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Numerical Study of MHD Effects on Drop Formation in a T-Shaped Microchannel

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***Abstract*—**The effect of a uniform magnetic field on the formation of drops of specific size has been investigated numerically in a T-shaped microchannel. Previous researches indicated that the drop sizes of secondary stream decreases, with increasing main stream flow rate and decreasing interfacial tension. In the present study the effect of a uniform magnetic field on the main stream is considered, and it is proposed that by increasing the Hartmann number, the size of the drops of the secondary stream will be decreased.

***Keywords*—**Drop formation, Magnetohydrodynamics, Microchannel, Volume-of-Fluid

I. INTRODUCTION

THE applications of MicroElectroMechanical Systems (MEMS) are developed extensively in recent decades.

Microfluidic systems play an important role in a wide range of MEMS devices. Lab-On-a-Chips (LOCs) are a subset of MEMS devices that are capable of handling great biotechnological and chemical operations, such as detection of cancer cells and testing blood samples [1], [2]. Microfluidics used in these applications are multiphase in general. Drop-based microfluidics are mostly preferred because of low consumption of samples and reagents, minimal dispersion, and flexible control of droplets' volumes [3], [4]. The size of the droplets can be controlled by changes in internal forces which are determined by fluid properties, such as interfacial forces, inertial forces, and viscous forces, or by exerting external fields, e.g. electrical, magnetic, and thermal fields, and so on [3], [4]. The unique advantages of *MHD actuation*, made it an alternative suitable way to control and manipulate droplet sizes. It is independent of PH, Ionic strength, and surface charge of the materials and therefore compatible with a broad range of materials and biochemical processes [3]. Preparation of an external magnetic field is not a complicated task and simply done by embedding a permanent magnet or an electromagnet around the microchannel.

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If the conductivity of the desired fluid is low, a defined quantity of *superparamagnetic particles* is added to the stream, so the fluid flow is affected by the draw force of these particles [3].

It should be noted that the order of Interfacial tension in micro- and nanoscales is high relative to the other forces [2], so it cannot be neglected and should be modeled correctly.

In the present study, a numerical simulation of a uniform magnetic field, exerting to the main stream of a T-shaped microchannel has been carried out, and the variation in drop sizes of secondary stream will be investigated.

II. MATHEMATICAL FORMULATION

A *volume-of-fluid* (VOF) interface tracking technique is used for interface calculations. A complete description of VOF method can be found elsewhere [5] and just a brief description is mentioned here.

A *color function* "C" is introduced in VOF method for tracking the interface. It is defined as:

$$C = \begin{cases} 1, & \text{if the cell is completely filled with the reference phase} \\ 0, & \text{otherwise.} \end{cases}$$

"C" may be varied between 0 and 1 with respect to the volume fraction of the phases in a cell.

Governing equations are as follows:

Continuity equation:

$$\nabla.\boldsymbol{V} = 0 \tag{1}$$

Fluid species transport equation:

$$\frac{\partial C}{\partial t} + \nabla.(\boldsymbol{V}C) = 0 \tag{2}$$

Momentum equation:

$$\rho\frac{D\boldsymbol{V}}{Dt} = -\nabla P + \rho\boldsymbol{g} + \mu\nabla^2\boldsymbol{V} + \boldsymbol{F}_S + \boldsymbol{F}_B \tag{3}$$

$\boldsymbol{V}$ is the velocity vector, P is the pressure, $\boldsymbol{F}_S$ is the surface tension force, $\boldsymbol{F}_B$ is the force caused by magnetic field called Lorentz force, $\boldsymbol{g}$ is the gravitational vector, and ρ and μ are the density and viscosity of the fluid respectively. The density and viscosity of the fluid can be estimated using weighted averages of different phases:

$$\rho = \rho_1 C + \rho_2 (1 - C) \tag{4}$$

$$\mu = \mu_1 C + \mu_2 (1 - C) \tag{5}$$

Surface tension is just applied at interfaces and can be expressed as [6]:

$$\boldsymbol{F}_S = \sigma_S \kappa \boldsymbol{n} \tag{6}$$

$\boldsymbol{n}$ is the interfacial normal vector and κ is the curvature of the interface, and both are defined as functions of the color function:

$$\boldsymbol{n} = \frac{\nabla C}{|\nabla C|} \tag{7}$$

$$\kappa = -\nabla . \left(\frac{\nabla C}{|\nabla C|} \right) \tag{8}$$

σ_S is the fluid surface tension coefficient (in newtons per meter).

The Lorentz force is calculated from the formula:

$$\boldsymbol{F}_B = \boldsymbol{J} \times \boldsymbol{B} \tag{9}$$

Where $\boldsymbol{J}$ is the current density (in amperes per meter squared) that computed from the Ohm`s law:

$$\boldsymbol{J} = \sigma_B (\boldsymbol{E} + \boldsymbol{V} \times \boldsymbol{B}) \tag{10}$$

TABLE I
PHYSICAL PROPERTIES

	Density(kg/m3)	Viscosity(kg/(m·s))	Interfacial tension(N/m)
Tetradecane	773.0	3.19×10^{-3}	0.0442
Water	998.2	1.0×10^{-3}	

All the properties are at the temperature of 20°C.

σ_B is the electrical conductivity (in reciprocal ohm meters), $\boldsymbol{E}$ is the electrical field (in volts per meter), and $\boldsymbol{B}$ is the magnetic field (in teslas) [7].

The direction of the Lorentz force vector is determined by the right hand rule.

In the present work, the gravitational force is neglected due to the micrometer scale of the channels, and no electrical field is used.

III. NUMERICAL IMPLEMENTATION

A 2D incompressible numerical scheme based on volume-of-fluid interface tracking technique is developed and a *Piecewise Linear Interface Calculation* (PLIC) method, with lagrangian advection is applied for accurate tracking of interface pieces [5]. A *SIMPLE* algorithm is used for numerical solution of momentum and continuity equations. Interfacial tension modeling is achieved using *Continuum Surface Force* (CSF) method [6], and an explicit finite difference is used for time advances.

A T-shaped microchannel with the channel width of 85 micrometers for the main stream inlet, and 30 micrometers for the secondary stream inlet is considered, as shown in Fig. 1. A mesh of 30×92 cells is used for the simulations. Tetradecane and water are selected for the main and secondary streams, respectively as used in simulations of Liow [8]. The fluid physical properties are listed in Table. 1. No slip boundary condition is assumed for channels walls [8].

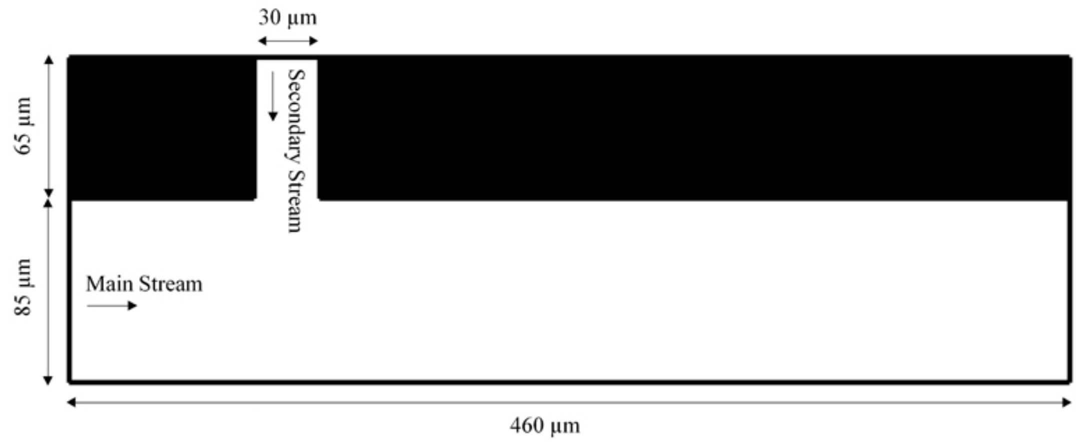

Fig. 1 Layout of the microchannel

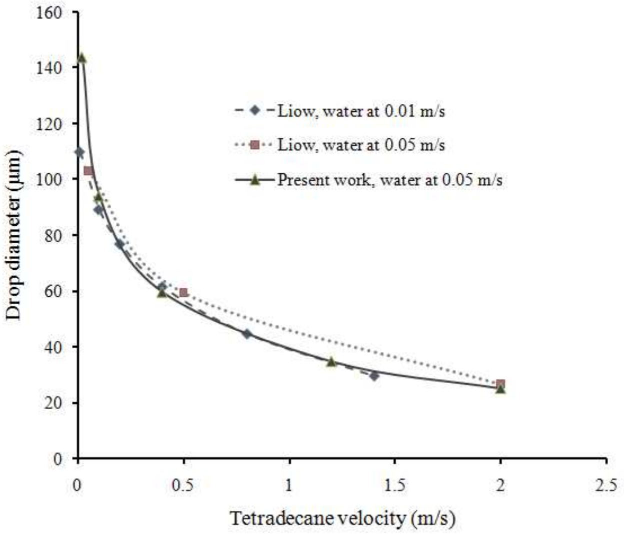

Fig. 2 Water drop size as a function of tetradecane velocity

IV. Results And Discussion

A similar simulation to a previous work, by Liow [8], is first carried out to verify the effect of changing main stream velocity on drop sizes. As shown in Fig. 2, the diameter of the generated drops of secondary stream is decreased, as the velocity of the main stream increased. The experimental results of Nisisako [9] (for different channel widths), shown in Fig. 3, have the same trends as present simulation.

Nisisako also reported that the drop sizes are decreased with increasing in secondary stream velocity, as can be observed in Fig. 3. The effect of interfacial tension on drop sizes was simulated by Liow and the decrease in drop diameters with a reduction in interfacial tension was shown numerically.

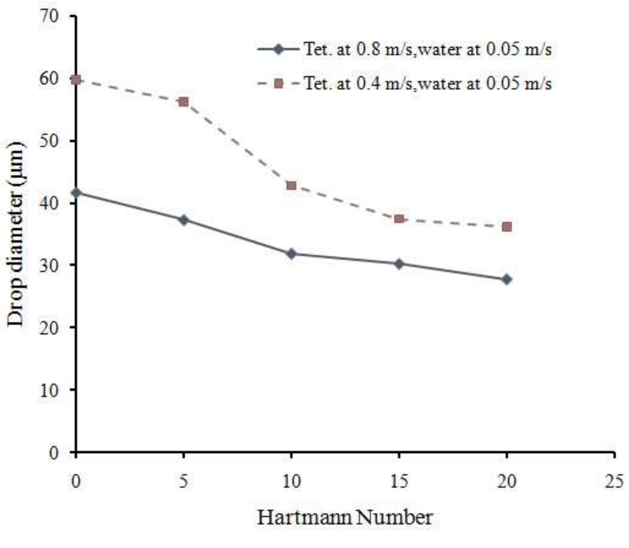

Fig. 4 Water drop size as a function of Hartmann number ("Tet." Stands for tetradecane)

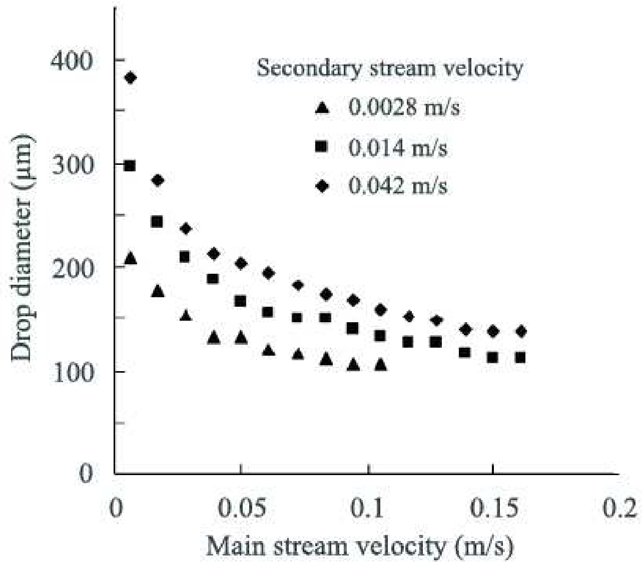

Fig. 3 Results of Nisisako [9] for water drop size as a function of tetradecane velocity

The variation in drop sizes under MHD effects is discussed in this part.

The *Hartmann Number* (*Ha*), is a nondimensional parameter, associated with MHD effects [7]. Hartmann number is the ratio of the magnetic forces to the viscous forces and defined as:

$$Ha = BL\sqrt{\frac{\sigma_B}{\mu}} \tag{11}$$

Where B is the magnetic field, L is characteristic length, and σ_B and μ are the electrical conductivity and viscosity of the fluid, respectively.

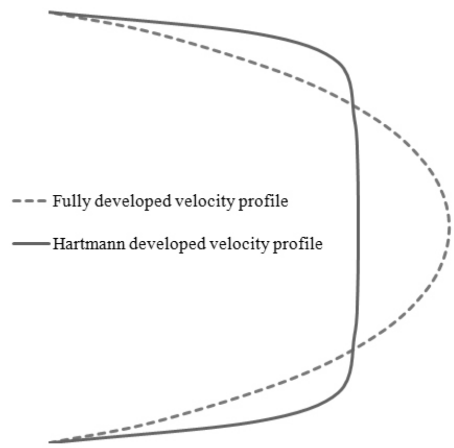

Fig. 5 A comparison of different types of velocity profile

The order of viscous forces in microscales is high, relative to the other forces (except interfacial forces) [4], and this causes Hartmann numbers of small magnitude in ordinary configurations of microfluidic systems. Low orders of Hartmann number does not have any influence on flow field. The influence of higher orders of Hartmann number can be observed in microscale flows. Higher orders of Hartmann number can be physically achieved by utilizing defined quantity of superparamagnetic particles that injected to the desired stream, as mentioned more in [3]. The surface of the superparamagnetic particles should be hydrophilic for sufficient adhesion between these particles and fluid particles, so the fluid flow is influenced effectively by the draw force of superparamagnetic particles.

In the present work, a magnetic field is applied to the main stream of the michrochannel and the effect of Hartmann number, varying between 0 to 20, is investigated on the size of the generated drops. Results are shown in Fig. 4. It can be observed that, as the Hartmann number increases, the diameter of the drops decreases. This is due to the velocity profile of the main stream affected by the magnetic field i.e. alike Hartmann developed velocity profile, as shown in Fig. 5. The exclusive property of manipulation of droplets using MHD effects is that drop diameter changes are occurred in constant flow rate of main stream, without any change in physical properties of the fluid (e.g. interfacial tension).

A detailed schematic representation of the separation of a droplet, is shown in Fig. 6.

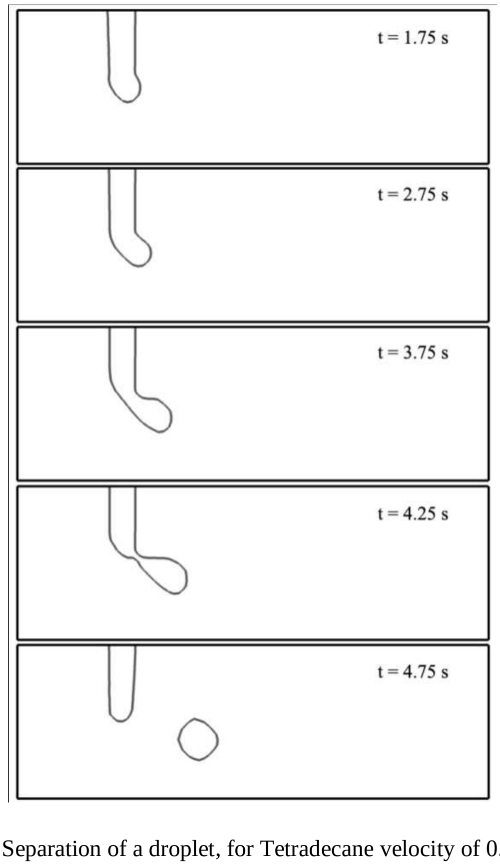

Fig. 6 Separation of a droplet, for Tetradecane velocity of 0.8 m/s, water velocity of 0.05 m/s, Ha = 5.

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