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Dynamics of magnetic modulation of ferrofluid droplets for digital microfluidic applications

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Active control of droplet generation in a microfluidic platform attracts interest for development of digital microfluidic devices ranging from biosensors to micro-reactors to point-of-care diagnostic devices. The present paper characterizes, through an unsteady three-dimensional Volume of Fluid (VOF) simulation, the active control of ferrofluid droplet generation in a microfluidic T-junction in presence of a non-uniform magnetic field created by an external magnetic dipole. Two distinctly different positions of the dipole were considered – one upstream of the junction and one downstream. While keeping the ferrofluid flow rate fixed, a parametric variation of the continuous phase capillary number, dipole strength, and dipole position was carried out. Differences in the flow behaviour in terms of dripping or jetting and the droplet characteristics in terms of droplet formation time period and droplet size were studied. The existence of a threshold dipole strength, below which the magnetic force was not able to influence the flow behaviour, was identified. It was also observed that, for dipoles placed upstream of the junction, droplet formation was suppressed at some higher dipole strengths, and this value was found to increase with increasing capillary number. Droplet time period was also found to increase with increasing dipole strength, along with droplet size, i.e. an increase in droplet volume.

1. Introduction

The subdomain of microfluidics where fluid volumes are handled by manipulating discrete, individual droplets by means of an external field or actuation is termed ‘digital microfluidics’. The advantage of digital microfluidics, in contrast to traditional continuous microfluidics, lies in the considerable reduction in the volume of analyte used. Moreover, difficulties in handling toxic material and cross-contamination in microchannels are also mitigated. In digital microfluidic platforms, each droplet acts as an individual, isolated reaction chamber, thus resulting in the increased flexibility and programmability as compared to channel-based microfluidics. Thus, digital microfluidics can be used in applications where a high degree of flexibility is required [1]. These advantages have led to the successful integration of digital microfluidics in ‘Lab-on-a-chip’ applications. Significant application areas of digital microfluidics include proteomics [2], point-of-care diagnostics [3], molecular probe synthesis [4], immunoassays [5], cell culture [6], and chip-based PCR [7], among others [8–10].

For a functional digital microfluidic device, the two most important components are the droplet generation system and the droplet actuation system. From an operational point of view, microfluidic droplet generation configurations that are popular in the community include co-flow devices [11–13], flow-focusing devices [14–17], and T-junctions [18–21]. The methods of manipulation of droplets in digital microfluidic devices can be diverse, such as electrical [22,23], optic [24], electrophoretic [25], dielectrophoretic [26], and magnetic [27,28]. Ferrofluids provide a viable option for the choice of fluid in magnetically actuated digital microfluidic systems.

Ferrofluids are colloidal suspensions of single domain magnetic nanoparticles, typically of 5–15 nm diameter, containing Ni, Co, Mg, or Zn compositions of ferrite (Fe_2O_4), magnetite (Fe_3O_4), or maghemite (g-Fe_2O_3) in a nonmagnetic liquid (aqueous or hydrocarbon) carrier phase [29,30]. The particles at this size range exhibit superparamagnetic nature, implying that the particle magnetization curves do not show any hysteresis, although their

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Nomenclature

b	characteristic droplet width
f	volume fraction
$\vec{F_s}$	body force due to surface deformation
$\vec{H}$	magnetic field
$\vec{M}$	magnetization
p	pressure
t	time
$\vec{V}$	velocity vector
V_0	volume of droplet in non-magnetic case
x, y, z	coordinates
Ca	capillary number
$\vec{F_m}$	magnetic Kelvin Body Force
h	characteristic droplet height
m	magnetic dipole strength
$\hat{n}$	unit normal vector
$\vec{r}$	position vector
U_{cp}	continuous phase velocity
V	volume of droplet
V_e	percentage of excess volume of droplet

Greek symbols

κ	curvature of the interface
μ_0	permeability of free space
σ	interfacial tension
χ	magnetic susceptibility
μ	viscosity
ρ	density
τ	droplet shedding time period

Subscripts

c	continuous phase pressure probe
1	continuous phase property
d	discrete phase pressure probe
2	discrete phase property

magnetization is comparable to ferri- or ferromagnetic particles. While such a ferrofluid is nonmagnetic in the absence of a magnetic field, the magnetic moments of the superparamagnetic nanoparticles of ferrofluids are readily aligned (against the thermal Brownian disturbance) with an externally imposed magnetic field, making the fluid magnetically responsive. This feature is advantageous, since transport of individual ferrofluid droplets can be influenced by 'action at a distance' in microfluidic environment either by an active device, e.g., a miniaturized permanent magnet or electromagnet, or by a passive device, e.g., a macro-scale biasing magnet in conjunction with micro-scale magnetizable elements for creating local field gradient. Ferrofluids have been extensively used in microfluidics [31], having diverse application areas.

In the context of droplet generation at a T-junction, the capillary number ($Ca = \frac{\mu U_{cp}}{\sigma}$, where μ and U_{cp} are the viscosity and velocity of the continuous phase, respectively, and σ is the interfacial tension) plays a key role. Existing literature [18,32] shows that there are three major regimes of flow at a microfluidic T-junction: squeezing, dripping, and jetting (see the schematic diagram in Fig. 1). In the squeezing regime ($Ca \leq 10^{-2}$), the interfacial force is much stronger and dominates over the shear force

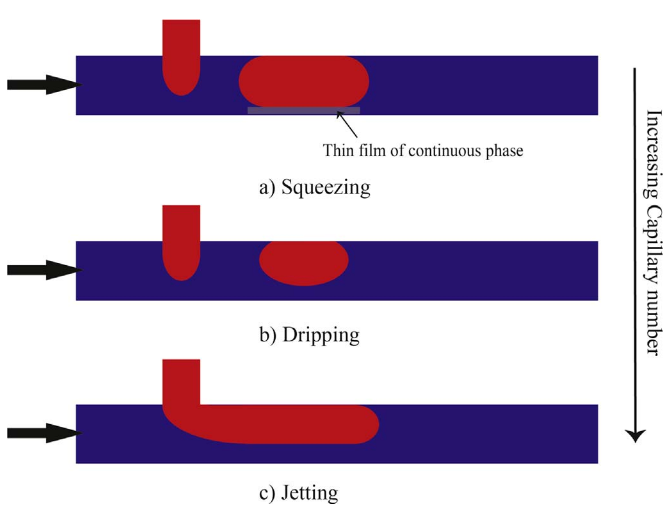

Fig. 1. Schematic of the three distinct regimes of flow through a microfluidic T-junction.

(Fig. 1(a)). The dispersed phase, in this regime, blocks off almost the entire cross-sectional area of the main channel, reducing the continuous phase to a thin film between the dispersed phase and the walls of the channel. The resulting pressure difference squeezes the neck of the dispersed phase, thus forming droplets. Droplet volumes in the squeezing regime are governed by the ratio of the flow rates of the two fluids. At a higher value of $Ca(\approx 0.025)$, the shear forces become significant for droplet generation, and this regime is known as the dripping regime (Fig. 1(b)). At an even higher Ca, droplet formation is not observed. Instead, the dispersed phase enters the main channel and flows parallel to the continuous phase; the regime being known as the jetting regime (Fig. 1(c)).

Ferrofluid droplet-based digital microfluidic platform has the unique advantage of magnetic manipulation of the dispersed magnetic phase to alter the droplet dynamics. However, dynamic interaction of magnetic, surface tension, and viscous forces makes investigation of such a system extremely complicated. Early work [33] on the dynamics of ferrofluid droplet breakup, as it passed through a narrow orifice, showed strong influence of orifice diameter on the droplet size and stretching length, while the number of total breaking droplets depended on the orifice diameter and local magnetic field. Sivasamy et al. [34] demonstrated CFD modelling of the droplet generation at a microfluidic T-junction using the VOF method; however, the effect of magnetic field was not considered in that work. The literature, therefore, lacks in a comprehensive understanding of the different regimes of droplet generation and its interdependence with the applied magnetic field.

Digital microfluidics obviously has advantages of flexibility and precise control, but the robustness of channel-based microfluidics is unmatched. In the present work, an attempt has been made to bridge the two apparently contrasting aspects of robust droplet generation and precise control of dynamics inside a T-junction microchannel. Although ferrofluid droplet generation has been studied both experimentally [35–38] and numerically [39] in other droplet generating geometries such as flow-focusing, such an investigation was lacking in a T-junction geometry. A numerical investigation of ferrofluid droplet generation in a surfacted medium in a T-junction microchannel in the presence of an externally imposed magnetic field is carried out. The motivation of the present work lies in understanding the fundamental flow physics of