Single Bubble Behavior Induced by Nd:YAG Laser Focusing near Solid Wall in Liquid Nitrogen

By Yoshihiro YAMAMOTO¹, Sho NAKAJIMA¹, Soju WATANABE², Masanori OTA³ and Kazuo MAENO⁴

¹ Graduation Students, Graduate school of Engineering, Chiba University, Chiba, Japan
² Graduated Student, Graduate school of Science and Technology, Chiba University, Chiba, Japan
³ Department of Urban Environment Systems, Graduate school of Engineering, Chiba University, Chiba, Japan
⁴ Department of Mechanical Engineering, Graduate school of Engineering, Chiba University, Chiba, Japan

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This paper deals with an experimental investigation and visualization on the dynamics of laser induced single bubble in liquid nitrogen near an aluminum wall in cryostat. The cryogenic liquid nitrogen has the characteristic feature of the low latent heat, surface tension, and viscosity, as compared with the normal temperature water. Cavitation phenomena in cryogenic liquid may be different from the phenomena in water at normal temperature. However, there have been only a few reports on the single bubble dynamics combined with laser beam irradiation in cryogenic liquid. In this experiment the plasma is produced by focusing of Nd:YAG laser beam of second harmonics in liquid nitrogen. Laser induced bubble dynamics and interaction with the solid wall have been studied by flow visualization. This paper also shows the comparison between the dynamics of laser-induced single bubble in liquid nitrogen and in distilled water. We have clarified that the behavior of laser induced bubble in liquid nitrogen is different from that in distilled water at normal temperature.

Key Words: Single Bubble Dynamics, Nd:YAG Laser, Cryogenics, Liquid Nitrogen, Distilled Water

Nomenclature

\( t \) : actual time from laser irradiation
\( \gamma \) : non-dimensional distance
\( R \) : bubble radius
\( T \) : temperature of the liquid
\( \Delta T_0 \) : difference of temperature between boiling point and melting point
\( \Delta T_{sub} \) : degree of subcooling
\( \kappa_{sub} \) : non-dimensional degree of subcooling
\( Top \) : distance from wall surface to the bubble top
\( Bottom \) : distance from wall surface to the bubble bottom
\( X^- \) : non-dimensional \( X \)

Subscripts

\( max \) : maximum
\( b \) : boiling point
\( \infty \) : surrounding environment

1. Introduction

Cavitation, which occurred in the flowing liquid where the local pressure is lower than the saturated vapor pressure, causes vibration, noise, damage and/or loss of efficiency to fluid machine. Though cavitation phenomena have been widely investigated in science and technology, they are mainly on the cavitation of such normal temperature liquid as water¹-³, except for ultrasonic cryogenic cavitations. As for the progress in such new energy systems as LNG, CH₄, and H₂ handling, together with the superconductivity technology and aerospace technology, the cryogenic liquid has become significantly important research objectives. The cryogenic liquid has the characteristic feature of the low latent heat, surface tension, and viscosity, as compared with the normal temperature water. Therefore, cavitation phenomena in cryogenic liquid may be different from the phenomena in water at normal temperature. However, there have been only a few reports on the single bubble dynamics combined with laser beam irradiation in cryogenic liquid⁴-⁵.

In this paper we have performed the visualization of the interaction of laser-induced single bubble with an aluminum wall in liquid nitrogen. We utilize a specially-designed cryostat for laser beam irradiation and flow visualization. The plasma is produced by focusing of the strong pulsed-irradiation of Nd:YAG laser second harmonics (532 nm) into the cryogenic liquid nitrogen. The interaction between the laser-induced single bubble and the aluminum wall is visualized by shadowgraph method or schlieren method, and their images are captured by high-speed imaging camera system (Shimadzu, Hyper V) or a digital still camera (Canon, EOS Kiss Digital). The inflation, and shrinking/rebounding behavior of the laser-induced single bubble, together with the ionized nitrogen plasma are observed. This paper also shows comparison between the dynamics of laser-induced single bubble in liquid nitrogen and that in distilled water.
2. Experimental Apparatus and Measurement

A specially-designed cryostat is utilized for cryogenic experiments. A schematic diagram of the cryostat is shown in Fig. 1. As for the cryostat, laser-induced single bubble experiments can be realized in temperature range from liquid argon and liquid nitrogen to liquid hydrogen. Lens array to focus the laser beam and three optical windows are settled to the test section of cryostat with a cylindrical type of $\phi 38 \text{mm} \times 150\text{mm}$. Replacing an optical window with solid wall holder, we can observe the single bubble behavior near a solid wall in cryogenic liquid. Two cylindrical heat shields are fixed outside the test section and have holes to pass the observation light or laser beam. The experiments under pressurized conditions are also possible by introducing the gas nitrogen through the pressure line in Fig. 1.

In this study we have carried out the visualization experiments by high-speed imaging camera system (Shimadzu, Hyper V) or a digital still camera (Canon, EOS Kiss Digital). Nd:YAG laser system (LOTIS TII, LS-2135) is utilized to produce the bubble. The pulsed second harmonic wave (532 nm) of about 90mJ/pulse oscillates at 1Hz. The laser beam is shaped by the beam trimming parts (Iris and Stop) in order to control the laser beam energy and to make spherical bubble, and passes lens array. Experimental arrangement for bubble generation and visualization in liquid nitrogen by a digital still camera with schlieren method is shown in Fig. 2. The laser focuses in cryogenic liquid nitrogen and produces plasma and a single bubble. At the same time an irradiation signal from the laser controller is sent to a signal generator (Sugawara, RE-306), and by the signal a flash lamp (Sugawara, NPL-5) emits a pulse light of 180ns duration for visualization after designated delay time. A pinhole and rejection band filter are settled at a focal position near the camera to prevent the double exposure by plasma and to weaken the laser light noise.

Experimental arrangement for bubble generation and visualization in distilled water by a high-speed imaging camera system with shadowgraph method is shown in Fig. 3. The distilled water is kept in the acrylic tank at atmospheric pressure. A strobe light (Canon, SL540EZ) of long light duration is utilized for high-speed camera. This strobe light emits after 69us from emission of the master flash lamp. The emitted light passes through the water tank as parallel light, and captured by the high-speed camera with a series of images of the bubble behavior. The side view of the laser focusing and solid wall is shown in Fig. 4.
3. Definition of Parameters and Coordinates

In this section the definition of the several parameters in our study are described.

[1] Time \( t \): The pulsed Nd:YAG laser is used for generating a plasma at time \( t = 0 \).

[2] Coordinates (Laser-induced bubble): The origin is a solid wall surface. “Top” is the distance from the solid wall surface to the top of the bubble. “Bottom” is the distance from the solid wall surface to the bottom of the bubble (see Fig. 5).

[3] Non-dimensional distance \( \gamma \) (see Fig. 6).

\[
\gamma = \frac{h}{R_{\text{max}}} \tag{1}
\]

\( h \): Distance from the solid wall surface to the focusing point

\( R_{\text{max}} \): Maximum bubble radius

[4] Degree of subcooling \( \Delta T_{\text{sub}} \):

\[
\Delta T_{\text{sub}} = T_b - T \tag{2}
\]

\( T_b \): Boiling point
\( T \): Temperature of the liquid

[5] Non-dimensional degree of subcooling \( \kappa_{\text{sub}} \):

\[
\kappa_{\text{sub}} = \frac{\Delta T_{\text{sub}}}{\Delta T_b} \tag{3}
\]

\( \Delta T_{\text{sub}} \): Degree of subcooling
\( \Delta T_b \): Difference of temperature between boiling point and melting point

The experimental conditions about temperatures and \( \kappa_{\text{sub}} \) are shown in Table 1.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Distilled water</th>
<th>Liquid nitrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T ) [K]</td>
<td>298</td>
<td>76</td>
</tr>
<tr>
<td>( \Delta T_{\text{sub}} ) [K]</td>
<td>75</td>
<td>12</td>
</tr>
<tr>
<td>( \Delta T_b ) [K]</td>
<td>100</td>
<td>16</td>
</tr>
<tr>
<td>( \kappa_{\text{sub}} )</td>
<td>0.75</td>
<td>0.75</td>
</tr>
</tbody>
</table>

Non-dimensional time \( t' \): Rayleigh defined \( t' \) by the following equation for the data.

\[
t' = \frac{t}{R_{\text{max}}} \sqrt{\frac{P_s}{\rho_\infty}} \tag{4}
\]

\( t \): Actual time from laser irradiation [s]

\( R_{\text{max}} \): Maximum bubble radius [m]

\( P_s \): Surrounding pressure [Pa]

\( \rho_\infty \): Density of the liquid [kg/ m³]

[7] Non-dimensional bubble position:

\[
\text{Top'} = \frac{\text{Top}}{\text{Top}_{\text{max}}} \tag{5}
\]

\[
\text{Bottom'} = \frac{\text{Bottom}}{\text{Top}_{\text{max}}} \tag{6}
\]

\( \text{Top'} \): Non-dimensional position of bubble top

\( \text{Top} \): Distance from solid wall surface to the bubble top

\( \text{Bottom'} \): Non-dimensional position of bubble bottom

\( \text{Bottom} \): Distance from solid wall surface to the bubble bottom

\( \text{Top}_{\text{max}} \): Maximum value of the bubble top

Some effects caused by the size of bubble can be ignored by using \( t' \). Therefore, the positions of bubble surface can be normalized by \( \text{Top}_{\text{max}} \).

![Fig. 5. Coordinate of the bubble](image)

![Fig. 6. Focusing point and \( R_{\text{max}} \)](image)
4. **Experimental Results and Discussion**

The visualized single bubble is observed as shown in Fig. 7.

![Image](image.png)

**Fig. 7.** Laser-induced single bubble near an aluminum wall

The visualized single bubbles near an aluminum wall are shown in Figs. 8(a)-11(a). The top and bottom positions of the deforming bubble and the averaged center position are shown in Figs. 8(b)-11(b). The center of the bubble is defined by the following Eq. (7).

Center = \frac{\text{Top} + \text{Bottom}}{2} \quad (7)

Figure 8 shows the visualized bubble-wall interaction and bubble behavior under the pressurized conditions (+196kPa) in liquid nitrogen in case of \(\gamma = 1.41\). This graph shows the averaged values and 1\(\sigma\) error bars obtained from over 10 images. The bubble expands spherically until about 60\(\mu\)s and starts to shrink. It subsequently deforms, collides with the aluminum wall and collapses. The deviation of the deforming bubble to the aluminum wall surface is also observed from the graph.

Figure 9 shows the visualized bubble-wall interaction and bubble behavior under the pressurized conditions (+196kPa) in liquid nitrogen in case of \(\gamma = 2.01\). This graph shows the averaged values and 1\(\sigma\) error bars from over 10 images. In this case the distance between the laser focusing point and aluminum wall surface is larger than that of the former case. Similarly, the bubble expands spherically until about 50\(\mu\)s, starts to shrink and collides with the aluminum wall. The deviation of the deforming bubble to the aluminum wall surface is also observed from the graph. There is a difference in shape of bubble bottoms in both cases.

![Image](image.png)

**Fig. 8.** Visualized bubble and bubble behavior near aluminum in liquid nitrogen (\(\gamma = 1.41, \kappa_{\text{sub}} = 0.75, R_{\text{max}} = 0.94 \text{ mm}, T = 76 K, \text{Pressurized conditions +196kPa})

![Image](image.png)

**Fig. 9.** Visualized bubble and bubble behavior near aluminum in liquid nitrogen (\(\gamma = 2.01, \kappa_{\text{sub}} = 0.75, R_{\text{max}} = 0.81 \text{ mm}, T = 76 K, \text{Pressurized conditions +196kPa})
Figure 10 shows the visualized bubble-wall interaction and bubble behavior under the atmospheric pressure in distilled water in case of \( \gamma = 1.41 \). This graph shows the behavior of one bubble taken by high-speed camera. The bubble expands spherically until about 140\( \mu \)s and starts to shrink. It subsequently deforms, collides with the aluminum wall and collapses. The deviation of the deforming bubble to the aluminum wall surface is also observed from the graph. Figure 11 shows the visualized bubble-wall interaction and bubble behavior under the atmospheric pressure in distilled water in case of \( \gamma = 2.10 \). This graph shows the behavior of one bubble taken by high-speed camera. Similarly, the bubble expansion and shrinkage can be observed from the graph and visualized bubble behavior. However, the deviation of the deforming bubble to the aluminum wall surface and the collision between the bubble and the wall are not observed in this case. The laser-induced bubble near a solid boundary deviates to the wall surface during its rebounding process. It is known that the phenomenon depends on the non-dimensional distance \( \gamma \) and is caused by asymmetric flow fields in liquid. Therefore, the bubble did not collide with the wall in case of \( \gamma = 2.10 \) in distilled water.

Compared with the oscillation period of the bubble in liquid nitrogen, the period in distilled water is relatively long. As the maximum bubble radii are different on each experiment, non-dimensional time \( t' \) is introduced for these experimental data.

The data of the bubble behavior described with non-dimensional time \( t' \), which is defined by Eq. (4), are shown in Figs. 12 and 13. The horizontal axis is non-dimensional time \( t' \) and the vertical axis is non-dimensional bubble position defined by the Eqs. (5) and (6). Figure 12 shows the comparison of the bubble behavior in liquid nitrogen (\( \gamma = 1.41 \), \( T = 76K \), \( \kappa_{\text{sub}} = 0.75 \), Pressurized conditions + 196kPa) and the bubble behavior in distilled water (\( \gamma = 1.41 \), \( T = 298K \), \( \kappa_{\text{sub}} = 0.75 \), Atmospheric pressure). In these two cases, \( \gamma \) and \( \kappa_{\text{sub}} \) are nearly equal respectively. The bubble behavior in liquid nitrogen is different from that in distilled water, especially after the first rebound of each bubble.

Figure 13 shows the comparison of the bubble behavior in liquid nitrogen (\( \gamma = 2.01 \), \( T = 76K \), \( \kappa_{\text{sub}} = 0.75 \), Pressurized conditions + 196kPa) and the bubble behavior in distilled water (\( \gamma = 2.10 \), \( T = 298K \), \( \kappa_{\text{sub}} = 0.75 \), Atmospheric pressure). In these two cases, \( \gamma \) and \( \kappa_{\text{sub}} \) are nearly equal respectively. Similarly, the bubble behavior in liquid nitrogen is different from that in distilled water especially after the first rebound of each bubble.

(a) Temporal variation of bubble shape, shadowgraph method

(b) Bubble behavior near an aluminum wall

Fig. 10. Visualized bubble and bubble behavior near aluminum in distilled water (\( \gamma = 1.41 \), \( \kappa_{\text{sub}} = 0.75 \), \( R_{\max} = 1.21 \) mm, \( T = 298K \), Atmospheric pressure)

(a) Temporal variation of bubble shape, shadowgraph method

(b) Bubble behavior near an aluminum wall

Fig. 11. Visualized bubble and bubble behavior near aluminum in distilled water (\( \gamma = 2.10 \), \( \kappa_{\text{sub}} = 0.75 \), \( R_{\max} = 1.10 \) mm, \( T = 298K \), Atmospheric pressure)
Some effects on bubble dynamics caused by the size of bubble, surrounding pressure and density of liquid can be ignored by using non-dimensional time \( t' \). The difference between bubble behavior in liquid nitrogen and that in distilled water, however, can be observed. Therefore, the differences of the physical properties (latent heat, surface tension, viscosity and so on) except for density of liquid between liquid nitrogen and distilled water appear after the first rebounding of each bubble and following oscillating phase. Therefore, we can predict that cavitation bubble generated in liquid oxygen or liquid hydrogen used as a fuel in aerospace technology is different from that in water.

5. Conclusion

In this paper, the laser-induced bubble behavior near an aluminum wall in liquid nitrogen and in distilled water is investigated by visualization. The main results are as follows:

1. The deviation of the deforming bubble to the aluminum wall and the collision with the aluminum wall can also be observed in liquid nitrogen.
2. The bubble does not collide with the aluminum wall when \( h \) is large (In this study \( \gamma = 2.10 \) in distilled water).
3. The differences of the physical properties except for density between liquid nitrogen and distilled water appear after the first rebounding of each bubble and following oscillating phase.

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