

Experimental Investigation on Droplet Formation through a Minichannel Y- Junction

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Abstract. Start your abstract It is a challenging task to understand the bubble formation mechanism and to predict the size distribution of bubbles and its length. Different mechanisms are involved in the generation of bubbles. The objective of the study is to understand the detailed mechanisms of surface breaking and bubble generation due to interactions between boundary-layers (BL) and free-surfaces (FS) in two phase air water flow regimes. In present work an experiment is performed on isothermal two phase flow through minichannel to investigate the droplet formation mechanism. Effect of dimensional number and superficial velocities of gas and liquid on droplet formation is studied. Results show that when the superficial velocity of gas is increased, the bubble length is observed to increase while increasing the superficial velocity of liquid decreases bubble length. It is also observed that by increasing Reynolds number of dispersed phase (air), bubble length increased while increasing Reynolds number of continuous phase (water) bubble length is observed to decrease. Capillary number also plays a significance role in droplet formation which describe in the paper.

1. Introduction

Two phase flow is the simplest case of multiphase flow in which two phase are present as component. Two-phase flow is classified into two major categories such as dispersed flow or separated flow. A dispersed phase flow is defined as the flow in which one phase consists of discrete elements, such as droplets in a gas or bubbles in a liquid. In a separated flow, a line of contact separates the two phases. Droplet formation can be considered as the first step in the mini/microfluidic system. The formation of droplets in two-phase flows through miniscale is achieved by shearing one liquid into another, immiscible one. The main channel carries the continuous fluid (water) and the orthogonal channel supplies the fluid that will be dispersed (air) (Garstecki et al. 2006). Micro-droplets have been used widely to increase the diffusion rates between the interfaces of two immiscible fluids and have many applications in the chemical and bio-chemical fields. Two main regimes can be distinguished for drop or slug formation as the parameters are varied: Dripping or Shearing and Squeezing. In the Dripping (breakingslug) regime, droplet breakup occurs when the viscous shear stress overcomes the interfacial tension, analogous to the breakup of spherical droplets. In the Dripping or Shearing regime, the main direction of the continuous (liquid) phase is along the interface and the interface will break off in the main stream near the upper wall. In this regime, droplets break when the viscous shear stress overcomes the interfacial tension, corresponding to spherical droplet breakup (GuH. et al. 2011). In the Squeezing (snapping slug) regime, the main flow direction of the continuous (liquid) phase is perpendicular to the gas-liquid interface and the continuous (liquid) phase pushes the interface toward the corner of the wall and the interface will break at the sharp corner (T or Y joint). This causes a dramatic increase of the hydrodynamic pressure in the upstream part, which in turn induces the pinch-off of the droplets. This is the so-called squeezing regime (Bedram, A., & Moosav, A. 2013). In Dripping regime formation of droplets occurs at a higher capillary number flows, typically greater than 10⁻², In case of squeezing regime, formation of droplets occurs at a lower capillary number flows typically less than 10⁻². If the capillary number is chosen large enough, the droplets are emitted before



they can block the channel. Alternatively, if the capillary number is low, the formed droplets will obstruct the channel and hence restrict the continuous phase.

2. Literature Review

Santos, R. M., & Kawaji, M. (2010) experimentally and numerically investigated Gas–liquid two phase flow in a microfluidic T-junction with nearly square microchannels of 113 μm hydraulic diameter. Air and water superficial velocities were 0.018–0.791 m/s and 0.042– 0.757 m/s, respectively. They investigate slug formation in two phase microchannels. Slug flow (snapping/breaking/jetting) and stratified flow were observed experimentally. (Garstecki et al. 2006) studied droplet formation in a square T junction microchannel. They found out that the inlet geometry influenced the drop formation mechanism. The squeezing mechanism was observed where the inlet channel width was wider than the channel height and the width of the inlet should be ≥ 0.5 times of width of the main channel. Hence, the bubble length was observed proportional to the width of the main channel. (Oishi, M et al. 2009) investigated a mechanism of micro droplet formation at a micro T shaped junction using a “Multicolor Confocal Micro Particle Image Velocimetry” technique. They found that the droplet formation mechanism was changing from squeezing to dripping at a critical Capillary number. This indicated the force balance between shear force and interfacial tension. (Hongtruong et al. 2009) numerically studied the VOF model using CFD-FLUENT software. A numerical flow pattern maps were drawn to compare their results with available experimental results. They found that when the capillary number, Ca is higher than 10-2, the jetting slug formation was observed. They showed at lower Ca numbers, the gas flow rate could be the dominant factor for the slug formation and size. (Bedram, A., & Moosav, A. 2013) employed a numerical simulation to investigate the droplet breakup in micro- and nanoscale T-junction, which were used to produce small droplets from large droplets. For this purpose, they used volume of fluid (VOF) based method. They verified the reliability of the numerical outcomes with the available experimental results. (Harish et al. 2013) presented a CFD analysis using a phase flow field method for simulation of Taylor bubble formation in order to identify the dominant mechanisms responsible for bubble detachment. They analysed different regime which are responsible for formation of droplet and found agreed with the data available from others researchers. They also correlated void fraction with bubble formation time and bubble length. (Menech et al. 2008) described the results obtained from numerical investigation of the dynamics of breakup of streams of immiscible fluids in the confined geometry of a microfluidic T-junction. They identified three distinct regimes of formation of droplets i.e. squeezing, dripping and jetting. This providing a complete picture of emulsification processes typical for microfluidic systems. (Sang et al. 2009) investigated the viscosity effects of the continuous phase on droplet formation in a T-shaped microchannel. They observed that the drop diameter was decrease with the increase of viscosity of continuous phase. The droplet formation was studied numerical by using the three-dimensional volume of fluid model. (Kim et al. 2008) studied mechanism of formation of droplet using Lattice Boltzmann (LB) method. They take water and oil as fluid. They investigated effect of the surface tension and the flow rate of water phase fluid on the droplet length and the interval between droplets. They showed as the surface tension of continuous phase increased, the droplet length and the interval between droplets were increased. Droplet formation is one of the important phenomena in two phase flow. This literature review covers both experimentally as well as numerical investigation of droplet formation. A gap is found in experimentally investigation on droplet formation through mini channel. This work presents experimental investigation on droplet formation in mini channel having a diameter of 2.60 mm with ($l/d= 350$).

3. Breakup Mechanism of Droplet Formation

The first step in the microfluidic life cycle of a droplet is its production. This is achieved through passive techniques which generate a uniform, evenly spaced, continuous stream of droplets. In this technique, the flow field causes the interface between the two fluids to deform, leading to a growth of

interfacial instabilities. This technique used for experimental work, these follow most common strategies to use of T and Y-junction and flow focusing geometries. In the present study, attention is focused to understand the squeezing mechanism for the formation of droplets. As stated earlier, the squeezing mechanism of break-up occurs particularly to low values of capillary numbers. The squeezing regimes of droplet formation are dependent on the channel cross section. The reason behind is that to increase the pressure drop along a droplet, it should fill the entire cross section of the channel like in slug flow. That can be expected in channel with cross section different than rectangular e.g. circular and thus the squeezing regime is generally observed in such geometries. Figure 1 shows a process flow which describes the formation of droplets in squeezing regimes. The droplet formation in this regime can be divided into five stages,

- i. Air first intrudes at the junction,
- ii. Air grows and blocks almost the entire cross section of the restriction channel,
- iii. Water squeezes the air at the junction,
- iv. Air thread starts to break at the junction, and
- v. Air droplet detaches from the air thread.

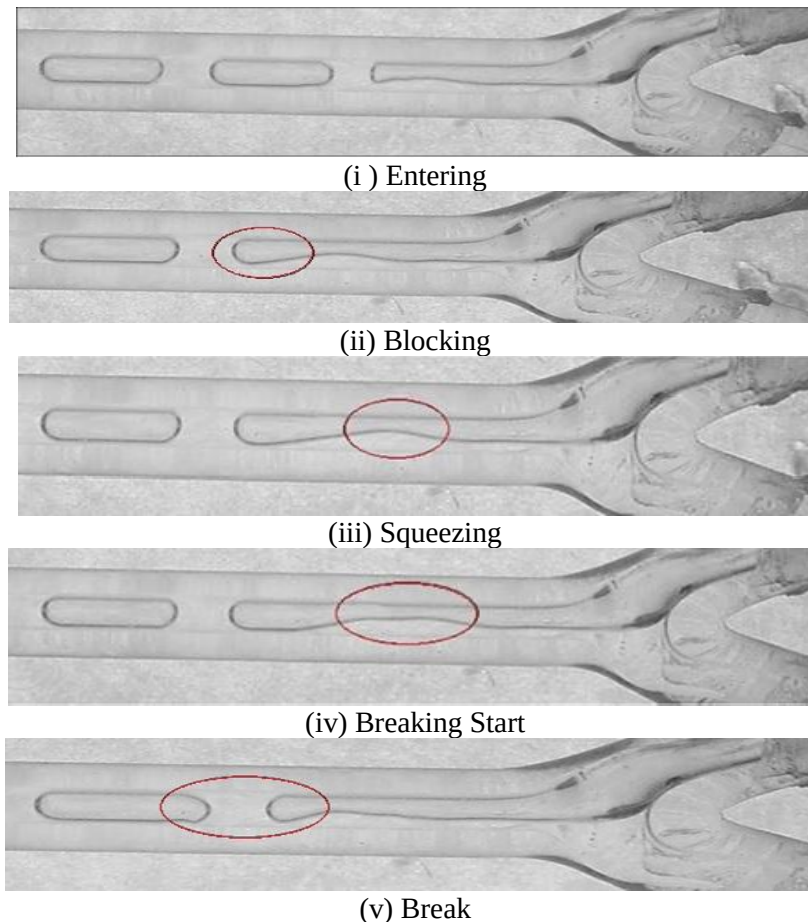


Figure 1 Mechanism of droplet formation.

4. Experimental Setup

The capillary setup is composed of a horizontally mounted, Y-junction mini channel with $d = 2.60$ mm internal diameter. The test rig is made up of acrylic sheet which can rotate through 0° to 360° . Test section is made up of borosilicate glass tubing and has a length of $350d$. Gas and liquid are fed at the

inlet of the channel, as shown in Figure 2. Air is used as a gas phase while water is used as a liquid phase in all experiments. All experiments are conducted at room temperature and atmosphere pressure.

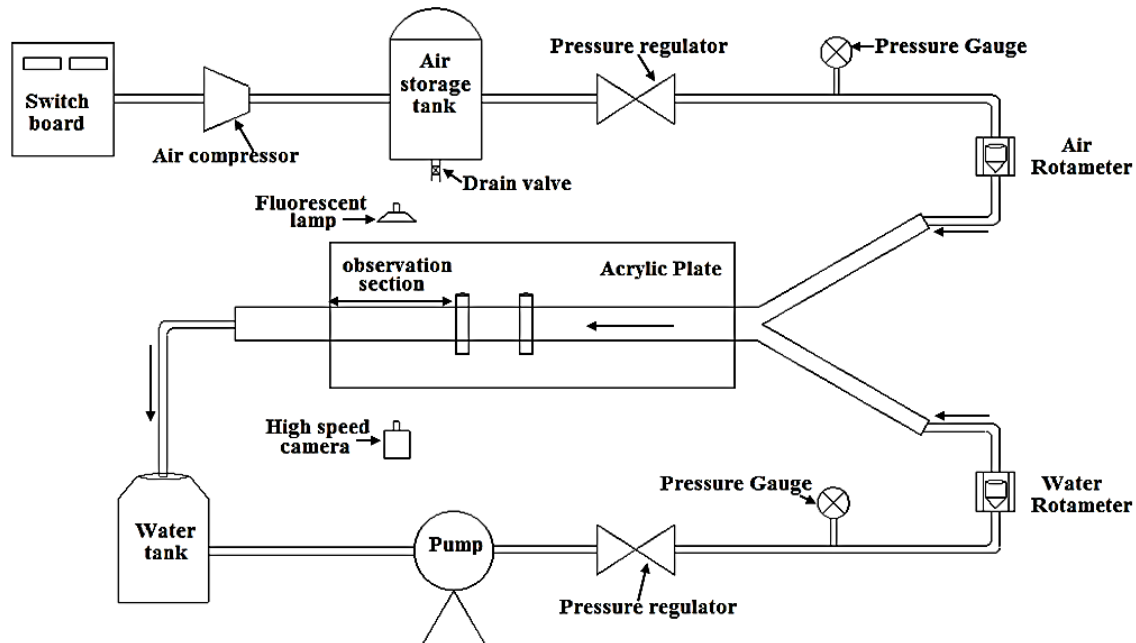


Figure 2 Experimental test setup

the test section is made transparent in order to visualize two-phase flow through channel. Glass tube of diameter 2.6 mm and length of tube is 350 times of diameter ($\frac{l}{d} = 350$). The test section photograph is shown in figure 3. Vision measuring system is used to take the image of cross section. Figure 4 shows cross section image of test section.

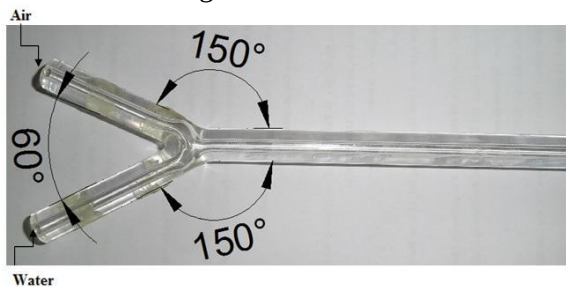


Figure 3Y- junction Test Section

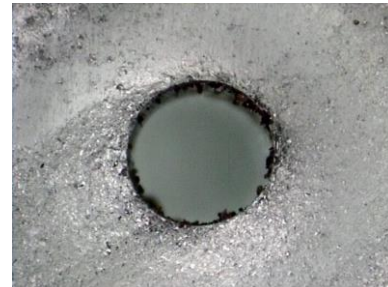


Figure 4 Circular cross section of 2.6 mm tube

5. Analysis of Droplet Formation

Droplet formation analysis is essential in mini/microfluidic devices for emulsification system. The droplet formation is dependent on various parameters. Superficial velocities of gas and liquid, capillary number and Reynolds number are some parameters which affect the droplet formation. Present section describes the effect of all those parameter on droplet formation.

6. Effect of superficial velocities on droplet formation:

The formation of bubble length is a very crucial parameter for the analysis of breakup theory. Droplet breakup is strongly dependent on flow parameters like superficial velocity of air and water. In present study, an analysis is done on formation of droplet. To understand the effect of flow parameters on bubble length, a generalized map is developed which shows the effect of superficial velocity of air and water on bubble formation.

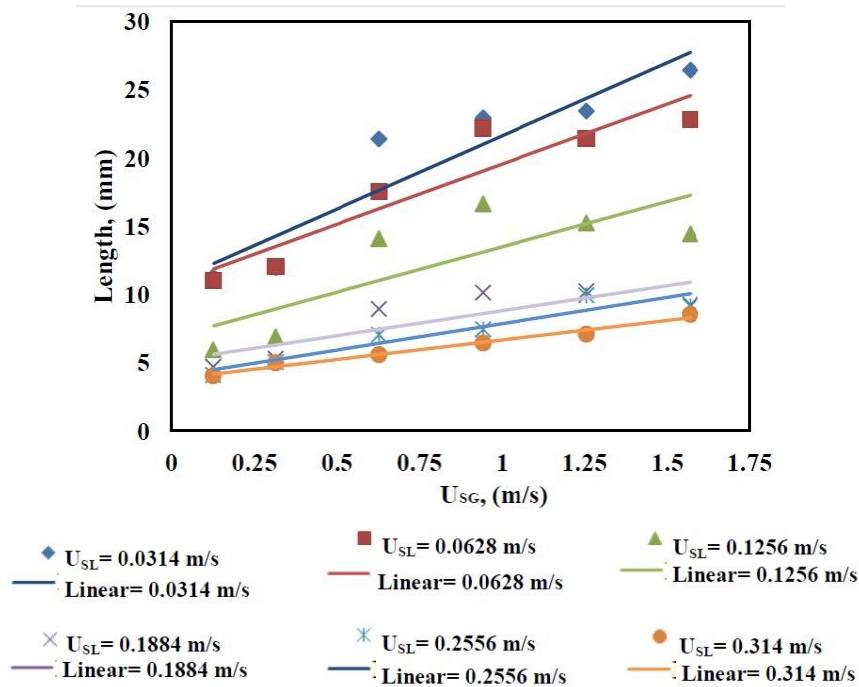


Figure 5. Generalised map between superficial velocity of gas and bubble length.

Upon observing the figure 5, it is found that bubble length increasing with increasing the superficial velocity of gas phase keeping superficial velocity of liquid constant. The superficial velocities of gas are ranging from 0.1256 m/s - 1.57 m/s.

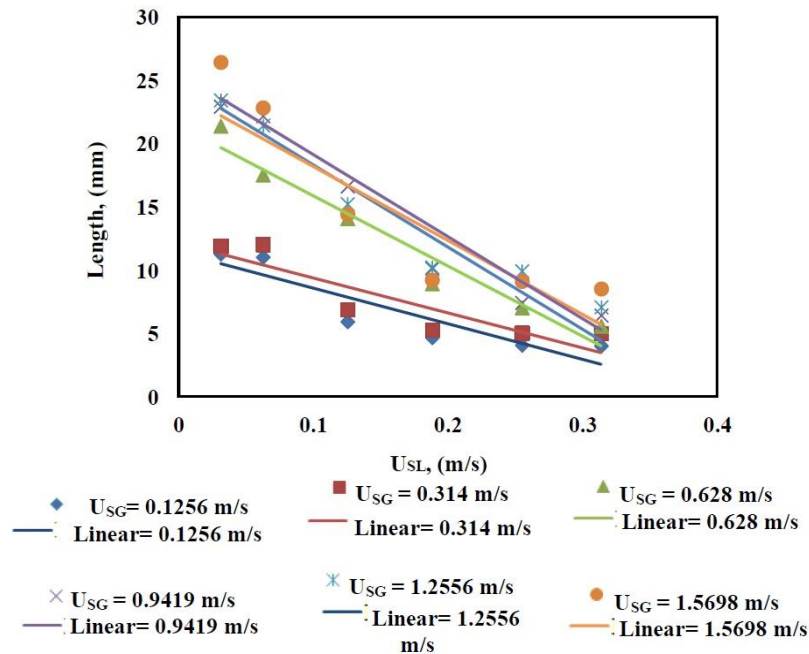


Figure 6 Generalised map between superficial velocity of liquid and bubble length.

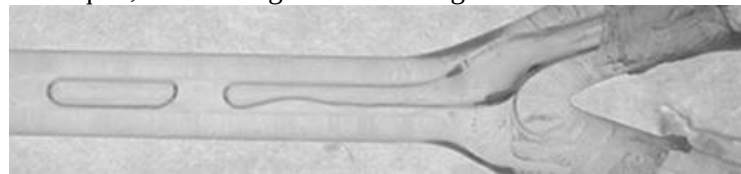
One can observe the figure 6 and it is found that bubble length decreasing with increasing the superficial velocity of liquid phase keeping superficial velocity of gas constant. The superficial velocities of liquid are ranging from 0.0314 m/s - 0.314 m/s.

7. Effect of Capillary number on droplet formation

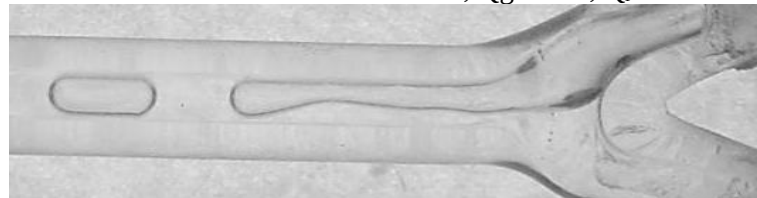
Capillary number is a dimensionless number which is defined as

$$Ca = \frac{\text{Viscous Force}}{\text{Surface Tension Force}} = \frac{\mu_{SL} U_{SL}}{\sigma}$$

Capillary number plays a very important role in the formation of droplet in mini or microfluidic system. The effect of capillary number on bubble formation is shown in figure 7. When the Capillary number is less than 0.01, the two phase flow is in the squeezing regime. In this regime, the breakup is occurring due to the initial rise of pressure in continuous phase. It is observed from that if capillary number is less than 0.01 so the squeezing regime will dominate instead of dripping regime. The dynamics of breakup is dominated by the balance between the shear force and interfacial force. Here, one can conclude that when the capillary number is increased the bubble formation length is decreased. Effect of flow rate of air and liquid on formation of bubble is also observed. As increasing the flow rate of liquid, bubble length is decreasing.



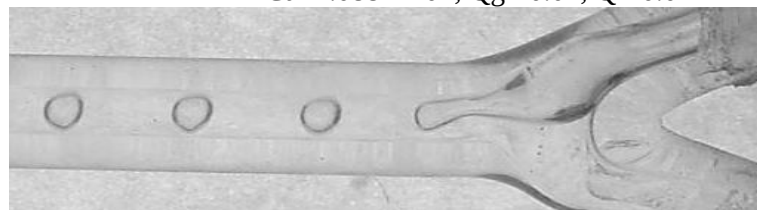
$Ca = 2.7208 \times 10^{-5}$, $Q_g = 0.04$, $Q_l = 0.01$



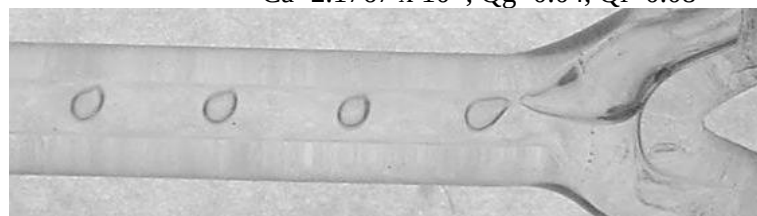
$Ca = 5.44 \times 10^{-5}$, $Q_g = 0.04$, $Q_l = 0.02$



$Ca = 1.088 \times 10^{-4}$, $Q_g = 0.04$, $Q_l = 0.04$



$Ca = 2.1767 \times 10^{-4}$, $Q_g = 0.04$, $Q_l = 0.08$



$Ca = 2.72 \times 10^{-4}$, $Q_g = 0.04$, $Q_l = 0.1$

Figure 7 View of capturing images at different capillary number.

Droplet size is defined as the ratio of bubble length to the main channel width. Figure 8 shows the effect of capillary number on droplet size. It is found that droplet size is decreasing as the capillary number is increasing keeping the superficial velocity of gas constant.

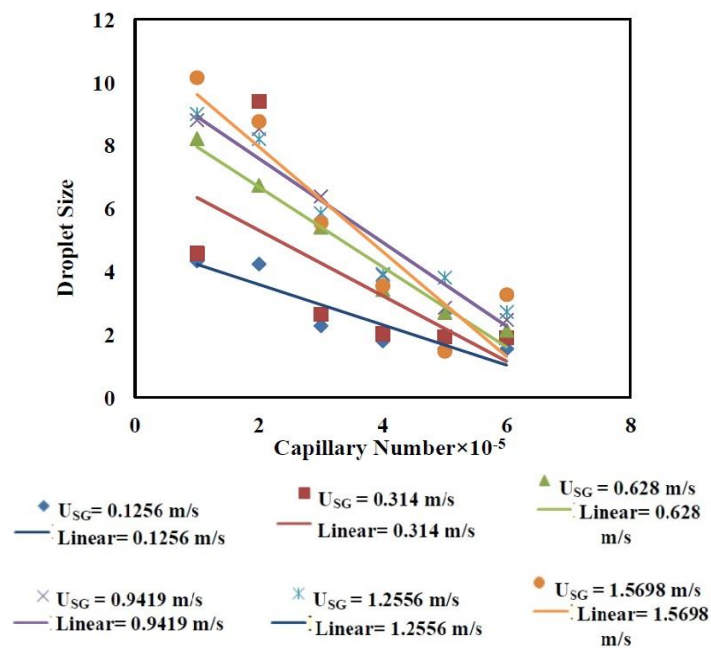


Figure 8 Effect of capillary number on droplet size.

8. Effect of superficial velocities on droplet formation time:

Droplet formation time is dependent upon the superficial velocities of gas and liquid. Figure 9 shows the time of bubble formation with varying superficial velocities of liquid. It is found that bubble time formation is shorter as the liquid superficial velocity increased, while it is increasing when superficial velocity of gas increased.

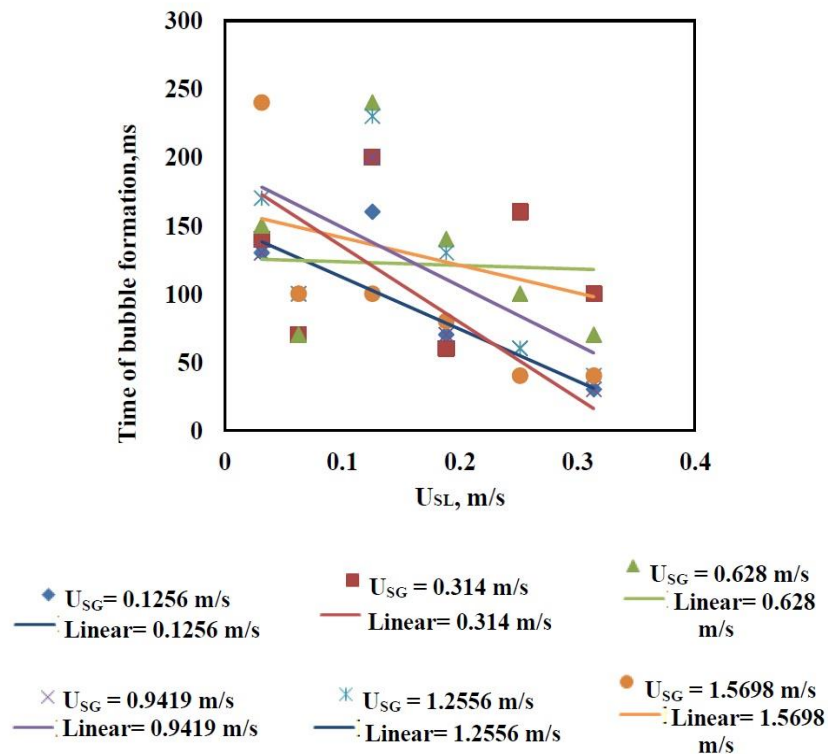


Figure 9 Time of bubble formation with varying superficial velocities of liquid.

9. Effect of Reynolds number on droplet formation:

Reynolds number is a dimensional number which is defined as

$$Re_{SL} = \frac{\text{Inertia Force}}{\text{Viscous Force}} = \frac{\rho_L U_{SL} D_h}{\mu_{SL}}$$

$$Re_{SG} = \frac{\rho_G U_{SG} D_h}{\mu_{SG}}$$

It is observed from figure 10, that the bubble length increasing when increasing the Reynolds number of dispersed phase, keeping Reynolds number of continuous phase constant. On the other hand it is observed from figure 11 that the bubble length decreased when increasing Reynolds number of continuous phase keeping Reynold number of dispersed phase constant.

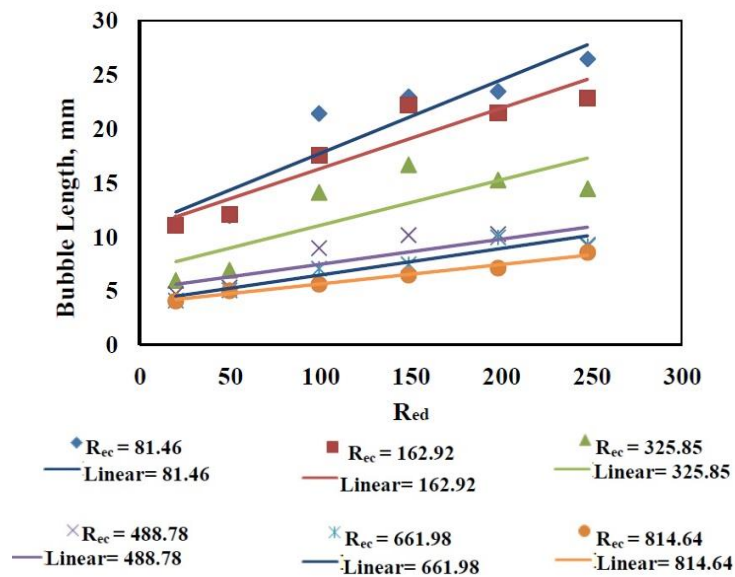


Figure 11 Generalised map of Reynolds number of dispersed phase(air) and bubble length.

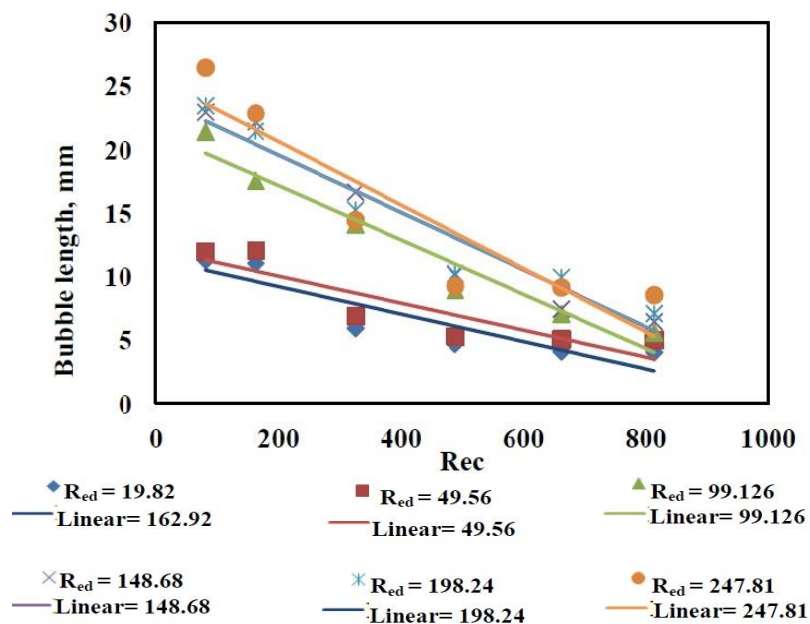


Figure 12 Generalised map of Reynolds number of continuous (water) phase and Bubble length.

10. Conclusion

Following conclusions have been drawn from experimental investigation:

- Experimental investigation shows the squeezing regime for formation of droplet in minichannel when capillary number is less than 0.01. This work highlights basic mechanism for formation of bubble droplet in minichannel.
- The effect of fluid flow parameters such as superficial velocity of gas and liquid on bubble formation is discussed. Results show that when the superficial velocity of gas is increased, the bubble length is observed to increase while increasing the superficial velocity of liquid decreases bubble length.
- The effect of capillary number on formation of droplet describes that the capillary number is increased, bubble formation length decreased and bubbles are formed.
- Increasing Reynolds number of dispersed phase (air), bubble length increased while increasing Reynolds number of continuous phase (water) bubble length is observed to decrease.
- The results on the effect of droplet formation time shows that the formation time is reduced with increase in the superficial velocity of liquid and decreases in the superficial velocity of gas.

11. References

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