VISUALIZATION OF MICRO BUBBLE GROWTH IN TEMPORAL PRESSURE GRADIENTS

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ABSTRACT: *The micro bubble growth in an ambient liquid has been visualized under temporal pressure gradient. The micro bubble is generated by reducing the liquid pressure gradually from the atmospheric pressure to a final pressure. Then, the growth rate of the micro bubble is measured using a microscope and analyzed by an image processing technique. As experimental parameters, the final pressure and the temporal pressure gradient are varied. As a result, there found a continuous growth in bubble radius even though the pressure is kept constant after it is reduced to its final pressure. While the pressure gradient has little effect on the growth rate of the micro bubble in the diffusion controlled growth region, the growth rate increases linearly with the increase of the pressure difference between the atmospheric pressure and the finally reduced pressure.*

1 Introduction

Micro bubbles have a variety of possibility for medical applications and industrial facilities. It is very important to understand the bubble dynamics in order to control the size and volume fraction of bubbles in fluidic systems and thus to make the system more useful. In the fundamental research for the bubble dynamics, Rayleigh [1] suggested an equation about the dynamics of single bubble based on the assumption that there is no mass transport across the bubble boundary, and the surface tension and viscous forces are also negligible. Then, Plesset [2] first applied the equation to the problem of traveling cavitation bubbles. Recently, Robinson and Judd [3] studied the dynamics of spherical bubble growth through delineation of the parameters governing the changes in the growth dynamics from surface tension, to inertia dominated, to diffusion controlled, and the domains between them. Yang et al. [4] slightly modified the equation considering the fulfillment of the energy conservation law in mathematical model of evolution of single spherical bubble.

With regard to the micro bubble growth under the variation of the ambient pressure, the experimental results of Takahira and Ito [5] showed that when the ambient liquid pressure increases, a stationary micro bubble with a radius of 5 μm shrinks accompanied with surface depression and does not return to the initial size even after the pressure is reduced to its initial value. Kawashima and Kameda [6] measured the radius-time curves of micro bubbles in a shock tube experiment with sudden pressure reductions. In their experiments, the initial bubble with a radius ranged from 118 to 281 μm grew quickly due to the rapid decompression and kept constant radius when the constant low pressure is applied. If the pressure was reduced below the saturated vapor pressure, the bubble experienced a continuous growth even in a constant pressure. Their numerical results showed that the bubble growth rate was very sensitive to initial bubble radius, ambient pressure, and liquid temperature. In spite of the above achievement on the bubble growth in varying pressure fields, the effect of the rate of pressure change on the micro bubble growth is not uncovered yet.

The present study focuses on the change of bubble radius under different temporal gradients of ambient pressure. With the help of CCD camera and image processing techniques, the images of bubbles are captured and the radii of bubbles are evaluated. In order to set the temporal pressure gradient, a test chamber filled with water is connected to a vacuum chamber through a tube with porous materials inside to give a resistance to the exhausting flow. The time-varying pressure inside the test chamber is monitored by a dynamic pressure sensor. The images of the bubble growth are acquired using a microscope and a high speed CCD camera. Then, the radius of bubble and the rate of bubble growth are calculated by an image processing technique. Finally, the radius-time curve of a micro bubble and its growth rate are discussed according to the amount of pressure drop and the decreasing rate of pressure.

2 Experimental Setup\

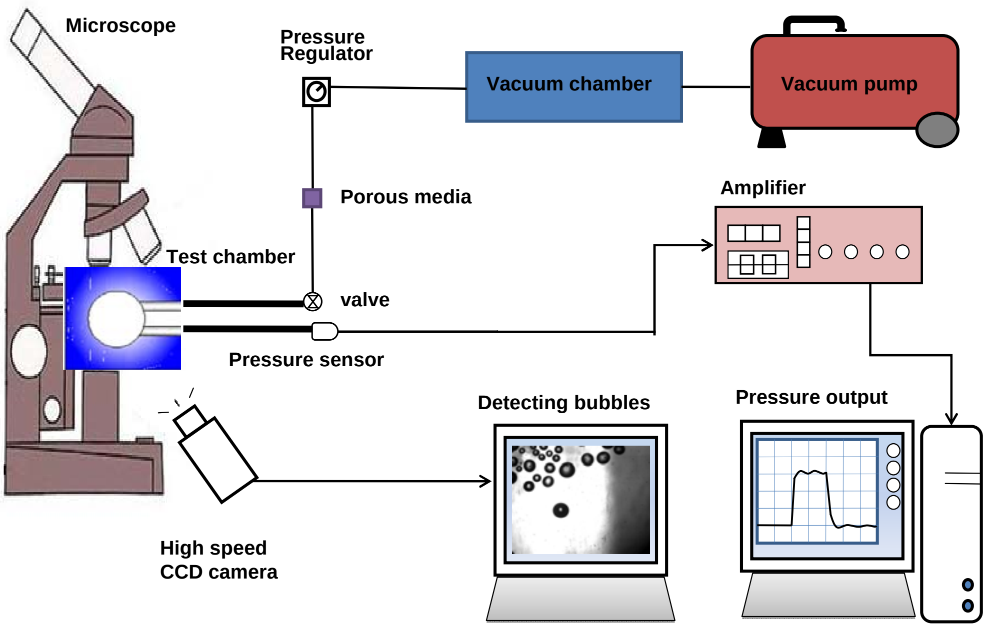
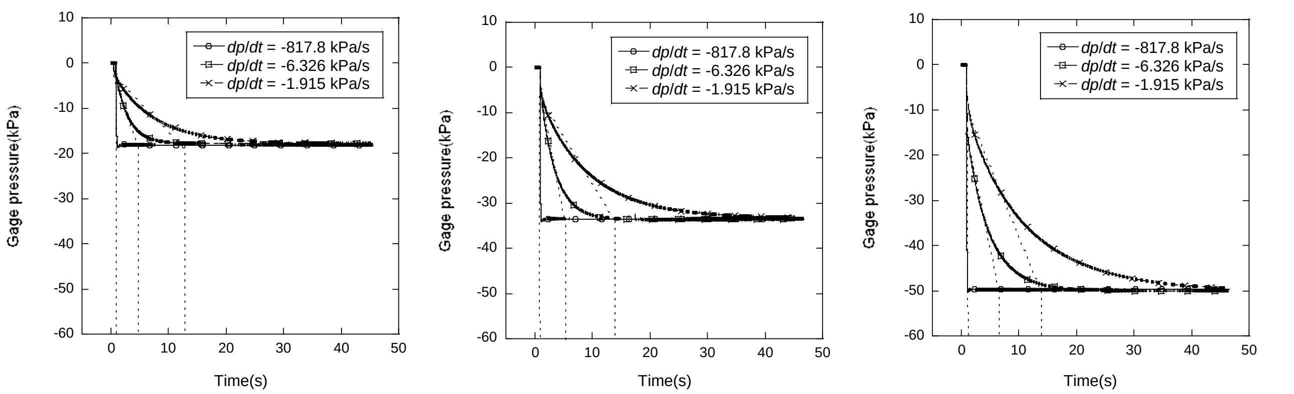


Fig. 1 Experimental setup to visualize the micro bubble growth under temporal pressure gradients

Fig. 1 shows the experimental setup for the measurement of micro bubble growth under temporal pressure gradients. First, a vacuum pump exhausts the air in a vacuum chamber (50 x 50 x 50 mm^3). The pressure in the vacuum chamber can be set constant by a vacuum pressure regulator (PISCO, VR100-M5). An acrylic test chamber (32 x 22 x 13 mm^3) containing a liquid is put on the stage of a microscope to visualize the bubble growth. The test chamber is connected to the vacuum chamber through a tube. When a valve in the tube is open, the pressure in the test chamber starts to decrease and then it reaches the final pressure set in the vacuum chamber. Then, micro bubbles are generated in the acrylic test chamber. The bubbles that rise and attach on the surface of the chamber can be observed by a microscope objective lens (10X). The bubble images are recorded using a CCD camera (SVSI), which is synchronized with the data acquisition of the pressure sensor. D.I Water is used as a working fluid and the temperature is kept constant at 298K for all experiments.

To measure the bubble size, an image processing technique is applied. The first step is to apply a median filter which eliminates noises included during the image acquisition process. The second step is a binarization process which discriminates bubble (black) from background (white) by a threshold level in the image. The values of threshold for the binarization process are specified after looking up the individual image. The third step is a dilation/erosion process which removes spot noise generated by the refraction of light inside the bubble. The final step is an edge detection which seeks the boundary of bubble and calculates the area of inner region in a pixel unit. The real size of the bubble is obtained by multiplying a scale factor between the dimensional length and pixel unit. In order to control the decreasing rate of the pressure, a porous material whose diameter is 2 mm and hole size is 10~20 μm is inserted inside the tube. The longer is the length of the porous material, the smaller pressure gradient can be obtained. The pressure in the test chamber is measured using a dynamic pressure sensor (Measurement Specialties, EPX-N03-1B).

In this study, three different cases for both the final pressure difference Δp and the pressure gradient dp/dt are tested. Fig. 2 shows the pressure-time curve measured under the three different pressure gradients. The final pressure differences are 22, 33 and 50 kPa, respectively. Although the pressure in the test chamber varies non-linearly when it approaches the final pressure, the major portion of the pressure variation has linearity so that the data is fitted to a linear function to get the gradient. Thus, the three pressure gradients applied in this study are -817.8, -6.326 and -1.915 kPa/s, respectively. As the pressure gradient is smaller, the time of bubble generation more delays. By the linear fitting function, the time delays to reach the final pressures are determined as 1 s, 7 s and 15 s, respectively.



(a) (b) (c)

Fig. 2 The pressure-time curve measured under the three different pressure gradients (-817.8, -6.326 and -1.915 kPa/s). For each case, the pressure is also varied from the atmospheric pressure to (a) -22 kPa, (b) -33 kPa and (c) -50 kPa

3 Result and discussion

According to the applied pressure variations in Fig. 2, the time-varying radius of bubble is measured as shown in Fig.3. After the pressure reaches the final pressure, the bubbles start to occur. There is a time delay to reach the final pressure, which is dependent of the pressure gradient. Thus, the amount of the time delay is subtracted in this figure to compare the data for the different pressure gradients. On the whole, the bubbles grow steadily even though the pressure is kept constant after arriving at the final pressure. Since the evaporation at the bubble wall becomes predominant for the radial motion, the bubble expands continuously. However, there is no influence of the pressure gradient. On the other hand, the final pressure affects significantly the bubble growth. As the final pressure is lower, the radius of bubbles becomes bigger, which means that the growth rate of bubble is faster.

Fig. 4 shows the sequential images of the bubbles for the different pressure gradient at the same final pressure of -50 kPa. Here, the top image is for the case of *dp*/*dt* = -817.8 kPa/s, the middle image is *dp*/*dt* = -6.326 kPa/s and the bottom images is *dp*/*dt* = -1.915 kPa/s. If the pressure gradient is gradual, the bubble generation is delayed. Thus, the bubble generated at the slowest pressure gradient is the smallest at a given time from the beginning of pressure decrease. In all cases, the bubbles have a spherical shape in this study.

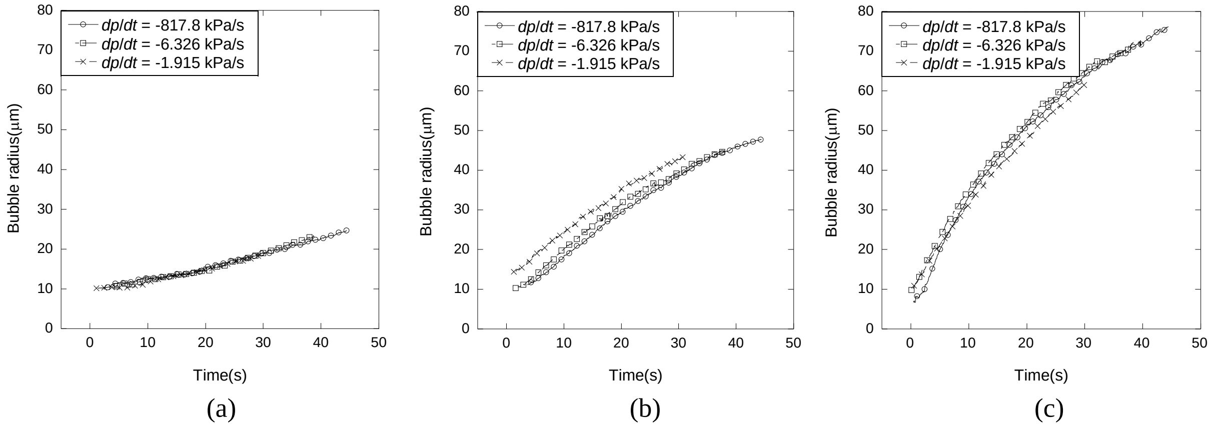


Fig. 3 Radius-time curve measured at (a) Δp = 22 kPa, (b) Δp = 33 kPa and (c) Δp = 50 kPa

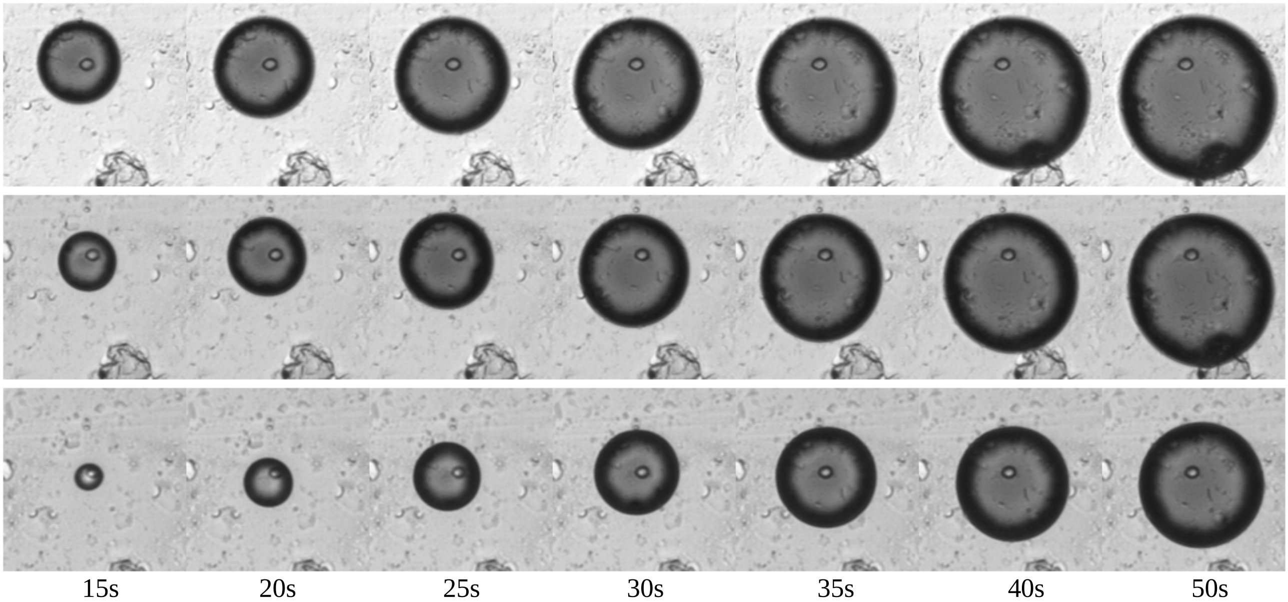


Fig. 4 Sequential images of bubbles for the different pressure gradient at the same final pressure of -50 kPa; *dp*/*dt* = -817.8 kPa/s (top), *dp*/*dt* = -6.326 kPa/s (middle) and *dp*/*dt* = -1.915 kPa/s (bottom)

Fig. 5 shows how the pressure gradient influences on the bubble growth rate. The growth rate is calculated from the radius-time curve in Fig. 3. The result shows that regardless of the pressure gradients, the growth rates of bubbles are nearly constant at the same final pressure. The bubble growth rate is considered separately in the two limiting regions; the inertia and diffusion controlled growth regions [3]. The inertia controlled growth is restricted to the initial stages of expansion during which the bubble growth is primarily determined by its ability to push back the surrounding liquid independent of the rate of vapor generation into the bubble. The diffusion controlled growth is relatively slow during which the rate is determined by the evaporation rate in the interface of bubble. It is not known in the previous literatures which region the pressure gradient plays a dominant role in. In this study, the bubble in the diffusion controlled growth regions is measured since it is difficult to capture the images at the initial stages of expansion. According to the present results, the pressure gradient seems to have little influence on the diffusion controlled growth. In order to know the influence on the inertia controlled growth, a more sophisticated technique to detect very tiny bubbles in the initial stage needs to be developed. The growth rate in this stage is so fast that the combination of a high speed imaging with a short exposure time (less than 10 μs) and a high power light source based on laser illumination (more than 2 W) can be an alternative.

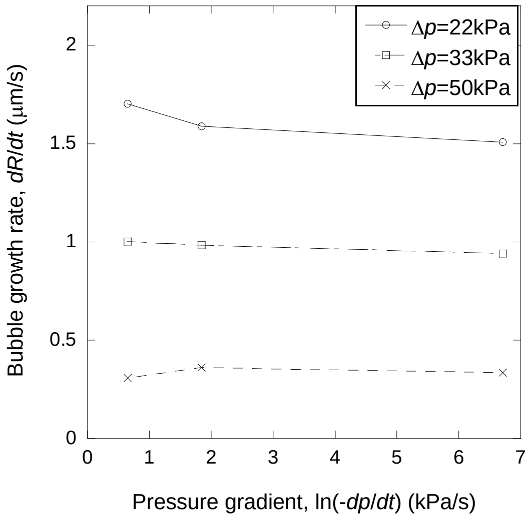


Fig. 5 Influence of the pressure gradient on the bubble growth rate

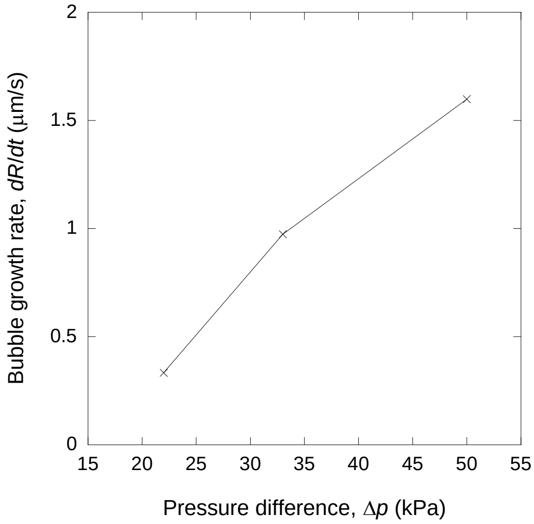


Fig. 6 Influence of the pressure difference on the bubble growth rate

Finally, Fig. 6 shows the influence of the pressure difference on the bubble growth rate. The data of the bubble growth rates in Fig. 5 are averaged for all pressure gradients at a given pressure difference since the growth rate of bubbles is not associated with pressure gradients. The result shows that the bubble growth rate increases with the pressure difference. In this experimental range of the pressure difference (~ 50 kPa), the relationship between the bubble growth rate and the pressure difference is linear. In further study, it is required to analyze the trend in bubble growth in view of non-dimensional parameters by collecting more data in a wide range of pressure difference.

4 Conclusions

In the present study, the micro bubble growth has been investigated under the time-varying pressure drop. The bubble radius and pressure in the different temporal pressure gradients were monitored simultaneously using a microscope and a pressure sensor. As a result, it is found that the micro bubble grows continuously even though the pressure is kept constant after it is reduced to its final pressure. However, the growth rate of the micro bubble is not affected by the magnitude of the pressure gradient in the diffusion controlled growth region. On the other hand, the growth rate of the micro bubble increases linearly with the increase of the pressure difference between the atmospheric pressure and the finally reduced pressure.

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