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Experimental study of Microbubble formation in Micro channel

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ABSTRACT

The formation of unconfined spherical microbubbles in a micro channel is investigated in this study. A liquid channel (primary channel) and a gas channel (secondary channel) which is perpendicular to each other form a T-Junction where the microbubbles are formed. Fused silica tubes of 20µm inner diameter and 360µm outer diameter is used as the secondary channel. The hydraulic diameter of the liquid channel is varied to study its effect on the bubble formation. Because of the small size of the gas orifice compared to the hydraulic diameter of the liquid channel the microbubbles formed are completely spherical, thus giving enough facility to study its formation and detachment criteria. The microbubble formation inside the micro channel is studied subjected to variable parameters such as liquid flow rate, gas flow rate, and the hydraulic diameter of the liquid channel. Silicon wafer subjected to dry etching techniques is used to make both the primary micro channels and channels which holds the fused silica tube (secondary channel). A glass piece is anodically bonded to the silicon wafer which seals both the channel from the top. Holes are drilled on to the glass piece to provide the inlet and outlet of the channels and the T-junction is continuously monitored using an Olympus i-speed camera capable of taking 10000 frames per second. Di ionized water is used as the liquid and nitrogen is used as the gas for bubble formation. The results obtained show that the bubble diameter decreases with the increase in the liquid flow rate, and decrease in hydraulic diameter of the liquid channel. The gas flow rate does not have any effect on the bubble diameter, as the gas flow rate was increased the frequency of the bubble formation increases.

KEYWORDS

Microbubble, Bubble, cross flow, T junction, micro bubble generator.

INTRODUCTION

Understanding the dynamics behind droplet and bubble formation in micro channels has a variety of applications in micro fluidics such as bubble-jet printing, lab-on-chip devices, and chemical micro reactors. One of the most potential applications of microbubble generators is the oxygenation of blood. Researchers have shown that a microbubble of diameter less than 20µm will escape the pulmonary filtration and will dissolve in blood within 5 seconds [1]. Other biomedical applications of microbubbles includes using ultra sound activated microbubbles for cancer detection and treatment, targeted drug delivery for cells, and gene therapy [2,3]. Using microbubbles as a biomedical valve is one among the several potential applications of bubbles [4]. The use of microbubbles in chemical reactors enable the precise mixing of chemicals (in gaseous form) in micro reactors, which enhances the reaction rate, reduces the amount of the reactants, trims down processing time, increases the ease of reactions and reduces the expense of reactions by increasing throughput [5]

The microbubble formation in micro channels are classified into three sub-types based on the direction of the liquid flows in the microchannels; co-flow, cross flow, and focused flow [6] (fig. 1). The liquid into which the bubble is dispersed is referred to as the base fluid. The base fluid flows continuously in the microchannel and helps the detachment of bubble by exerting viscous stress on the growing bubble. In this paper the cross flow bubble formation method is subjected to study. In the cross flow bubble generation method, the gas enters the microchannel carrying the base liquid through a micro channel which is placed perpendicular to it [7-12] as shown in Fig. 1c. This arrangement forms a T-junction where the bubbles are generated due to the viscous force of the base fluid acting on the gas bubble during its formation.

In the cross flow device viscous stress and interfacial tension between the fluid and gas are considered to be the most dominating factors in the detachment mechanism of the bubble and certain models have been developed based on this mechanism [13]. However, these assumptions are made based on the macro level experiments done in the last decade and has not been experimentally validated in microchannels until now [6]. The major constraint that adds to the complexity in the prediction of detachment mechanism and detachment diameter is the bubble confinement inside the base channel, which in turn is due to its size which is often bigger than the hydraulic diameter of the micro channel in which they are formed [7-13].

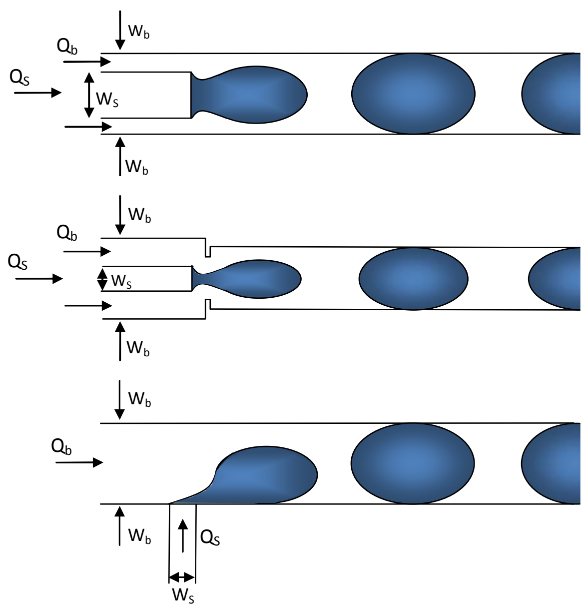


Figure 1: Categories of bubble generating devices a) co-flow b) flow focusing c) cross flow

In all currently available passive bubble generation methods the base channel and the secondary channel are of the same depth [7-13]. So, as the bubble starts to grow inside the base channel it is already confined to both the top and the bottom walls of the base channel. And as the bubble continues to grow the confinement effect increases and depending on the ratio of flow rate of the base fluid to that of the gas the bubble can get confined to the side walls of the base channel as well. Thus if this ratio is high the bubble will get confined to all the four walls of the base channel blocking the entire flow through it (fig. 2). If the ratio is low the bubble will get confined only by the top and bottom walls of the base channel. The confinement of the bubble on to the channel walls generally creates problems for detachment that require greater stresses to be created by the base fluid to get the bubble detached from the orifice. In addition to confinement, when the bubble gets confined to the channel walls a thin layer of the base fluid is assumed to be formed between the walls and the bubble preventing the bubble from being attached to the walls [15]. This phenomenon demands the usage of a fully wettable surface for the base microchannel and increases the complexity of both mathematical modeling and experimental setup [14]. Even though some models were proposed to predict the bubble detachment with the confinement effect, none of them provided a complete characterization of the detachment conditions with experimental validation [15].

Figure 2: Bubble confined by all four sides in a micro channel

Another major issue with the usage of microchannels of the same depth for both the base and secondary channel of the bubble generator is the constraint it automatically generates on the minimum size of the micro bubble that can be produced. For both the co-flow and the cross flow bubble generators the minimum size of the bubble generated depends on the hydraulic diameter of the secondary channel. The bubble is assumed to detach from the orifice when the neck length of the bubble becomes equal to the diameter of the orifice from which they are generated [18,19].

In the cross flow bubble generator fabricated and studied in this paper, secondary channels are at least ten times smaller than the base channel and the orifice for the bubble generation is situated at the center of one of the base channel walls. Fused silica tube is used as the secondary channel. The schematic of the basic concept is shown in fig. 3.

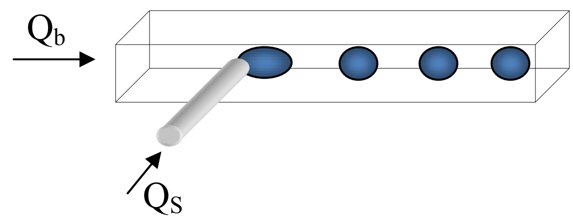


Figure 3: Schematic representation of the new generation droplet generator in cross flow device

The outer diameter of the fused silica tube is the same as the depth of the base channel. For example, if the depth of the base channel is 150µm, then a fuse silica tube with outer diameter of 150µm is selected as the secondary channel. The inner diameter of the fused silica tube in this study is limited to two values - 20µm and 15 µm. Since the orifice diameter of the secondary channel is same as that of the inner diameter of fused silica tube the bubble formation will not be confined to any channel walls. A fully spherical bubble will start growing from the orifice and the detachment will take place before it gets confined to any of the channel walls. As the inner diameter of the fused silica tube is kept less than the base micro channel diameter at least by a factor of 10, the chance of the bubble confinement is greatly reduced.

RELEVANT LITERATURES

The study of the bubble generation and detachment in macro scale started in late 1960's. One of the first works which studied the bubble generation in stagnant liquid was reported in 1969 by Ramakrishnan, Kumar and Kuloor [16]. Since then the study of bubble generation in macro scale, both mathematically and experimentally, has been carried out by several researchers[17]. Marshall and Chudacek proposed a mathematical model in 1993 which studied the bubble formation from an orifice in cross flowing liquid [18]. The results obtained from the mathematical model were compared with the experimental results and were validated. Bhunia et al. studied the bubble formation using a co-flow device both under normal and reduced gravity in 1998 [19].The study proved that the gas momentum flux, buoyancy, surface tension and drag force were the important factors affecting the bubble growth and detachment, under both normal and micro gravity conditions. Nahra and Kamotani studied the bubble formation in cross current liquid flow under reduced gravity conditions in 2000 [20]. They developed a simple mathematical model to predict the bubble formation and experiments were conducted to support the mathematical model. Later in 2002 they came up with an improved model for the prediction of bubble growth and detachment diameter. Experiments were conducted under both the normal and reduced gravity conditions to validate the mathematical model [21]. Sadatomi et al. developed a micro bubble generator in 2004 using a macro scale cylindrical tube with a spherical body inserted in it [22]. All the above studies were limited to macro scale bubbles. Zhang and Wang experimentally studied the bubble formation in the cross flow micro channel in 2009 [10]. Bubbles formed in the study were of quasi cylinder shape due to the small aspect ratio of the channels. The experiment found that both the capillary number and the pressure drop inside the base channel (from the T-junction to the outlet of the base channel) influence the bubble formation and bubble volume. The bubble volume was found to decrease exponentially with the increase in the capillary number.

Among the various literatures reviewed in this section only one study was conducted in the micro level. The bubbles generated in this study was non spherical and was confined to the base channel walls. There had been some numerical studies on the bubble formation in micro channels but none of them were validated using experimental data. The experimental studies of bubble generation in micro channel have shown that bubbles inside the micro channels are always confined to the channel walls. To the knowledge of the authors, none of the pervious studies done on bubble generation inside micro channels were able to generate fully spherical and unconfined bubbles in microchannels.

FABRICATION

The fabrication of one bubble generator involves the fabrication of two micro channels on the silicon wafer; one channel acts as the base channel and the other acts as the slot to hold the fused silica tube (fig. 4a). After the micro channels are fabricated on the silicon wafer, the fused silica tube which has the same outer diameter as the depth of the base channel is placed in the micro channel fabricated for it (fig. 4b). The tip of the fused silica tube is aligned to the channel wall of the base channel with the help of a microscope setup connected to a computer. A glass plate with two holes drilled in it (serving as the inlet and outlet for the fluid flow) is positioned on the top of the silicon wafer and is bonded to the silicon wafer using anodic bonding. The glass plate will hold the fused silica tube in place once the bonding is done. The length of the fused silica tube is maintained as low as possible so that the pressure drop across it is low. Teflon tubes which act as the inlet and outlet of the base fluid are inserted into the device and fixed using UV curable epoxy.

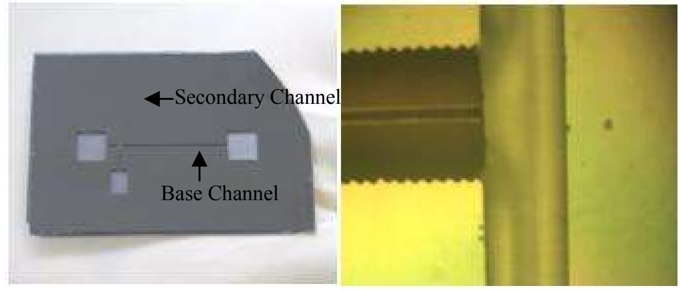
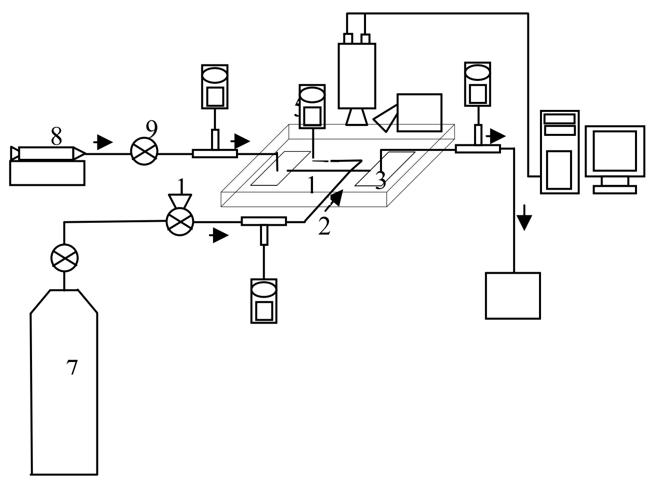


Figure 4: Cross flow bubble generation device. A) Micro channels B) T junction with fused silica tube

EXPERIMENTAL SETUP

A schematic diagram of the experimental setup is shown in Fig 5. The arrows represent the direction of the liquid or gas flow through the base channel and secondary channel. A syringe pump (NE 1010), which is highly precise and programmable is used to feed the base fluid into the bubble generator. The syringe pump using a 5ml syringe is capable of pumping liquid volumes as low as 11.17 µl/hr. A pressurized tank containing gas (nitrogen, air, or oxygen) is used as the source of gas for the gas bubble formation. A high precision pressure regulator valve is connected in the line of gas flow to control the gas flow rate through the secondary channel. A similar approach is used by many researchers for bubble generation. High precision pressure gauges are connected at both the inlet and outlet sections of the channels to monitor the pressure drop across both the channels. A pressure gauge is connected to the outlet section of the secondary channel by means of an additional slot fabricated on the silicon wafer to



1.) Base channel 2.) Secondary channel 3.) Manifold 4.) High speed camera 5.) Pressure gauge 6.) PC interface 7.) Gas tank 8.) Syringe pump 9.) Close valve 10.)

Figure 5. Schematic of the test bench

study the variation of the local pressure in front of the orifice during the bubble formation inside the base channel. The additional slot fabricated to connect the pressure gauge in front of the secondary channel is shown in Fig. 4a. A high speed camera, Olympus i-speed TR which can capture up to 10,000 fps at a resolution of 804×600 is mounted on a microscope to capture the bubble formation in the base channel (at a full resolution of 1280×1024 it can capture up to 2000fsp). The video being captured is stored in a memory card integrated inside the camera and is subsequently moved into a computer connected to the camera through the PC interface slot. The images are processed using software and the formation of the bubble and the diameter at its detachment can be determined. An optical fiber enabled light source which has two flexible arms provides a 150w light source to ensure the quality of picture being captured.

As the gas flow rate in the micro bubble generator is very small an experimental method is used to determine the gas flow rate through the gas channel. In this technique, the number of bubbles generated in one second is determined by counting it for a small time slot. The diameter of the bubble formed is measured and the volume of the bubble is calculated from the diameter. The gas flow rate in a second is calculated by multiplying the micro bubble volume to the number of bubbles formed in second. Since the diameter of the micro bubbles formed is very uniform in size this method provides an effective way to measure the gas flow rate through a secondary channel.

RESULTS

The bubble formation inside the micro channel from an orifice placed at the center of one of the side walls of the liquid channel is shown in figure 6. The bubble growth cycle at an interval of 0.2 ms is shown in the figure. The liquid channel used for the bubble formation is of width 330 micrometers and 360 micrometers depth. The inner diameter of the fused silica tube used as the orifice for the bubble formation is 20 micrometer. The picture is taken at a speed of 5000 frames per second, at a liquid flow rate of 80ml/hr and a gas flow rate of 5.90ml/hr. The bubble takes 1.8 ms to grow to its full diameter of 178 micrometer before it detaches from the orifice. The pictures shown in figure 6 are taken in an interval of 0.2ms each. It can be observed from the figure that the bubble has a spherical shape throughout its formation and continues to be spherical after its detachment from the orifice into the liquid channel. As discussed earlier the fully spherical bubble formation inside the liquid channel will help the researchers to investigate the actual phenomenon behind the bubble formation inside the micro channel. Figure 7 shows the plot of the bubble diameter at an interval of 0.2 ms throughout the formation of the micro bubble. It can be observed that during the initial stages of the bubble formation the bubble diameter increases rapidly. That is the slop of the bubble diameter during its formation is higher during the initial stages of the bubble growth. But as the bubble grows bigger, the slop of the bubble formation diameter decreases and gets nearly close to zero before the bubble detaches from the orifice. Another important

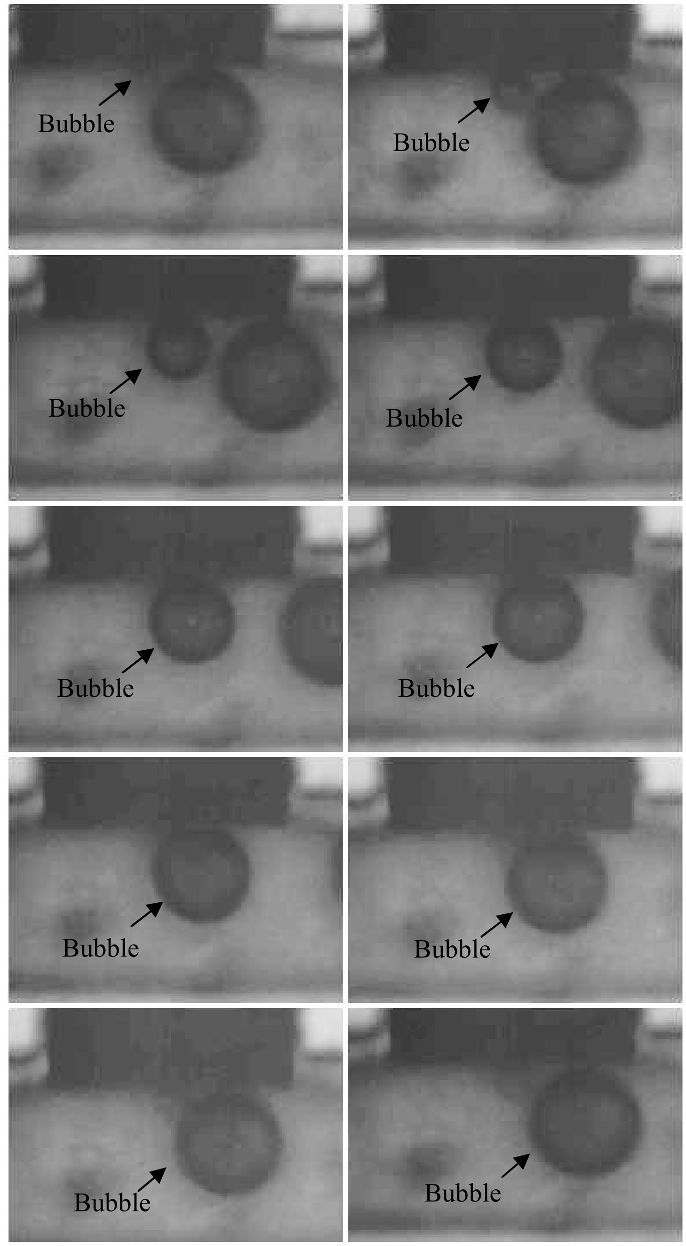


Figure 6: Microbubble (178μm) formation in a micro channel (330×360μm) . (pictures taken at an interval of 0.2ms)

observation from figure 6 is that the bubble is not getting elongated into the liquid channel before its detachment from the orifice. Almost all the research done on the bubble formation in micro channels till now has reported an elongation of the bubble into the liquid channel (bubble will take a nearly oval shape with its neck attached to the orifice) as shown in the schematic diagram given in figure 1. From figure 6, it can be noted that the bubble retains its spherical shape throughout its formation and will shift towards the fluid flow direction before it gets detached. The elongation of the bubble into the micro channel is caused by the confinement of the bubbles to the liquid channel walls (the confinement is caused by the usage of same depth micro channel as both liquid channel and the gas channel). The elongation of the micro bubble into the micro channel due to the confinement effect makes the prediction of the detachment bubble diameter inside the microchannel a complicated process.

In the new generation bubble generator studied in this paper, once the microbubble gets detached from the orifice the next bubble starts its formation process without any delay. Constant gas flow bubble generation technique is used in this study. The usual delays in the bubble formation in microchannels like weeping time and the satellite bubble formation is completely eliminated in the new generation micro bubble generators. An experimental uncertainty of 2.2 micrometer is present in all the micro bubble diameter measurements made in this study.

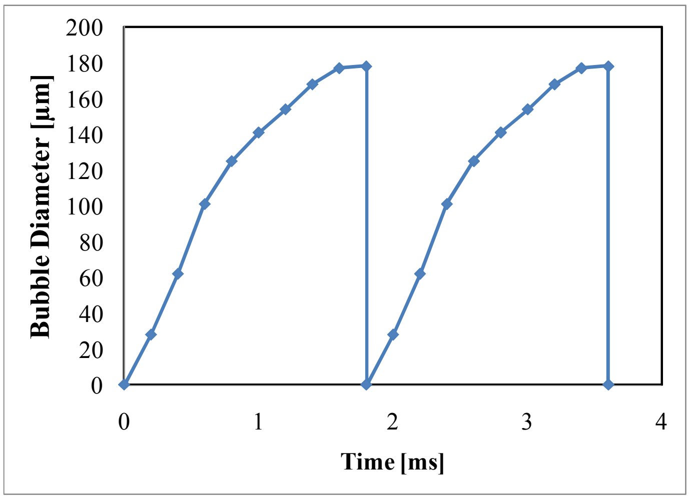


Figure 7: The bubble diameter during its formation and detachment from the orifice.

The effect of the liquid flow rate and the gas flow rate on the bubble detachment diameter is investigated in this present work. The liquid flow rate is varied from 20 ml/hr to 200 ml/hr. The liquid channel used had a width of 330 micrometer and depth of 360 micrometers. The gas channel used in this case study was also having an inner diameter of 20 micrometer. Two different gas flow rates were used to generate the micro bubbles in the micro channel to study its effect on the micro bubble detachment diameter. The results obtained from the study are presented in figure 8. From the figure it can be observed that as the liquid flow rate is increased the micro bubble diameter at its detachment from the orifice decreases. Initial decrease in the micro bubble diameter is rapid with the increase in the liquid flow rate. The slope of the decrease in bubble diameter attains a constant value at higher values of liquid flow rate. It can be observed that even at a very slow liquid flow rate of 20 ml/hr, the bubbles formed inside the micro channels are fully spherical in shape and is not confined to any of the liquid channel walls. This proves the superiority of the new microbubble generator over the present techniques. Another important observation from figure 8 is that micro bubble of around 65 micro meters are generated in a micro channel of hydraulic diameter of 345 micrometers with a liquid flow Reynolds number of 185. This shows the capability of the new generation bubble generator to generate smaller bubbles inside bigger micro channels at low liquid flow rates. The present cross flow micro bubble generation techniques uses micro channels of smaller hydraulic diameter to generate smaller micro bubbles in the micro channels. This technique has the disadvantage of increased pumping power needed to attain desired liquid flow rate through the base channel.

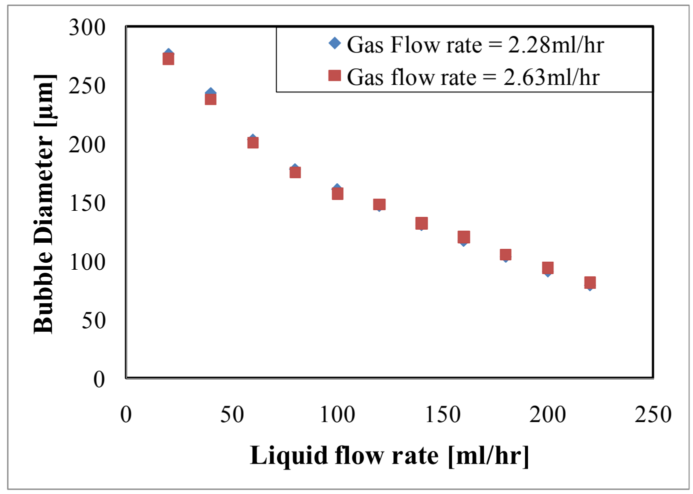


Figure 8: Plot of micro bubble diameter inside the micro channel for different liquid and gas flow rates.

The effect of gas flow rate on the detachment diameter of the micro bubbles inside the micro channel is also studied in figure 8. Two different gas flow rates are used to generate micro bubbles in the micro channel. It is interesting to note from figure 8 that the diameter of the micro bubbles generated using two different gas flow rate remains the same. This leads to the conclusion that the gas flow rate does not have any effect in determining the detachment diameter of the micro bubbles. However, the gas has an effect on the frequency of the bubbles generated from the orifice. At a gas flow rate of 2.28 ml/hr and a liquid flow rate of 140 ml/hr the bubble generation frequency was 505 bubbles per second. As the gas flow rate was increased to 2.63ml/hr the bubble diameter remained the same but the bubble generation frequency increased to 606 bubbles per second.

The effect of the hydraulic diameter of the liquid channel on the bubble diameter is also studied in this paper. Two devices with two different liquid channel hydraulic diameters were used for this purpose. The first device had a liquid channel with a hydraulic diameter of 345 micrometer and the second device had a channel with a hydraulic diameter of 257 micrometers. The gas orifice diameter was kept constant and the diameter of the bubble formation at different liquid flow rates was studied. The results obtained from the case study are presented in figure 9. As seen in the previous case study the microbubble diameter decreased with the increase in the liquid flow rate for both the devices. The bubble formed from the device having smaller liquid channel were small compared to the bubbles from the device with larger liquid channel. The trend in the reduction of the bubble diameter with the increase in the liquid flow rate remained the same for both the devices.

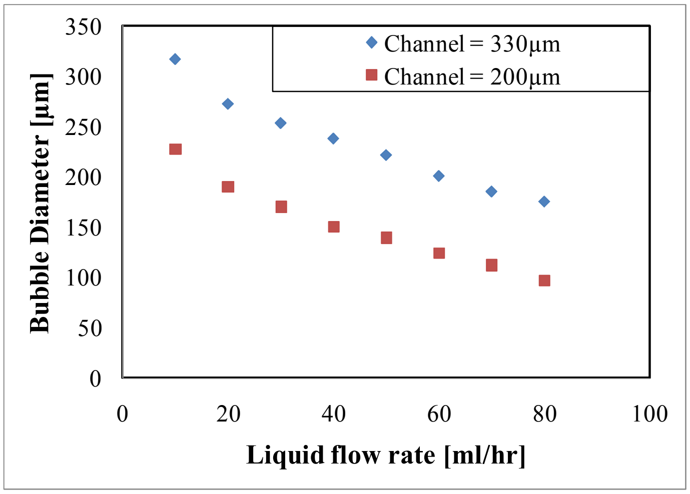


Figure 9: Plot of micro bubble diameter inside two different devices with different liquid channel hydraulic diameter.

CONCLUSION

A new generation microbubble generator is fabricated and tested in this study. The new generation micro bubble generator avoids the drawbacks of the present micro bubble generators such as bubble confinement to the channel walls, weeping time between the bubble formation, satellite bubble formation etc. For the new generation micro bubble generators the base channel was fabricated on silicon wafer and a fused silica tube served as the gas channel. Glass with inlet and outlet holes drilled on it served as the top cover for the device. The major conclusions of the study are as follows.

1. A new generation micro bubble generators capable of generating unconfined spherical bubbles inside a microchannel is introduced in this paper.
2. The drawbacks of the current micro bubble generators like bubble confinement, weeping, satellite bubble formation etc are eliminated using new generation bubble generators.
3. The diameter of the bubbles generated inside the micro channel decreases with the increase in the liquid flow rate through the base channel.
4. The gas flow rate does not have any effect on the bubble detachment diameter, but determines the frequency of bubble formation inside the microchannel.
5. The diameter of the bubbles generated inside the micro channel decreases with the decrease in the hydraulic diameter of the liquid channel.

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