Study on the formation characteristic of microbubbles used in sewage treatment

Lixia Sun¹², Mingxu Fan², Bo Xu², Huadong Yu¹³, Yue Wang³, Yufeng Zhang³ and Peng Li²

¹College of Mechanical and Electrical Engineering, Changchun University of Science and Technology, Changchun 130022, Jilin, China;
²College of Mechanical Engineering, Beihua University, Jilin 132021, Jilin, China
³Email: Huadong2004@163.com

Abstract. Microbubble usually has very small volume, and it is difficult to rise in the water, so it can be used to wrap ozone for sewage treatment. In the present study, the experiments of bubble formation in a mechanical microfluidic device are developed. The effect of liquid flow rate and gas pressure on bubble formation characteristic was obtained through experiments. By observing experimental phenomena, it can be concluded that bubble growth process can be divided into three stages, and the law of the detachment volume and formation frequency of microbubbles under single variable factor was investigated by the control variable method. The investigation of bubble formation characteristic can help to control bubble detachment volume and formation frequency precisely.

1. Introduction

Microbubble refers to the bubble with an effective diameter below 100 µm, compared to conventional bubble, its specific surface area is larger, the rising speed is slower [1,2], and the mass transfer efficiency is higher [3]. Microbubbles have been applied to different degrees in many fields such as biology, chemical engineering and medical treatment [4-5]. In the preparation method of microbubbles, the microfluidic technology can generate bubbles with uniform volume and generation frequency by using microchannels with a size of several tens of microns and has been widely used. From the past to the present, characteristics of microbubbles in microfluidic device are widely investigated, such as bubble formation [6-7] and breakup [8-9]. Usually, there are microchannels in microfluidic device, and the shape of the microchannels are also may be different due to the principle of bubble formation, including co-flowing Microchannel [10-11] and T-junction microchannel [12-13]. The various structural forms of the microchannels lead to different preparation effects of microbubbles.

As early as 1970, Bowonder [14] et al. began to study the technology of making bubbles in porous disks. In recent years, microfluidic technology has developed rapidly, and microbubble generation methods have gradually increased. Wenting Wang [15] et al. designed a one-step microfluidic device based on the principle of coaxial flow focusing, which can generate gas-water-oil three-phase double emulsion droplets. Yong Zeng [16] et al. used a pneumatic pump to develope a microfluidic device that can regulate the droplet size by adjusting the gas pressure and the liquid flow rate. The growth process of microbubble is affected by many factors, and the bubble growth process will vary depending on the input conditions. G. Biswas [17] et al. simulated the shape of two co-axial bubbles in stagnant Newtonian liquid through a coupled level-set and volume-of-fluid (CLSVOF) method. Li D [18]...
introduced the microfluidic device that can generate droplets in the Encyclopedia of Microfluids and Nanofluids, and studied the influence of the structure of the device on the gas-liquid two-phase fluid mixing reaction. The experiments of microbubble formation in a co-flowing focusing mechanical microfluidic device are developed. Bubble growth process in co-flowing microchannel is first observed, the growth mechanism of microbubble through force analysis method is investigated, and bubble detachment volume and formation frequency under the influence of the double coupling factors of gas pressure and liquid flow rate are obtained. It is well known that ozone has the ability of effectively removing organic pollutants from water due to its strong oxidizing property. The ultimate purpose of the present study is to design a microfluidic device that is used for generating microbubbles under different controlled volume and formation frequency. Due to the series of advantages of microbubble, it can carry ozone and dissolve in water and react efficiently with organic pollutants, which overcomes the problem that ozone is hardly dissolved in water, and the utilization of ozone is improved at the same time.

2. Experiments

2.1. Experimental device and system
A mechanical microfluidic device which is used for generating microbubbles has been developed, it is mainly made up of a capillary metal tube, a square quartz tube and 3D printed part, and the actual structure and three-dimensional structure of the device are shown in Figure 1. The microfluidic device uses a capillary metal tube having an inner diameter of 60 μm as a gas channel, and a square quartz tube having a size of 1 mm × 1 mm is treated as a liquid channel. Microbubbles are generated at the end of the capillary metal tube and flow out along the quartz tube after being detached. The liquid used in experiments is polyvinyl alcohol (PVA) solution and the concentration of the solution is 2%, and the gas is nitrogen.

Figure 1. Structure of the mechanical microfluidic device.

Figure 2 describes the schematic diagram of the experimental system. In the experimental system, a syringe pump is used for adjusting liquid flow rate \((Q_L)\), and gas pressure \((P_g)\) is adjusted in real time by a relieve valve and a precision digital pressure gauge. The images of microbubble growth process are collected by an image acquisition system that includes a microscope and a high-speed camera.
2.2. Calculation of microbubble Volume
Firstly, Image Pro Plus 6.0 is used for opening an image of a complete detached microbubble. The size of the gas channel in the image is calibrated and the size of each unit is associated with the actual size to obtain the converted coefficient that applies to all experiments performed on the same microfluidic device. Then, the brightness and contrast of a single bubble image is adjusted by Photoshop, turning the original image of the bubble into a grayscale image. Finally, the bubble contour image can be obtained through the processing of grayscale image by MATLAB, so that it could also be used for writing a bubble image processing program. Similarly, MATLAB is used to divide the bubble contour into many tiny units, and then the integral method is used for obtaining the bubble volume. The processing results of bubble image are shown in Figure 3.

![Figure 2. The schematic diagram of the experimental system.](image)

![Figure 3. Bubble image processing results.](image)

2.3. Experimental process
Prior to the experiment, physical parameters such as liquid density and viscosity were measured, and the gradient ranges of the input values of gas pressure and liquid flow rate were set respectively. The input range of \( P_g \) is 0.01 MPa ~ 0.05 MPa and the gradient is set to 0.01 MPa. The input range of \( Q_L \) is 100 mLh^{-1} ~ 350 mLh^{-1} and the gradient is set to 50 mLh^{-1}. Other experimental parameters including their values are listed in Table 1. During the experiment, liquid and gas were first introduced into the
microfluidic device to generate microbubbles, and then images of bubble growth process under all working conditions were captured by an image acquisition system. Finally, Photoshop and MATLAB were used to further process and analyze these images to calculate detachment volume and formation frequency of microbubbles.

| Parameter                        | Value             |
|----------------------------------|-------------------|
| Liquid dynamic viscosity $\mu_L$ [Pa s] | $4.9 \times 10^{-3}$ |
| Gas density $\rho_g$ [kg m$^{-3}$] | 1.25              |
| Liquid density $\rho_L$ [kg m$^{-3}$] | 1002              |
| Surface tension coefficient $\sigma$ [N m$^{-1}$] | 0.053             |

3. Results and discussion

3.1. Growth process of microbubble

A specific working condition was selected during the experiment: $Q_L = 140 \text{ mL h}^{-1}$ and $P_g = 0.03 \text{ MPa}$, and images of bubble growth process under this working condition were obtained, as shown in Figure 4 a). As is observed in the figure, the bubble growth process is divided into three growth stages that includes a spherical growth stage, an ellipsoid growth stage, and a necking detachment stage respectively. In fact, bubble growth is inseparable from the interaction between multiple forces. The forces including the liquid pulling force ($F_D$), the gas thrust ($F_M$), the surface tension ($F_\sigma$), and the inertial force ($F_I$) will directly affect the size and shape of the bubble, as shown in Figure 4 b), and the moment when the bubble are detached is the moment of forces balance.

![Figure 4. Growth process and force analysis of microbubble.](image-url)
3.2. Bubble detachment volume

The growth process of microbubble can be divided into three stages due to the interaction of four forces, and the bubble will be detached from the end of the gas channel and remain the same size when the four forces are balanced with each other, at which time the volume of the bubble is called bubble detachment volume \( V_d \). During the experiment, \( P_g \) values were set to 0.01 MPa, 0.03 MPa and 0.05 MPa respectively, the adjustment range of \( Q_L \) was 100 mLh\(^{-1}\) \( \sim \) 350 mLh\(^{-1}\), and the gradient was set to 50 mLh\(^{-1}\), and \( V_d \) at different working conditions were measured by experimental system and data processing software. Similarly, \( Q_L \) values which were set to 100 mLh\(^{-1}\), 200 mLh\(^{-1}\) and 300 mLh\(^{-1}\), the gas pressure adjustment range was 0.01 MPa \( \sim \) 0.05 MPa, and the gradient was 0.01MPa. Curves of \( V_d \) under different liquid flow rates and gas pressures are shown in Figure 5.

![Figure 5. Curves of bubble detachment volume under different working conditions.](image)

As is addressed in Figure 5 a), the mechanical microfluidic device can be able to prepare microbubble with a volume of less than 1 mm\(^3\), and \( V_d \) decreases with \( Q_L \) increases under the condition that the gas pressure is constant. This may be because \( F_D \) increases with \( Q_L \) increases, so that the time for the bubble to generate the neck is shortened and the bubble quickly detached, thereby reducing the bubble volume. It can be seen from Figure 5 b) that \( V_d \) increases with \( P_g \) increases under different liquid flow rates. This may be because \( F_M \) increases with \( P_g \) increases, and the ability of \( F_M \) to overcome \( F_D \) and \( F_\sigma \) increases, thereby promoting the growth of the bubble.

3.3. Formation frequency of microbubble

When formation frequency of microbubble was measured, the preset \( Q_L \) and \( P_g \) input values were the same as those for the above-mentioned measurement of bubble detachment volume. Similarly, the bubble formation frequency under different working conditions can be obtained through experimental system and data processing software, as shown in Figure 6.

It can be summarized by analyzing the trend of the curves in Figure 6 a) and b) that bubble formation frequency shows a trend of increasing with \( Q_L \) and \( P_g \) increase. On the one hand, \( F_D \) increases with \( Q_L \) increases, which speed up the process of necking and detachment of bubble. On the other hand, the increase in \( P_g \) represents an increase in the \( F_M \) inside the bubble, and the greater the \( F_M \), the easier it is to overcome the gas-liquid interfacial tension, thus accelerating the expansion and detachment of the bubble.
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Figure 6. Curves of bubble formation frequency under different working conditions.

4. Conclusions
In this paper, formation characteristic of microbubble in a mechanical microfluidic device is investigated experimentally. According to the investigation of the present study, there are following conclusions:

1. It is observed through the microbubble formation experiment that growth process of microbubble is divided into three stages, and through further theoretical analysis, it is known that the shape and size of microbubble are actually affected by the interaction between multiple forces between the gas-liquid two phases.

2. Microbubble detachment volume and formation frequency under different working conditions are obtained by multiple sets of comparative experiments. It can be known by analysing the change law of bubble detachment volume and formation frequency that the liquid pulling force and gas thrust will be changed by the variation of liquid flow rate and gas pressure, which affects growth process of microbubble.

Results of the experiments can obviously help us understand more about the bubble growth process in co-flowing focusing microfluidic devices, and they fully demonstrate that the microbubble detachment volume and formation frequency could be effectively controlled by changing liquid flow rate and gas pressure. This study laid the foundation for the design of integrated microbubble generating device based on microfluidic technology.

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