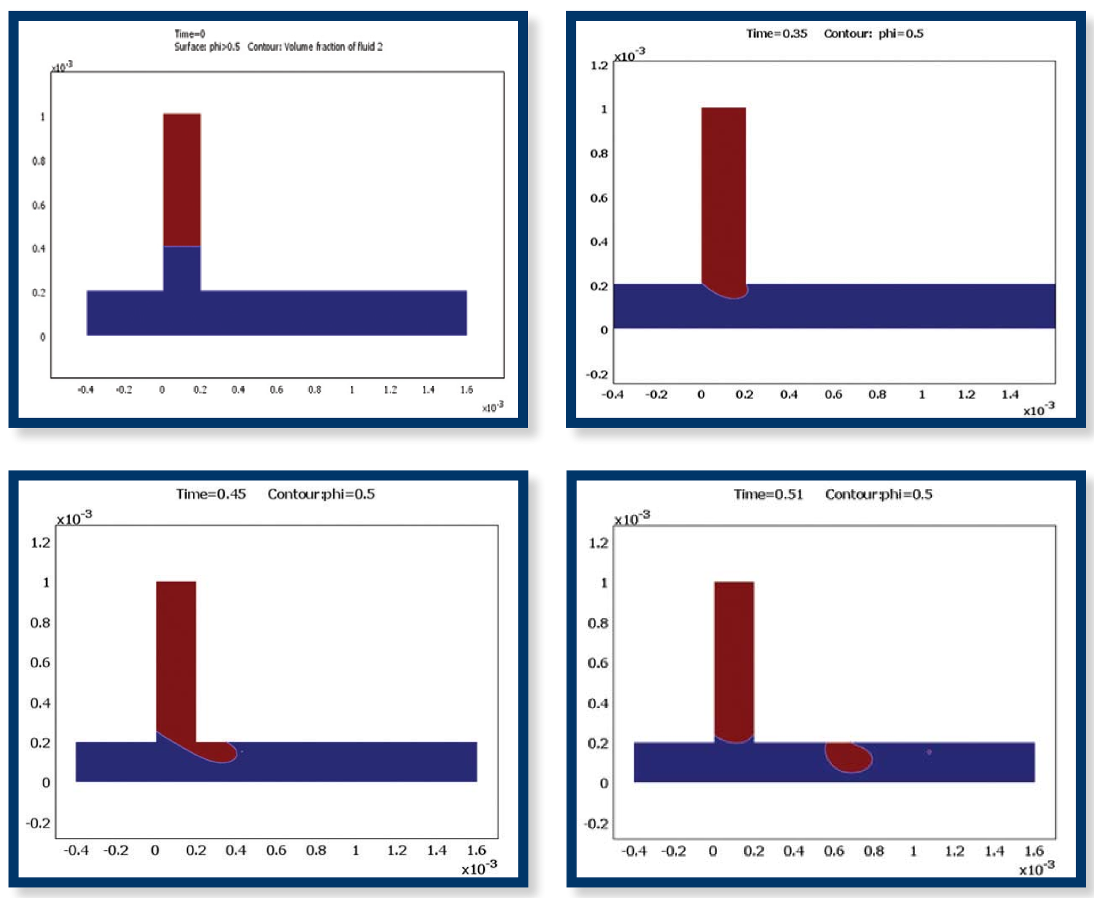

Figure 5: Snapshots of two-dimensional (2D) simulation sequence of w/o droplet formation in microfluidic T-junction corresponding to the experiment shown in Figure 2.

CONLUSIONS

Various two-phase flow regimes exist in a microfluidic T-junction as a function of the capillary number and the relative flows of the two immiscible fluids. Experiments and CFD provide useful tools for further study of biphasic microfluidic flows.

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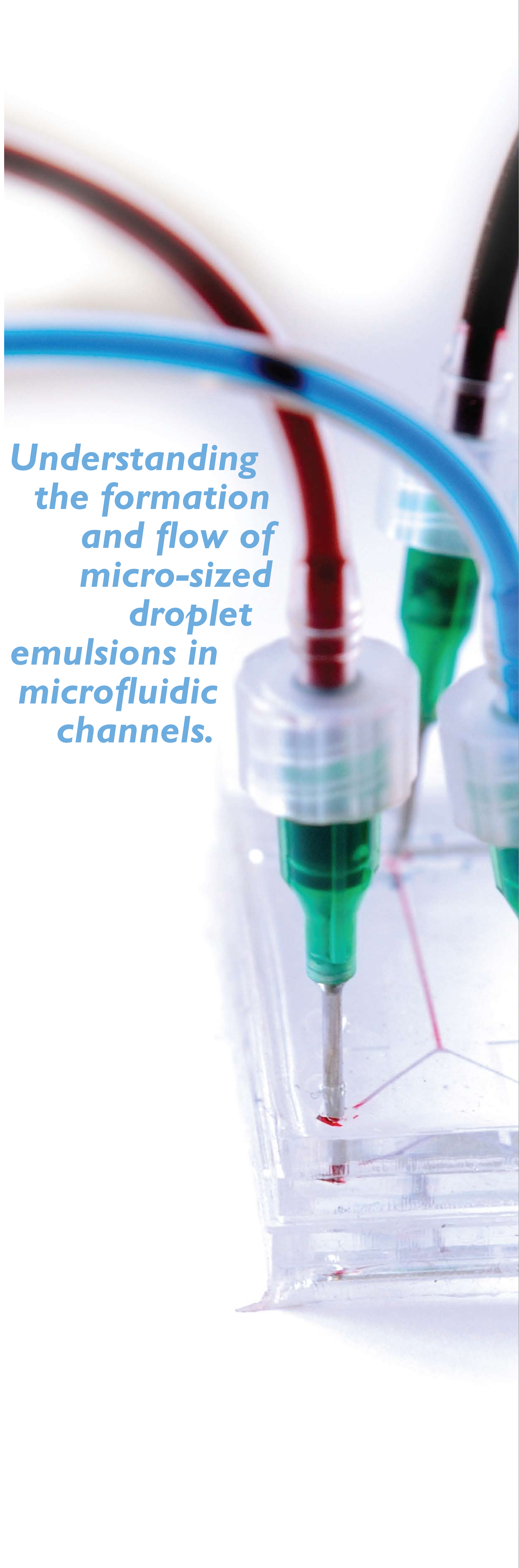

Understanding the formation and flow of micro-sized droplet emulsions in microfluidic channels.