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Bubble translation at low-frequency actuation in a resonator-shaped microfluidic chamber

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Abstract

Bubble dynamics in bulk flow has been widely investigated at high-frequency actuation (normally above 20 kHz, up to several MHz); however, bubble translation in microfluidics has seldom been investigated, especially at low frequencies (below 10 kHz). This paper presents a study on bubble translation in a resonator-shaped microfluidic chamber. The experimental results show that under the actuation at 1 kHz, the bubbles are observed to occur near the center of the chamber, grow up in size and then move upstream against the main flow. The bubble translation upstream against the main flow is attributed to the attraction of the image bubbles which exist behind the chamber sidewall.

1. Introduction

Bubble dynamics in bulk flow has been widely investigated because of the applications in many technologies such as ultrasonic cleaning, sonochemistry and erosion of bubble collapses and ultrasonography and so on [1]. The radial oscillation of a bubble in incompressible liquids was firstly investigated by Rayleigh and Plesset who gave the famous Rayleigh-Plesset equation [2]. A family of Rayleigh equations was proposed by researchers when the effects of liquid compressibility, heat transfer and mass transfer were considered. Further studies [3,4] reveal that bubbles under actuation not only undergo volume oscillations but also move in space – translations. The strong coupling between radial oscillation and translation makes it difficult to obtain the radius and displacement of a bubble under

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actuations. Crum and Eller [5] calculated the translation velocity of an oscillating bubble by introducing the averaged acoustic force and recently, Doinikov derived [6] coupled equations for radial and translational dynamics of a bubble in an infinite liquid domain.

In contrast to numerous studies of bubble dynamics in bulk fluids at high-frequency actuation (normally above 20 kHz, up to several mHz), bubble dynamics, especially bubble translation has seldom been investigated in microfluidics, especially at low frequencies (below 10 kHz). Previously, our group demonstrated that in a novel microfluidic chamber under actuation, single or multiple bubbles, which are generated within a frequency range between 0.5 kHz and 5 kHz, can enhance the mixing effectively [7]. After being generated, the bubbles tend to move to a position upstream, where drastic oscillation of the bubbles leads to enhancement of the mixing efficiency all over the chamber. However, how the bubbles translate under actuation and why the bubbles move against the hydrodynamic flow have not been clarified. This paper aims to investigate the dynamics of a bubble in the microfluidic chamber under the actuation at 1.0 kHz. Experiments have been conducted to observe bubble translation by photographing the motion of an oscillating bubble.

2. Experimental methods

The microfluidic chamber used in the present study is shown in Fig. 1. The chamber is made by two PMMA (polymethylmethacrylate) plates sandwiched by a dry adhesive layer with 300 μm in thickness (Arclad 8102 transfer adhesive, Adhesives Research, Inc.). The chamber contains two parts, a 16 mm diameter circular chamber and a nozzle with an acoustic resonator profile. The overall geometric profile of the chamber can be expressed by

$$y = \begin{cases} \sqrt{8^2 - x^2} & , \quad -8 \le x \le 4 \\ 0.5e^{0.101(30-x)} & , \quad 4 \le x \le 30 \end{cases} \tag{1}$$

Two inlets are connected at a 60-degree angle to the chamber by a straight channel of 10 mm in length and 1 mm in width, and another straight channel is connected to the other end of the chamber to form the outlet. A piezoelectric disk (PZT) is attached to the bottom of the circular chamber to provide actuation. The PZT disk consists of a PZT ceramic layer of 15 mm diameter and a brass sheet of 22 mm diameter.
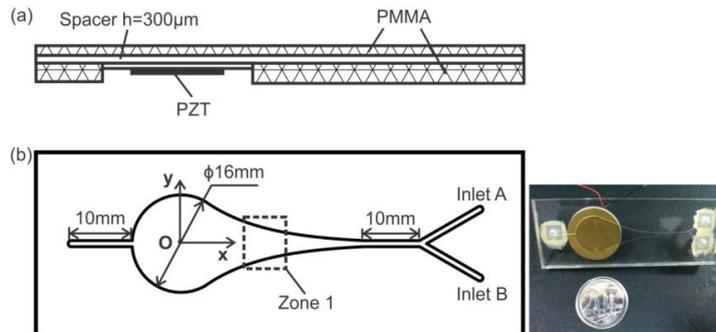

Fig. 1. Schematic illustration of the microfluidic chamber. (a) Side view of the configuration. (b) Top view of the chamber with geometric dimensions. The rectangular region Zone 1 is selected to record the bubble's motion.

The schematic of the experimental setup is illustrated in Fig. 2. The working fluid, DI water, is supplied to the microfluidic chamber by two inlets in the experiment. The flowrate is controlled by two syringe pumps (KD Scientific Inc., USA). The piezoelectric disk is driven by an external signal generator (33120A, Hewlett Packard) and an amplifier (790, PCB Piezotronics). A high speed CCD camera (Phantom V711, Vision Research, USA) is mounted on top of the chamber to record the flow field and bubble motion.
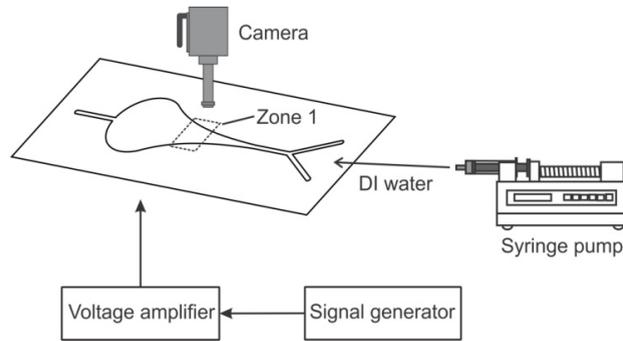
Fig. 2 Schematic illustration of the experimental setup.

3. Results and discussion

An individual bubble moving through Zone 1 (indicated in Fig.1) is recorded by the camera set at 4000 fps, i.e. 4 images captured in one cycle based on the actuation frequency of 1 kHz. The images of the oscillating bubble at the radius = 0.075 mm are stacked at the same phase of each cycle, as shown in Fig. 3. The time between two selected images is 6 periods, that is, 0.006 second. It shows that a single bubble moves towards upstream, against the direction of the main stream along a straight line. The transient displacement of the bubble is measured by processing recorded images with MATLAB. The time-dependent displacement of the moving bubble at the same phase of different cycles is plotted in Fig. 4. The time interval between two successive images is 3 periods, that is, 0.003 seconds and finally normalized with one actuation period $T = 0.001s$. It can be seen that the bubble displacement almost linearly increases with time and the average velocity is estimated to be 0.19 m/s based on the displacement curve. Such velocity is much greater than the mean flow velocity, about 0.0093 m/s, inside the chamber. The translation velocity of the bubble in our experiment is also much higher than the maximum bubble translation velocity reported by Crum [5], which was 0.023m/s at the frequencies ranging from 23.6 kHz to 28.3 KHz.
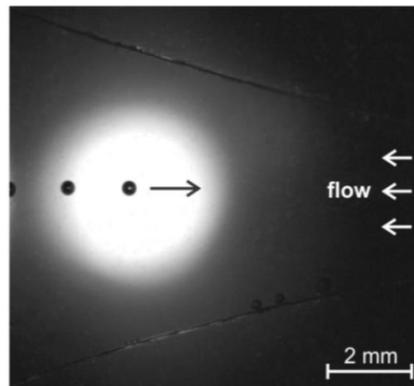

Fig. 3. Movement of a single bubble towards upstream along a straight line after being generated in the chamber. The trajectory is obtained by stacking four images of the bubble corresponding to four different phases in a cycle and the time between two successive images shown in the figure is 6 periods, that is, 0.006 seconds.
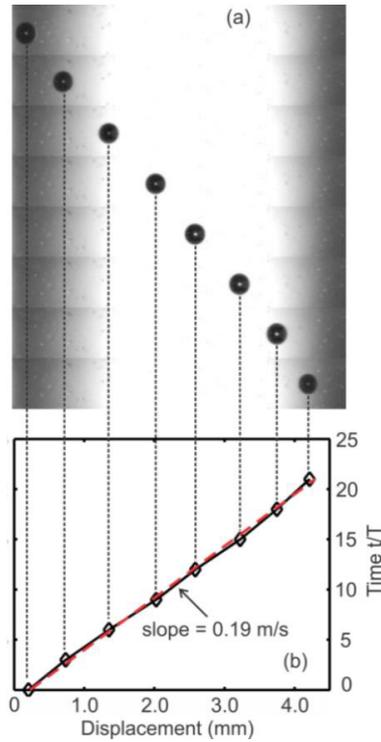
Fig. 4. (a) Images of a moving single bubble captured at the same phase in different cycles. (b) The displacement of the bubble versus time normalized with one actuation period $T = 0.001$s. The average translation velocity of the bubble is estimated to be 0.19 m/s, based on the slope of the displacement curve.
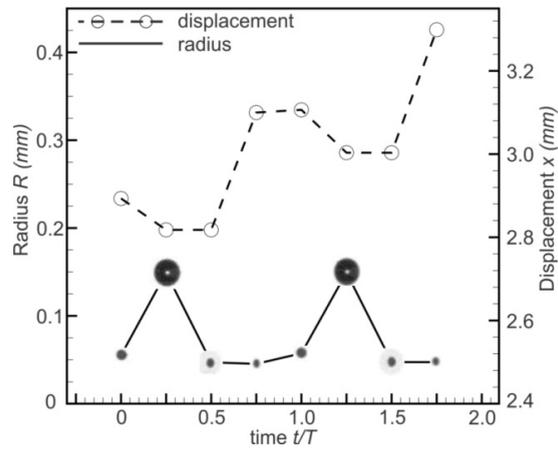

Fig. 5. Variations of radius (solid line) and displacement (dashed line) of the bubble in two successive cycles. The bubble moves forward when the bubble is at the phase of collapse. $T = 0.001$s, is the actuation period.

Fig. 5 shows the radius (solid line) and displacement (dashed line) of the bubble in two successive cycles. From the solid line, it can be seen that the bubble volume undergoes a great change within one actuation cycle: the bubble

radius varies from 0.05 mm to 0.14 mm during one cycle and the ratio of the maximum radius R_{max} to the minimum radius R_{min} is about 2.8, indicating that the ratio of maximum volume to the minimum is about 22. Accompanied by periodical volume variation, the bubble translates in a "jerky" way: the forward movement of the bubble occurs during the collapse phase, and then the bubble moves backward slightly when growing up in volume. This observation is consistent with the observation reported by Reddy and Szeri [8] for bubbles driven at high frequencies that the translation velocity was maximized when the bubble collapsed violently. In our case shown in Fig. 5, a steeper portion in the displacement (dashed line) corresponding to the phase when the bubble is in its minimum volume.

It is reported that the impact of the wall on an oscillating bubble in liquid can be described by the image bubbles [9]. Furthermore, two pulsating bubbles with the same radius attract each other because of the secondary Bjerknes force [10]. In our case, because of the existence of the inclined walls, image bubbles, with the same size as the real bubble, are generated in the positions upstream behind the inclined walls. Therefore attractive force can be exerted toward the real bubble and the real bubble will move towards the image bubbles. This is probably the reason why the bubbles generated in the microfluidic chamber can move against the hydrodynamic flow in our experiments.

4. Conclusion

In this paper the translation of a bubble in a microfluidic chamber under low-frequency actuation has been investigated. The bubble's motion is recorded by a high-speed camera. A single bubble or multiple bubbles can be generated in the microfluidic chamber with low frequency actuation. After being generated, the bubble moves against the hydrodynamic flow until some place upstream. The bubble under actuation translates intermittently along a straight line at an average velocity up to 0.19 m/s and the bubble undergoes significant expansion and compression synchronously with actuation frequency, showing a remarkable volume variation with a ratio of maximum to minimum volume up to 22.

Acknowledgements

References

[1] D. Cosgrove, Ultrasound contrast agents: An overview, Eur. J. Radiol. 60 (2006) 324-330.
[2] M.S. Plesset, The dynamics of cavitation bubbles, J. Appl. Mech. 16 (1949) 277-282.
[3] W. Lauterborn, T. Kurz, R. Mettin and C.D. Ohl, Experimental and theoretical bubble dynamics, Adv. Chem. Phys. 110 (1999) 295-380.
[4] T.J. Matula, Inertial cavitation and single−bubble sonoluminescence, Phil. Trans. R. Soc. Lond. A 357 (1999) 225-249.
[5] L. Crum and A. Eller, Motion of bubbles in a stationary sound field, J. Acoust. Soc. Am. 48 (1970) 181-189.
[6] A.A. Doinikov, Translational motion of a spherical bubble in an acoustic standing wave of high intensity, Phys. Fluids 14 (2002) 1420-1425.
[7] S.S. Wang, X.Y. Huang and C. Yang, Mixing enhancement for high viscous fluids in a microfluidic chamber, Lab Chip 12 (2011) 2081-2087.
[8] A.J. Reddy and A.J. Szeri, Coupled dynamics of translation and collapse of acoustically driven microbubbles, J. Acoust. Soc. Am. 112 (2002) 1346-1352.
[9] R.H. Cole, Underwater explosions, Princeton University Press, Clinton, 1948.
[10] R. Mettin, I. Akhatov, U. Parlitz, C. Ohl and W. Lauterborn, Bjerknes forces between small cavitation bubbles in a strong acoustic field, Phys. Rev. E 56 (1997) 2924-2931.