Growth characteristic of microbubble in a T-junction microchannel in microfluidic chip

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Abstract: Microbubble formation in a T-junction microchannel in polydimethylsiloxane (PDMS) microfluidic chip were developed. The experiment based on high-speed microscopic camera system was set up to investigate the effects of liquid flow rate, gas pressure and gas channel width on microbubble growth. Three stages of microbubble growth process were obtained through the experiment firstly. The control variable method was used for investigating the growth characteristics of microbubble, including volume change rate and the ratio of length to width. The present study provided an empirical reference for the growth of microbubble in microchannel, which helped to achieve precise control of microbubble volume.

1. Introduction

Compared to ordinary bubble, microbubble have many characteristics due to their size on the micrometer scale, including large specific surface area, slow rising velocity\textsuperscript{[1-2]}, and high mass transferring efficiency\textsuperscript{[3]}. The development of many industry sectors is inseparable from the contribution of microbubble, such as chemical industry, biology, medical and cell research\textsuperscript{[4-10]}. With the rapid development of microfluidic technology, the use of microfluidic chips to prepare microbubbles and the study of microbubble characteristics in microchannels has become a research hotspot in recent years\textsuperscript{[11]}. Microfluidic chip has different microchannel structures, and T-junction microchannel\textsuperscript{[12-14]} is the most widely used for the preparation of microbubble in academic research.

The gas phase and the liquid phase meet in the T-junction microchannel, which will generate bubble flow due to the action of flow focusing. Since the 1970s, theoretical studies on the formation of microbubbles in T-junction microchannels have been carried out, including bubble volume prediction, growth stage and kinetics. Yu\textsuperscript{[15]} et al. proposed a theoretical model of bubble formation and pointed out that bubble formation can be divided into three stages: the expansion stage, the elongation stage, and the pinch-off stage. MARIUSZ R. RZĄSA\textsuperscript{[16]} created a static spherical one-stage model to obtain bubble volumes at different gas flow rates and compared the theoretical values with the experimental data. GERALD RICKAYZEN\textsuperscript{[17]} et al. established a theoretical model for bubble formation and break to investigate the mechanical and thermal behaviour of the collapse of a microscopically small bubble in a liquid.

The theoretical study is to fundamentally explore the dynamic properties of bubbles based on numerical analysis, but it is impossible to visually describe the bubble formation. The current research
shifts the focus to bubble formation experiments. Volkert van Steijn\cite{18} et al. used a T-junction microfluidic device to study the bubble and droplet formation characteristics. Jiang\cite{19} et al. developed a microfluidic device based on double T-junction, and investigated the bubble formation efficiency of the microfluidic device through experiments. D Caprini\cite{20} et al. designed a T-junction device allowing for two simultaneous orthogonal views and the device application to bubble formation and break-up.

Regardless of theoretical or experimental research, the exploration of the influence of various factors on the bubble growth process is still lacking. In this study, microbubbles were prepared based on T-junction microchannels, and the microbubble growth process was clearly observed through high-speed microscopic camera system. The influence of external factors on bubble volume change rate and the ratio of length to width during bubble growth was investigated.

2. Experimental

2.1 Experimental setup

A PDMS microfluidic chip was designed for preparing microbubble, and the structure and size parameters are shown in figure 1. The depth of all channels on the chip is 100 μm. As is evident in Figure 1, there are three gas channels in the chip with widths of 0.25 mm, 0.2 mm and 0.15 mm respectively, and the rest are liquid channels, each have a width of 0.5 mm. Microchannel structure includes a liquid inlet, a gas inlet, a bubble forming area, and a gas-liquid mixture outlet. The polyvinyl alcohol (PVA) solution flows into the PDMS chip through the liquid inlet, and nitrogen flows into the chip from one of the three gas inlets. The gas phase and the liquid phase converge at the bubble formation area, and forming a T-junction flow focusing to generate microbubbles.

The schematic diagram of the experimental system is shown in figure 2. A syringe pump(704500, Harvard Apparatus) is used to regulate liquid flow rate; A relieve valve(YQD-4), a precision barometer(OMEGA PRG200-25) and a precision digital pressure gauge(YK-100) are used to adjust gas pressure in real time; The image acquisition system includes a microscope(Olympus CX21) and a high-speed camera(Phantom v12.1, 100w fps) which is used for collecting image information during bubble growth.

![Figure 1. The structure (a) and size parameters (b) of PDMS chip](image-url)
2.2 Experimental parameters
During the experiment, the adjustment range of the gas pressure is 55 kPa to 75 kPa, and the gradient is 5 kPa; The range of liquid flow rate is 30 mLh⁻¹ to 50 mLh⁻¹, and the gradient is 5 mLh⁻¹; Other experimental parameters and their values are shown in table 1.

Table 1. Experimental parameters and their values

| Parameter                              | Value       |
|----------------------------------------|-------------|
| Gas channel width $l$ [mm]             | 0.15/0.2/0.25 |
| Liquid channel width $w$ [mm]          | 0.5         |
| Concentration of PVA solution          | 2%          |
| Liquid dynamic viscosity $\mu_l$ [Pa s] | 4.9×10⁻³     |
| Liquid density $\rho_l$ [kg m⁻³]       | 1002        |
| Gas density $\rho_g$ [kg m⁻³]          | 1.25        |
| Surface tension coefficient $\sigma$ [N]| 0.056       |

2.3 Bubble volume calculation
An image in a bubble formation cycle is selected and opened by Image Pro Plus 6.0. The size of the image is calibrated and the size of each pixel in the image is associated with the actual size to obtain the converted value, which applies to all images in the same experiment. Then, the single complete microbubble image is performed grayscale processing by Photoshop. Finally, MATLAB is used for processing the grayscale image to obtain the bubble contour and writing a bubble image processing program, the bubble detachment volume is obtained by the integration method.

The bubble is compressed into a "cake shape" for PDMS chips, and the detachment volume of the bubble is equal to the sum of the volumes of several cuboids. Bubble image processing results are shown in figure 3.
3. Results and discussion

3.1 Microbubble growth process
During the experiment, the image of the complete growth cycle of a single bubble was obtained by a high-speed camera, and the growth process of the bubble was observed. One of working conditions was selected: The gas channel width is 0.15 mm, the liquid flow rate is 50 mLh\(^{-1}\), the gas pressure is 70 kPa. The image of bubble growth process is shown in figure 4. It can be seen from the figure that bubble growth process can be divided into three stages: a vertical expansion stage, a horizontal elongation stage, and a necking detachment stage.

![Figure 4. Microbubble growth process](image)

3.2 Volume change rate
(1) Effect of liquid flow rate
During the experiment, the PDMS chip with a gas channel width of 0.15 mm is selected. The gas pressure is 60 kPa, liquid flow rate is 35 mLh\(^{-1}\), 40 mLh\(^{-1}\) and 45 mLh\(^{-1}\) respectively. The volume of a bubble at each moment in a growth cycle under different working conditions is measured. The curve of bubble volume changes with time is shown in figure 5.

![Figure 5. Curve of bubble volume with time under different liquid flow rates](image)

As is observed in figure 5, because the horizontal axis is time and the vertical axis is the real-time volume of the bubble, the slope of the curve is the bubble volume change rate. The slope of three curves are small before 4ms, which indicate that the bubble grows slowly. This may be because the gas flow rate is relatively small at the initial moment of bubble growth, and the gas pressure inside the bubble is difficult to overcome the surface tension at the gas-liquid interface. As the gas flow rate is gradually stabilized, the gas pressure inside the bubble gradually becomes larger and balances with the surface tension, causing the bubble to expand, and the slope of the curve is gradually increased. It can also be seen from the figure that the bubble volume change rate decreases with the liquid flow rate increases. This may be because when the liquid flow rate increases, the liquid pulling force generated by the liquid flow also increases, and the bubble is more easily sheared off due to the effect of flow focusing.
(2) Effect of gas pressure

Similarly, a gas channel of 0.15 mm width is selected. The liquid flow rate is 45 mL/h, gas pressure is 55 kPa, 60 kPa and 65 kPa respectively. The images of bubble growth under three working conditions were collected separately, and the bubble volume at each moment in the whole growth cycle under each working condition was obtained. The curve of bubble volume changes with time is shown in figure 6.

![Figure 6. Curve of bubble volume with time under different gas pressures](image)

As addressed in figure 6, bubble volume change rate increases with gas pressure increases. Since bubble growth is affected by multiple forces, and when the forces acting on the bubble balance each other, the bubble is completely detached. When the gas pressure increases, the gas pressure inside the bubble also increases, so that the time to overcome the surface tension can be shortened. The bubble expands rapidly in the vertical direction and is sheared off under the action of the horizontal liquid pulling force.

(3) Effect of gas channel width

The gas pressure is set to 60 kPa, the liquid flow rate is set to 45 mL/h, and replace gas channels of different widths. The curve of bubble volume changes with time is shown in figure 7.

![Figure 7. Curve of bubble volume with time under different gas channel widths](image)

It can be seen from the comparison of the three curves that the bubble volume change rate increases with the gas channel width increases. When the gas pressure is constant, the increase of gas channel width could result in the increase of gas flow rate per unit time, thereby also increasing the gas pressure inside the bubble.

3.3 The ratio of length to width

In order to better describe the contour change rule of the bubble during the growth process, the concept of the ratio of length to width is introduced, as shown in figure 8. In the figure, L is the distance from the right-side wall of the gas channel to the rightmost end of the bubble contour and is
defined as the bubble length; W is the maximum distance that the bubble expands in the vertical direction and is defined as the bubble width.

\[ \sigma_l = f(v_l, \Delta v_l) \]
\[ \sigma_g = f(v_g, \Delta v_g) \]

Figure 8. The length and width of bubble

During the experiment, the gas channel with a width of 0.15 mm was selected, the gas pressures were 55 kPa, 60 kPa, and 70 kPa respectively, and the liquid flows were 30 mLh\(^{-1}\), 40 mLh\(^{-1}\), and 45 mLh\(^{-1}\) respectively. The length and width of the bubble at each moment throughout the growth cycle were obtained under different working conditions. The curve of the ratio of length to width changes with time are shown in figure 9 and figure 10.

Figure 9. The ratio of length to width changes with time under different liquid flow rates

Figure 9 depicts the ratio of length to width changes with time under different liquid flow rates at a gas pressure of 55 kPa. It is easy to see that the ratio of length to width exhibits an increasing tendency throughout the growth cycle. However, at the initial moment, the ratio of length to width increases slowly, and even negative increases, which indicates that the length and width increase with a similar velocity in the initial stage of bubble growth. As time goes by, the ratio of length to width gradually increases, and the velocity is getting faster and faster. This is because when the gas pressure inside the bubble and the surface tension at the interface of the gas and liquid are balanced with each other, the width of the bubble is almost constant, and the factor affecting the growth of the bubble is mainly the liquid pulling force in the horizontal direction. The bubble is continuously elongated in the horizontal direction under the action of the liquid pulling force. It can be seen from the comparison of the three curves that the ratio of length to width decreases with the liquid flow rate increases. Liquid pulling force increases with liquid flow rate increases, and the bubble is more easily sheared off in the horizontal direction, resulting in shorter bubble length.
In figure 10, the liquid flow rate under each working condition is 45 mLh⁻¹. It can be seen from the figure that the ratio of length to width increases with gas pressure increases. This is because the gas pressure inside the bubble increases and it is easier to balance the surface tension with each other to cause the bubble to expand rapidly in the vertical direction. When the bubble expands to the maximum width, it will also be compressed in the horizontal direction to the maximum length under the action of the liquid pulling force.

4. Conclusions

In the present study, growth characteristic of microbubble in a T-junction microchannel in microfluidic chip was investigated experimentally. The effect of different environmental factors on the growth process of microbubble was reflected by the volume change rate and the ratio of length to width. According to the research content of this study, there are following conclusions:

1) From the three stages of bubble growth, it can be seen that the bubble is subjected to various forces caused by the gas phase and the liquid phase during the growth process, such as surface tension and liquid pulling force, which result in the final shape of the bubble not being a regular circle.

2) Under the influence of different environmental factors, the bubble volume change rate and the ratio of length to width both increase with time. Changes in liquid flow rate, gas pressure and gas channel width can cause changes in liquid pulling force, gas pressure inside the bubble and surface tension, so that the bubble volume change rate and the ratio of length to width will change. Bubble growth process reflects many hydrodynamic characteristics. In order to better describe the growth of microbubble, it is necessary to further investigate the effects of other forces on bubble growth.

Results of the present study vastly enhance our understanding of the growth process of single bubble in T-junction microchannel in microfluidic chip, and they provide a reference for the growth of microbubbles in different microchannels, and they can help to achieve precise control of bubble volume in microfluidic chip in the future. Since microbubble has the characteristics of slow floating rate and high mass transfer efficiency, the next research project is to use microfluidic chip to prepare microbubbles with smaller volume, and ozone can be injected into microbubbles to oxidize organic pollutants in water.

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