Numerical investigation of bubble diameter in branched microchannel

Balasekhar C S K, P Tanish, Ayush Mishra, Atul Kushwaha and Pankaj Kumar
Department of Mechanical Engineering, SRM Institute of Science and Technology, Kattankulathur, Chennai, Tamil Nadu, India

E-mail: pankajkr@srmist.edu.in

Abstract. With growing importance of microchannel in notable fields like medical, aerospace, food industry, it is necessary to improve the accuracy of pre-determining the mean droplet size to its maximum. We have analysed the various parameters that can influence the bubble size formed. Our main objective is to derive a relationship between diameter of microchannel, length of the junction, emulsion flow rate, and mean droplet diameter so that we would be able to determine the emulsion properties beforehand. It was found that bubble size increases as flowrate of continuous phase decreases.

1. Introduction

Research in Microfluidic Devices has grown tremendously for the past decade especially in the field of biomedical devices and analysis methods. Such microfluidic devices are used for cell sorting, fluidic mixing, Micro Total Analysis Systems (µTAS) which aims at better sensing, separation, mixing and chemical reactions.

Microfluidics is the manipulation of micro volumes of fluids in immiscible phases in laminar flow regimes. It allows the feasibility of handling miniature volumes of fluid conveniently, provide better mixing, encapsulation, sorting and sensing. Reduced sample size and reagent consumption along with higher surface to volume ratio makes this possible. Microfluidic synthesis application is being utilized for purposes like alternate droplet generation which is employed in controlled fusion mixing [2], efficient mixing and rapid chemical reactions at nanolitre and picolitre scale. Microchannel geometries are also used for better droplet size control [3], which improves scientific opportunities in physical, chemical and biological analysis. This increases the accuracy and efficiency of microfluidic devices and sensors employed. Major applications in the biological analysis include micro-scale nebulizers [4] and crystallization and analysis of proteins [5].

For droplet formation, there are two types of Microfluidic devices, namely, active and passive devices. Active devices need an external energy sources like mechanical, acoustic [6], ultrasonic, electro kinetic or even magnetic [7]. Although they provide better efficiency, the energy required for such small-scale devices is high. Because of this primary focus has been given to passive devices.

Different passive droplet generation techniques include T-junction, co-axial and flow focusing, out of which T junction has been used widely because of its simple geometry and for their ability to create complex droplets or manipulate them in whatever way we choose to. Geometry dependence [8], interfacial tension and viscosity [9] for a T-junction has been studied extensively at different flow regimes [10-11]. Parallel microfluidic systems can also be employed for improving the droplet generation intensity [12]. Using double-T junction microchannel, droplets of reagents can be generated at different ratios and fused, which enables better mixing and would result in precise chemical
reactions on a single chip. This improves the efficiency of chemical analysis done at an extremely small-scale level [13].

The dependence of geometry in the double-T junction has been studied in this paper. The change in bubble size is being studied by varying the diameter of the discrete phase inlet. The length of the channel in the junction has also been varied for determining the dependence of the bubble formation.

Furthermore, the dependence of the continuous phase flow rate on the bubble diameter is also analysed. A numerical simulation of the different geometry is performed in order to arrive at the conclusion. Major application of this field includes targeted drug delivery and reaction analysis of two fluids.

2. Numerical analysis

In the current work, an incompressible, laminar, steady-state, three-phase flow is considered in the microchannel. The flow is numerically modelled using the Volume of Fluid approach, and the governing equations for the simulation is given below.

Continuity Equation:

\[ \nabla \cdot (\rho_i \varphi_i \vec{V}_i) = 0 \]  \hspace{1cm} (1)

\[ \nabla \cdot (\rho_p \varphi_p \vec{V}_p) = 0 \]  \hspace{1cm} (2)

Where the volume fraction of continuous and discrete liquid are related as,

\[ \varphi_i + \varphi_p = 1 \]  \hspace{1cm} (3)

Momentum equation:

\[ (\rho_c \varphi_c \vec{V}_c) = -\varphi_i \vec{V}_i + \nabla \cdot [\varphi_c \mu_c (\vec{V}_c + \vec{V}_i^T)] \]  \hspace{1cm} (4)

\[ \nabla \cdot (\rho_d \varphi_d \vec{V}_d) = -\varphi_d \vec{V}_d + \nabla \cdot [\varphi_d \mu_d (\vec{V}_d + \vec{V}_i^T)] \]  \hspace{1cm} (5)

Non-dimensional Reynolds number is defined below

\[ Re = \frac{\rho \vec{V}_{in} D_h}{\mu_i} \]  \hspace{1cm} (6)

This study includes six different geometry as it compares the effect of junction length and diameter of discrete phase against the change in droplet diameter which is depicted in fig 1. The diameter of continuous phase inlet (d) is constant 100 \( \mu m \) for all geometry. The depth of the channel is 100 \( \mu m \) with the height after the junction kept at 200 \( \mu m \) in order to prove a minimal shear stress region for bubble formation.

![Figure 1](image)

**Figure 1.** Computational domain of the microchannel used in numerical simulation.
First three of six geometry has constant discrete phase diameter (D) of 120 \( \mu m \) and the junction length (L) varies as 3.33D, 4.16D, 5D respectively. Latter three geometry has constant junction length of 500 \( \mu m \) and diameter varies as 0.2L, 0.3L, 0.4 L respectively. In the discrete phase inlet DI water + 40% glycerol is given as input at a constant flowrate of 1.8 \( l/s \). Inlet flow rate of continuous phase inlet is varying at 4 \( l/s \), 8 \( l/s \), 12 \( l/s \) and 15 \( l/s \) respectively with Mineral Oil + surfactant flowing in them. Ansys Fluent\textsuperscript® was used to solve the above governing equations numerically. The Pre-processing of the contour image obtained was done using MATLAB. Image processing includes addition of the pixels involved in the contour to determine the diameter of bubble. Firstly, the average diameter of the bubble in the digital image was obtained. The number of bubbles analysed is increased to improve accuracy. The digital height obtained in pixels is then converted in terms of \( \mu m \), which is the required value.

![Typical mesh used for numerical simulation.](image)

**Figure 2.** Typical mesh used for numerical simulation.

The meshing is done by sizing of the 2D geometry where elements are divided to give accurate value. Example of Mesh used in the study is given in the Fig 2. The resulting mesh is unstructured and has an average of approximately 10000 elements for each geometry. They have one cell zone and 6 face zones.

3. Result and discussion

The bubble formation and its size in double T-Micro channel are obtained at various flow rates, discrete phase inlet diameter and junction length.

3.1. **Discrete phase inlet diameter**

The effect of discrete phase inlet diameter on the bubble size is shown in Fig 3. With increase in diameter of discrete phase inlet at constant flow rate, decrease in bubble size was observed. It can be seen that, at higher diameter of discrete phase inlet like 200 \( \mu m \), the bubble size has the least for the respective flow rate. As the flow rate increases, the bubble size decreases for the same inlet diameter of discrete phase. This is because, as there is increase in diameter the shear stress experienced by the discrete phase liquid at the inlet reduces significantly.
**Figure 3.** Variation of Bubble Size Diameter for Constant Junction Length(L) and different Discrete Phase Diameter(D).

### 3.2 Flow rate of continuous phase

![Image of flow rate diagram](image)

**Figure 4.** Bubble Size formed for geometry D=150 $\mu m$ and L=500 $\mu m$ for different Flow Rate(Q)

(a) $Q_c=4\frac{ml}{s}$  (b) $Q_c=8\frac{ml}{s}$  (c) $Q_c=12\frac{ml}{s}$  (d) $Q_c=15\frac{ml}{s}$

The volume fraction contours for different flow rates for microchannel with characteristic dimension of D=150 $\mu m$ and L=500 $\mu m$ are depicted in Fig 4(a), 4(b), 4(c) and 4(d) and for characteristic dimension of D=120 $\mu m$ and L=500 $\mu m$ are depicted in Fig 5(a), 5(b), 5(c) and 5(d). Bubble size decreases linearly for the rise in flow rates for each geometry and this can be attributed to less accumulation of discrete phase liquid at the higher flow rates. As we keep on decreasing the flow rate of continuous phase, at the certain point the shear force experience by the discrete phase would not be sufficient for formation of the bubble.
3.3. Junction length

Fig 6 depicts the dependence of the bubble size on the varying Junction length. From the figure, it is evident that the rise in junction length at constant flow rate gives to a linear decrease if bubble size and have a significant influence. Also, at higher flow rates, the change in junction length doesn’t influence bubble size much. However, there is significant change in the bubble size as flow rate of continuous phase is lowered and obeys the trend.

4. Conclusion

In this paper, we have conducted numerical studies on the double-T junction micro channel in order to determine the dependence of geometry of the micro channel on the Bubble diameter ($D_b$). Mineral oil+ surfactant was used as continuous phase liquid and 40% aqueous glycerol was used in discrete phase inlet. Observations were made for geometry with constant junction length and varying discrete inlet.
diameter and also for constant discrete phase inlet diameter for constant Junction length (L). For all the geometry in study, the continuous phase inlet is kept at 100 $\mu m$ and the discrete phase inlet is maintained at the flow rate of $1.8 \frac{\mu l}{s}$.

Following observations were made during the study,

- The diameter of the bubble decreases with increase in Discrete Phase diameter (D) for a constant Junction Length (L).
- Bubble size increases with increase in Length of the Junction (L) for the same Discrete Phase diameter (D).
- As the flow rate of the continuous phase (Q) increases the bubble diameter ($D_b$) decreases.

Nomenclature

**Abbreviations**

- $D_b$: Bubble Size Diameter
- D: Diameter of discrete phase inlet ($\mu m$)
- d: Diameter of continuous phase inlet ($\mu m$)
- H: Junction outlet height ($\mu m$)
- L: Junction length ($\mu m$)
- $Nu$: Nusselt number
- Re: Reynolds number
- Q: Flow rate of the Continuous phase ($\mu l/s$)
- $Q_d$: Flow rate of the discrete phase ($\mu l/s$)
- $u, v$: Velocity components in the x and y directions, respectively (m/s)
- $\vec{V}$: Velocity vector (m/s)
- T: Temperature (K)

**Greek Symbols**

- $\rho$: Density of fluid [kg/m$^3$]
- $\mu$: Viscosity of fluid
- $\varphi$: Volume concentration
- $\eta$: Dynamic viscosity

**Subscripts**

- L: Liquid phase
- P: Particle phase
- In: Inlet

5. References

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