Numerical simulation of droplet formation in T-shape microchannel using two-phase level-set method

Mohammad Raad[1], Sajjadollah Rezazadeh[2*], Abdolrahman Dadvand[3]

[1] Master of science student, Urmia University of Technology
[2] Assistant Professor, Urmia University of Technology
[3] Associate Professor, Urmia University of Technology

ABSTRACT

In this study a two-dimensional (2D) numerical simulation using two-phase level set method (LSM) have been carried out to investigate the influence of continuous phase entrance flow rate on the microdroplets generation process. Analysis of the breakup process of microdroplets in immiscible liquid/liquid two-phase flow in T-junction microchannel was predicted. Governing equations on flow field have been discretized and solved using finite element method. Obtained numerical results were validated by comparing the experimental data reported in the literature which show acceptable agreement. Results show that the continuous phase entrance flow rate has a major effect on the size of generated droplets. Studies have shown that pressure diagram of the junction point can reflect the number of formed droplets and the triple stages of droplet formation. Also, Examinations of the pressure and velocity gradient inside the main channel show that the pressure difference of the droplet's tip and rear and shear force caused by viscosity dominates the droplet formation which the pressure difference between two side of droplet is more effective. Finally, it could be concluded that by increasing the inlet flow rate of continuous phase, needed force for overcoming the surface tension increases and more droplets with small sizes are generated in short time.

KEYWORDS

Microfluidic technology, two-phase flow, droplet formation, level set method, T-shape microchannel.

* Corresponding Author: Email: sor.mems@gmail.com

1. Introduction

Over the past three decades, micro Total Analysis Systems (micro-TAS) have been developed dramatically. These systems cover a wide range of microscopic activities including Lab-On-a-chip (LOC), nanomaterial synthesis, biology, chemistry, pharmaceuticals, emulsions and related industries.

The process of forming droplets from two immiscible liquids is one of the most important phenomena in multi-phase flows that is seen in many industrial and natural phenomena. This process has a wide range of applications in pharmaceuticals, microactors, cosmetics, food and polymer industries, biochemical analysis and DNA analysis. Controlling the amount of formed droplets within microchannels has always been the subject of study by previous researchers as one of the most important study items in terms to micro-TAS technology [1-3].

Numerous studies have been performed on droplet-based microfluidic (DBMF) technology and the impact of important parameters on droplet formation, including the effect of capillary number, viscosity ratio, flow ratio, vertical to horizontal channel width ratio, and pressure and velocity distribution near the channel junction [4-8] [4-8]. Little attention has been paid to examining the effective forces in the droplet formation process. In the present study, the two-phase liquid/liquid flow inside a T-shape microchannel is studied using the level set method. Aim of this study is investigate the effect of two acting forces on the droplet formation process (i.e. the force caused by the pressure difference between the two sides of the droplet and the shear force due to the velocity gradient) in different flow rates of the continuous inlet phase.

2. Computational procedure

2.1. Governing equations

The equations governing the problem are continuity, Navier-Stokes and Level Set (LS) equations which are given as follows:

$$\nabla.\vec{u} = 0 \qquad (1)$$

$$\rho\frac{\partial\vec{u}}{\partial t} + \rho\left(\vec{u}.\nabla\right)\vec{u} = -\nabla P + \mu\nabla^2\vec{u} + F_{st} \qquad (2)$$

$$\frac{\partial\varphi}{\partial t} + u.\nabla\varphi = \gamma\nabla.\left[\varepsilon\nabla\varphi - \varphi\left(1-\varphi\right)\frac{\nabla\varphi}{|\nabla\varphi|}\right] \qquad (3)$$

In the above equations ρ represents the density (kg.m^{-3}), u is the velocity vector (m.s^{-1}), t is time (s), P is pressure (Pa), μ in dynamic visibility (Pa.s), F_{st} is volumetric force (N), σ represent surface tension (N.m^{-2}), φ denotes level set function (dimensionless), γ and ε are numerical stabilization parameters.

2.2. Geometry

Figure 1 schematically shows the geometry used in this study. As shown in Figure 1, fluid 1 enters the channel through the horizontal channel from its left side, and fluid 2 enters the channel through the vertical channel.

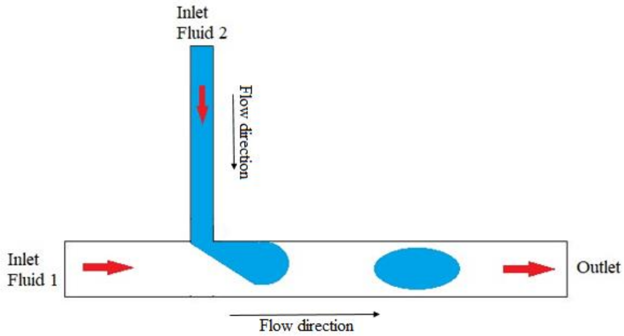

Figure 1. Used geometry

2.3. Boundary conditions

At the channel inlets, the boundary condition of the laminar inlet flow with a specified and developed volumetric flow rate has been applied. For the outlet of the channel, the boundary condition of constant pressure is considered. Also, wet wall boundary condition with a specific contact angle of 180 degrees has been applied on the channel walls.

3. Results and Discussions

Inside the T-shaped microchannel, the scattered phase becomes an integral element separated by a continuous phase. This process have a complex mechanism in which the forces of surface tension, viscous shear, and the pressure difference between two sides of the droplet are involved. The schematic of the effective forces acting in the droplet formation process is shown in Figure 2. These forces depend on the physical properties of two fluids (viscosity and surface features), channel geometry (channel width and depth), and flow conditions (flow rate and velocity).

Two-phase flows are divided into several main groups based on the common surface structures which are called flow regimes. Main two-phase droplet formation regimes include slug (or squeezing), droplet (or dripping), jet, and parallel.

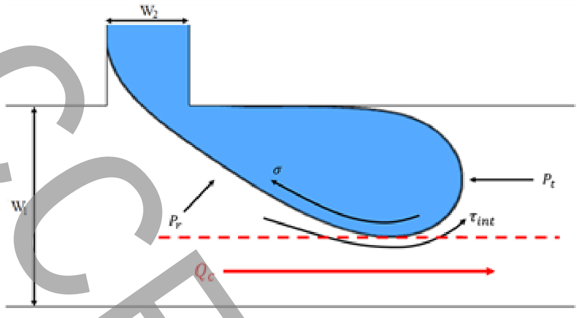

Figure 2. Schematic of the forces acting on a forming droplet

Since the shear force acting on the droplet is related to the velocity gradient, the shear force increases with increasing velocity gradient. The shear force along with the pressure difference between two sides of the droplet overcomes the surface tension. However, the amount of shear force is negligible compared to the force due to the pressure difference between the two sides of the droplet. According to obtained results (Table 1), it is clear that as the inlet flow rate of the continuous phase increases, the amount of both shear stress on the wall and the pressure difference between the two sides of the droplet increase. In the same continuous phase input flow rate, the amount of pressure difference between the two sides of the droplet is greater than the shear stress.

Table 1. Comparison of the pressure difference between the two sides of the droplet with shear tension at different inlet flow rates of the continuous phase

Inlet flow rate of continuous phase (ml/h)	Shear tension (Pa)	Pressure difference between two sides of droplet (Pa)
2	1.441	134
4	2.046	249
6	2.600	255

4. Conclusions

In this paper, the two-phase level set method is used to simulate the process of droplet formation in a T-shape microchannel. The effect of the continuous phase inlet flow rate on droplet size, pressure and velocity gradient within the main channel has been investigated. Followings are the most important results obtained from the present numerical solution:

1- As the inlet flow rate of the continuous phase increases, more droplets with smaller size are produced in a shorter time.

2- The number of formed droplets and the three stages of droplet formation process can be extracted well using the pressure diagram at the junction of vertical and horizontal channels.

3- Increasing the inlet flow rate of the continuous phase changes the pressure diagram at the intersection of the two vertical and horizontal channels.

4- Increasing the inlet flow rate of the continuous phase increases the two effective forces in the droplet formation process, i.e. the force caused by the pressure difference between the two sides of the drop and the shear force.

5- The effect of shear force is less than the force due to the pressure difference between the two sides of the drop in the droplet formation process.

5. References

[1] V.-L. Wong, K. Loizou, P.-L. Lau, R.S. Graham, B.N. Hewakandamby, Numerical studies of shear-thinning droplet formation in a microfluidic T-junction using two-phase level-SET method, Chemical Engineering Science, 174 (2017) 157-173.
[2] B. Pulvirenti, B. Rostami, G. Puccetti, G. Morini, Determination of droplet contours in liquid-liquid flows within microchannels, in: Journal of Physics: Conference Series, IOP Publishing, 2015, pp. 012028.
[3] A. Günther, M. Jhunjhunwala, M. Thalmann, M.A. Schmidt, K.F. Jensen, Micromixing of miscible liquids in segmented gas− liquid flow, Langmuir, 21(4) (2005) 1547-1555.
[4] T.B. Jones, M. Gunji, M. Washizu, M. Feldman, Dielectrophoretic liquid actuation and nanodroplet formation, Journal of applied Physics, 89(2) (2001) 1441-1448.
[5] S.H. Tan, B. Semin, J.-C. Baret, Microfluidic flow-focusing in ac electric fields, Lab on a Chip, 14(6) (2014) 1099-1106.
[6] J. Wang, Y. Li, X. Wang, J. Wang, H. Tian, P. Zhao, Y. Tian, Y. Gu, L. Wang, C. Wang, Droplet microfluidics for the production of microparticles and nanoparticles, Micromachines, 8(1) (2017) 22.
[7] I.-L. Ngo, S. Woo Joo, C. Byon, Effects of junction angle and viscosity ratio on droplet formation in microfluidic cross-junction, Journal of Fluids Engineering, 138(5) (2016).
[8] A. Gupta, R. Kumar, Effect of geometry on droplet formation in the squeezing regime in a microfluidic T-junction, Microfluidics and Nanofluidics, 8(6) (2010) 799-812.