Experimental study of a laser induced cavitation bubble near a complex boundary

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Abstract. In the present paper, the dynamics of the bubble near a complex boundary (represented by a series of triangle-type cross sections) are experimentally investigated with the aid of high-speed camera. The cavitation bubble is generated by a focused laser beam and the complex boundary is achieved through high-precision 3D printing technology. A plenty of experiments are carried with the variations of distances between the centre of bubble and the complex boundary, maximum radius of the bubble (adjusted through the energy dissipater) and other paramount parameters. A detailed data analysis is performed with a focus on the effects of the complex boundary on the collapsing phenomenon of bubble. Based on our analysis, the complex boundary could greatly alter the dynamic behaviour of cavitation bubbles especially in terms of the collapse shape of bubble and the jet phenomenon.

Nomenclature

X the distance between the centre of the bubble and the bottom of triangular boundary

Y the distance between two parallel lines that go through the centre of the bubble and the bottom vertex of the triangular

γ the length of the hypotenuse of the triangular boundary

α the angle of the vertex of the triangular boundary

Rmax the maximum radius of the bubble
\( D \) the projected distance of \( D \) coordinate axis between the centre of the bubble and the origin

\( L \) the projected distance of \( L \) coordinate axis between the centre of the bubble and the origin

\( \chi \) the non-dimensional parameter defined as the ratio between the maximum radius and the projected distance of the \( L \) coordinate axis (\( R_{\text{max}}/l \))

\( \lambda \) the non-dimensional parameter defined as the ratio between the projected distance of \( D \) coordinate axis divided by the maximum radius (\( d/R_{\text{max}} \))

1. Introduction

It is well-known that the cavitation bubbles lead to serious damage on the fluid passing component of various kinds of fluid machineries e.g. hydroturbines\(^1\), pumps and valves. Currently, cavitation is being applied into many practical engineering aspects (e.g. the promotions of the cleaning effects in the fluid flow\(^2,3\)). During the collapse of the cavitation bubbles, a strong pressure wave will be generated associated with a fast micro jet toward the boundary\(^4\). The above collapsing phenomenon of the cavitation bubbles plays an important role on the determination of the cavitation damage or cavitation-enhanced effects. To promote the cavitation effects, one of the practical directions is to employ a well-designed complex boundary in order to facilitate the collapse force and jet speed of the cavitation bubbles. In some existing applications of cavitation (e.g. sonochemical reactor in chemical engineering), some complex boundaries are also generally involved. Hence, in the present paper, an experimental system is designed in order to reveal the interactions mechanisms between cavitation bubbles and complex boundaries.

In the literature, most of previous works focus on the cavitation bubble dynamics near a solid flat boundaries (e.g. Shima and Nakajima\(^5\), Tomita and Shima\(^6\), Blake et al.\(^7\) and Brujan et al.\(^8\)). Lauterborn and Kurz\(^4\) comprehensively reviewed the previous works relating with bubble-boundary interactions. For theoretical and numerical aspects of the bubble-boundary interactions, readers are referred to a classical review by Blake et al.\(^9\). Recently, the cavitation bubble dynamics near a complex boundary (e.g. bubble-particle interactions in silt laden flow) attracts many attentions. Poulaın et al.\(^10\) experimentally investigated the motion of the particle induced by the spark-induced cavitation bubbles. For a review of bubble-particle interactions, readers are referred to Zhang et al.\(^11\). Recently, Zhang et al.\(^12\) experimentally investigated the bubble collapsing behavior near a stationary spherical particles and found that the presence of the particle could seriously affect the bubble collapsing shape and the generation of micro-jets.

In the present paper, cavitation phenomenon near a complex boundary (represented by a series of triangle-type cross sections) is investigated with the aid of the high-speed camera. A series of experiments are performed through varying several paramount parameters (e.g. distances between the bubble and the complex boundary, maximum bubble radius). The following sections of the present paper are organized as follows. Section 2 introduces the details of the experimental setup with the parameter definitions. Section 3 introduces the dynamics of the bubble with symmetrical setup (\( Y=0 \)). Section 4 shows the complicated characteristics of the bubble dynamics with un-symmetrical setup (\( Y \neq 0 \)) with examples given. Section 5 gives the conclusions with primary findings.
2. Experimental Setup

Figure 1 shows the schematic description of present experimental setup of bubble-triangular boundary interaction. The laser beam with high-level energy was generated by the Nd: YAG laser generator. Then, the laser beam was gathered at the focus point inside a water chamber through the focus lens with a well-controlled cavitation bubble generated. The present water chamber was filled with deionized water and the triangular boundary (manufactured through 3D printing technology) was completely submerged into it. The sizes of cavitation bubbles could be adjusted using laser energy dissipater, which was placed on the laser beam route. The triangular boundary was fixed at the certain position inside the water chamber with its movement controlled by a 3D movement control platform.

The whole dynamics of the bubble near the stationary triangular boundary were recorded by a high-speed camera (Phantom V1212). In our experiments, 90,000 fps (frame per second) was employed for recording the phenomenon with the exposure time 1 μs and the interval time between frames is 11.1 μs. Much higher speed of the camera was also tested during the experiments and no further significant scientific findings could be revealed. During the experiment, a digital delay generator was employed for adjusting the synchronization between the illuminating light source and the high-speed camera.

![Figure 1](image1.png)

Figure 1. The schematic description of present experimental setup of bubble-triangular boundary interaction[12].

Figure 2 shows the definition of several paramount parameters relating with the present bubble-triangular boundary interaction experiments. As shown in figure 2, the bubble is generated by a laser beam near the triangular boundary horizontally and its (equivalent) maximum radius during the dynamic oscillations is denoted as $R_{\text{max}}$. In the figure 2, $X$ is the distance between the centre of the bubble and the bottom of triangular boundary and $Y$ is the distance between two parallel lines that go through the centre of the bubble and the bottom vertex of the triangular respectively. The length of the equicrural triangle ($\gamma$) is 2 mm and the angle of the vertex of the equicrural triangle is 90°. The measurement of $X$ and $Y$ were fulfilled based on the frame of the incipient cavitation using the software Phantom Camera Control (PCC) application. During our experiments, the triangular boundary was fixed in the water chamber and could be safely regarded as a purely stationary one during the bubble collapse nearby. In the present paper, a series of experiments with different values of $X$ and $Y$ were conducted with the aid of the high-speed camera.
Table 1. A list of the values of the relevant parameters

| Parameter | Value     |
|-----------|-----------|
| $\gamma$  | 2 mm      |
| $\alpha$  | 90°       |
| fps       | 90,000    |

Figure 2. Definition of paramount parameters of the bubble and the triangular boundary. In the figure 2, $R_{\text{max}}$ is the (equivalent) maximum radius of the bubble during its dynamic oscillations; $X$ is the distance between the centre of the bubble and the bottom of triangular boundary; $Y$ is the distance between two parallel lines that go through the centre of the bubble and the bottom vertex of the triangular; $\alpha$ is the angle of the vertex of the equicrural triangle; and $\gamma$ is the length of the equicrural triangle.

3. The dynamics of the bubble with symmetrical setup ($Y=0$)

In this section, the dynamics of the cavitation bubble with symmetric setup ($Y=0$) will be shown. The purpose of this section is to provide a base case for further comparisons shown in section 4. Based on our experimental data, the phenomena of cavitation bubble behaviour are demonstrated using three typical examples of the collapsing process of the cavitation bubble. In order to fully and concisely reflect the whole dynamics of the bubble, for each example, twenty-four frames are selected in the following analysis. In the following figures, the subplots are all numbered together with its time (relative to the incipient cavitation) marked at the right corner of each frame.

Figure 3 shows the case corresponding to the largest distance between the bubble and the boundary ($X=1.4$ mm; $R_{\text{max}}=0.4$ mm). The whole bubble dynamics could be briefly introduced as follows. Firstly, the cavitation bubble grows approximately spherically at the incipient stage (referring to subplots Nos. 1-6 of figure 3) until reaching the maximum volume (referring to subplot No. 6 of figure 3). Then, the bubble shrinks and collapses (referring to subplots Nos. 7-13 of figure 3). During the bubble collapse, due to the effects of triangular boundary, the shape of the bubble shows significant non-spherical types. At the later stage of the collapse, a thin jet (referring to subplots Nos. 14-15 of figure 3) is produced with the directions towards the triangular boundary. Finally, the bubble rebounds (referring to subplots Nos. 16-24 of figure 3) and collapses again until the energy is fully dissipated.
Figure 4 shows a larger bubble with the same position as the bubble in figure 3 ($X=1.4\text{ mm}$; $R_{\text{max}}=0.79\text{ mm}$). Comparing with the figure 3, the non-spherical shapes of the bubble during collapse is much obvious. Figure 5 further shows the case with a shorter distance between bubble and boundary ($X=0.6\text{ mm}$; $R_{\text{max}}=0.33\text{ mm}$). Different figures 3 and 4, due to the limitations of the space, the bubble will contact the boundary during its growth, forming a cone-shaped bubble. Then, the bubble will collapse and rebound with a limited amplitude.
4. The dynamics of the bubble with un-symmetrical setup \((Y \neq 0)\)

4.1 The definition of a new coordinate system

In this section, a new coordinate system \((L-D)\) will be established in order to analyse more complicated phenomena with un-symmetric setup \((Y \neq 0)\). Figure 6 shows the schematic description of the \(L-D\) coordinate system for analysing the complicated dynamics of bubbles with \(Y \neq 0\). The origin of the new coordinate is the bottom vertex of the triangle. In figure 6, \(L\) axis is the leg of the triangle; \(D\) axis is the direction perpendicular to \(L\) axis; \(d\) is the projected distance between the centre of the bubble and the origin; \(l\) is the projected distance between the centre of the bubble and the origin. Because the corner angle of the present paper is 90°, \(D\) axis is in the same direction as the leg of the neighbour triangle.

![Figure 6. A brief description of the coordinate system for the un-symmetrical setup.](image)

For the convenience of the discussions, two non-dimensional parameters \(\chi\) and \(\lambda\) are defined as follows:

\[
\chi = \frac{R_{\text{max}}}{l} \tag{1}
\]

\[
\lambda = \frac{d}{R_{\text{max}}} \tag{2}
\]

4.2 The dynamics of the bubble with different \(\chi\) and \(\lambda\)

Figures 7-10 show three typical cases of the cavitation bubble depending on the parameters \(\chi\) and \(\lambda\). As shown in table 2, depending on the contact with the boundary or not during the bubble growth and collapse, the data could be categorized into three cases with their characteristics described below.
In figure 7, when the bubble grows, the bubble directly contacts the boundary forming a hemispherical bubble (referring to subplots No. 5 of figure 7). Then, the bubble keeps growing and also collapsing after reaching the maximum size (referring to subplots No. 7 of figure 7). Different with the growth phase, the collapsing bubble shows a significant and distorted shape with the top bending toward the origin of the coordinate. During the further rebound, the bubble will move toward the origins and finally collapse near the origin. Figure 8 further shows a similar case with figure 7 but with a smaller value of \( \chi \). Hence, the bubble will cross the corner vertex partially (referring to subplots Nos. 5-12 of figure 8) and the further collapse of the bubble will be also greatly altered by the presence of the corner vertex (referring to subplot No. 12 of figure 8).

| Case    | Characteristics                                                      | Figure               |
|---------|-----------------------------------------------------------------------|----------------------|
| Case 1  | During the growth and collapse, bubble directly contacts the boundary. | Figures 7 and 8      |
| Case 2  | During the 1\(^{st}\) growth and collapse, bubble has no direct contact with the boundary. 
          | During the 2\(^{nd}\) growth and collapse, bubble contacts the boundary. | Figure 9              |
| Case 3  | During the growth and collapse, bubble does not directly contact the boundary. | Figure 10             |

**Figure 7.** Experimental photography of the dynamics of the bubble near the stationary triangular boundary. \( \chi = 0.44 \), \( \lambda = 0.32 \).
Figure 8. Experimental photography of the dynamics of the bubble near the stationary triangular boundary. $\chi=0.35$, $\lambda=0.34$.

Figure 9 shows the case with a larger value of $\lambda$. In this case, firstly, the cavitation bubble grows approximately spherically at the incipient stage (referring to subplots Nos. 1-7 of figure 9) until reaching the maximum volume (referring to subplot No. 8 of figure 9). Then, the bubble shrinks and collapses irregularly (referring to subplots Nos. 9-12 of figure 9). Different with previous one, the bubble does not contact the boundary during its growth and collapse. A thin jet (referring to subplot No. 13 of figure 9) is produced towards the leg of the triangular boundary at the last stage of the collapse. However, during the rebound of the bubble, it will contact the boundary due to the movement of the bubble toward the wall. And then the bubble grows hemi-spherically (referring to subplots Nos. 14-16 of figure 9). The second collapse of the bubble is quite similar with those shown in the figures 7 and 8.

Figure 9. Experimental photography of the dynamics of the bubble near the stationary triangular boundary. $\chi=0.51$, $\lambda=0.95$. 
Figure 10 shows the dynamics process of case 3 ($\chi=0.30$, $\lambda=1.62$). Firstly, the cavitation bubble grows approximately spherically at the incipient stage (referring to subplots Nos. 1-6 of figure 10) and collapses (referring to subplots Nos. 7-10 of figure 10). Then, the bubble rebound with a thin and long jet produced (referring to subplots Nos. 11-17 of figure 10). Finally, the bubble collapses again with a new jet generated towards the bottom of triangle (referring to subplots Nos. 18-21 of figure 10). During the whole process, the bubble does not directly contact the boundary.

Figure 10. Experimental photography of the dynamics of the bubble near the stationary triangular boundary. $\chi=0.30$, $\lambda=1.62$.

5. Conclusion

In the present paper, the dynamics of the bubble near a triangle-type boundary were experimentally investigated with the aid of high-speed camera. In our experiments, influences of several paramount parameters (e.g. the distances between the centre of bubble and the complex boundary, the maximum radius of the bubble $R_{max}$) on the cavitation bubble dynamics are revealed. Both the symmetrical and un-symmetrical cases were investigated. Based on our analysis, the complex boundary greatly alters the dynamic behaviour of cavitation bubbles especially in terms of the collapse shape and jet. Depending on the contact with the boundary or not during the bubble growth and collapse, the phenomenon could be categorized into three cases with their characteristics briefly described below:

Case 1: during the growth and collapse, bubble directly contacts the boundary.
Case 2: during the first growth and collapse, bubble has no direct contact with the boundary; during the second growth and collapse, bubble contacts the boundary.
Case 3: during the growth and collapse, bubble does not directly contact the boundary.

In the future, the vortex generated by the cavitation bubble near the complex boundaries will be investigated with the aid of some advanced vortex identification methods (e.g. the newly proposed Omega method[13, 14]). Furthermore, the interaction between oscillating cavitation bubbles and waves in the liquids is also an essential topic for the further study[15, 16].

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