Experimental and numerical investigations of the bubble collapse at the center between rigid walls

T Ogasawara¹, N Tsubota¹, H Seki¹, Y Shigaki¹ and H Takahira¹
Osaka Prefecture University, 1-1 Gakuen-cho, Naka-ku, Sakai-shi, Osaka 599-8531, Japan
oga@me.osakafu-u.ac.jp

Abstract. The collapsing behavior of a bubble generated at the center of the rigid walls and its effect on the wall are investigated experimentally and numerically. The bubble collapse drastically depends on the ratio of the gap width to the maximum bubble radius \( w^* \). In case of \( 2.66 < w^* < 1.17 \), by the decrease in \( w^* \) to 2.5, the splitting collapse occurs; the bubble splits into two at the center of the gap during collapse and each bubble collapses near the wall with the translation toward nearer wall. Further decrease in \( w^* \) to 1.4 causes neutral collapse where the bubble collapses at the center of the gap without splitting and translation. These collapsing behaviors are successfully simulated by considering the bubble shape at the maximum bubble volume. The peak pressure on the wall decreases by the transition of the collapsing behavior from the splitting collapse to the neutral collapse due to the decrease in \( w^* \), which indicates the wall damage reduction due to the neutral bubble collapse in thinner gap.

1. Introduction
The collapse of cavitation bubbles near a solid wall cause the material damage and have been studied for many years [1]. Recently, in liquid mercury target systems, suppressing cavitation damages on the vessel walls is an important issue [2]. When the proton beams are injected, high pressure wave are generated by a sudden thermal expansion around the focus. One of the approaches to reduce the cavitation erosion is to adopt a double wall structure at a beam window, which is confirmed to have a positive effect [3]. On the other hand, it is indicated that the double wall structure can adversely cause larger pits on the wall of the narrow channel under a certain condition [4]. Bubble collapse within a narrow gap has been investigated by several researchers (ex. [5, 6]). However, the details about its dependence on the ratio of the gap width to the bubble size and its effect on the walls have not been clarified yet. In particular, the collapsing behavior under the condition that the bubble size is larger than the gap width becomes more important for the liquid mercury target system.

It is necessary to clarify the bubble collapse with the variation of the bubble size and its effect on the walls for mitigating the material damage in the narrow gap. To do this, the laser-bubble experiment and the visualization of corresponding shock waves have been conducted for the bubble between two parallel walls. Numerical simulations for the growth and collapse of bubbles have been also conducted and the pressure on the wall is evaluated.

2. Methods and conditions

2.1. Experimental setup
Figure 1 shows a schematic diagram of the experimental setup to generate a cavitation bubble within a narrow gap between two parallel rigid walls and to record a sequence of photographs of the bubble.
collapse and its corresponding shock waves by shadowgraph. The container is filled with distilled water and the U-shaped wall made of stainless steel is installed at the center of the container. The bubble is generated with expanded and refocused beam from a Q-switched Nd:YAG laser. The widely collimated beam and the refocusing by using an achromatic lens contribute to narrow focusing area. The bubble shape and the shock wave are recorded simultaneously by using a high-speed video camera with the frame rate of up to 1.25 Mfps. As a light source for the shadowgraphy, a collimated beam from CW laser is utilized.

\[
\text{w*} = \frac{w}{R_{\text{max}}},
\]

Therefore, a dimensionless parameter \( w^* \) is defined as \( w^* = w/R_{\text{max}} \). \( R_{\text{max}} \) is controlled by changing the diameter of an iris diaphragm and the pressure inside the container. In the present experiment, the bubbles are precisely generated at the center between two parallel walls. The characteristic time of the bubble collapse in experiment is \( \tau = \frac{R_{\text{max}}}{(p_\infty/\rho)^{1/2}} \) where \( p_\infty \) and \( \rho \) are the pressure and density of water inside the container, respectively. \( t = 0 \) represents the time when the bubble takes its maximum volume, and the dimensionless time \( t^* \) is defined as \( t^* = t/\tau \).

### Figure 1. Experimental setup and the configuration of the rigid walls with a gap width of \( w \).

#### 2.2. Numerical methods and conditions

The initial shapes of bubbles in numerical analysis, shown in Figure 3 at \( t^* = 0 \), are set to be similar to those in the experimental results when the bubble volume is maximum. The bubble shape is assumed to be symmetric to the axis perpendicular to the walls. The initial volume \( V_0 \) is the same as the maximum volume in the experiments; \( R_{\text{max}} \) in the simulations, which is identical to the initial equivalent radius \( R_0 \), is taken to be \( R_{\text{max}} = R_0 = (3V_0/4)^{1/3} \). The bubble is initially at rest in a water-filled gap and thin liquid films exist between the bubble surface and the walls. The initial internal gas pressure \( p_{g0} \) and liquid pressure around the bubble \( p_\infty \) are taken to be \( p_{g0} = 1.013 \times 10^5 \text{ Pa} \) and \( p_\infty = 10^8 \text{ Pa} \), respectively. Under the present numerical condition, the characteristic time scale in numerical analysis is defined as \( \tau = R_0/(\Delta p/\rho_0)^{1/2} \), where \( \Delta p = p_\infty - p_{g0} \), and \( \rho_0 \) is the initial density of ambient fluid. The governing equations are the two-dimensional axisymmetric Euler equations. The internal gas is assumed to be an ideal gas. Both gas and water are modeled with the equation of state for stiffened gas. Heat and mass transfer through the bubble interface and fluid viscosity are disregarded in the analysis. The ghost fluid method is used to treat a two-phase flow as two single-phase flows with satisfying the boundary conditions at the interface which is captured with the level set function [7].

### 3. Results and discussions

Figures 2 and 3 show some typical experimental results of the bubble shape for (a) \( w^* = 1.61 \) and (b) \( 1.25 \) and numerical schlieren images with bubble shapes correspond to the experimental conditions of (a) \( w^* = 1.61 \) and (b) \( w^* = 1.25 \), respectively. The typical shadowgraph images with shock wave emission are shown in figure 4.

As can be seen in figure 2 (a), the bubble becomes horizontally long ellipsoidal shape at its maximum volume in the case of \( w^* = 1.61 \). The shrinkage of the bubble surface around the middle of the gap towards the axis of symmetry occurs ahead. On the other hand, the bubble surface near the walls continues to expand outward (\( t^* = 0.791 \)). The shrinking velocity parallel to the wall toward the axis of
symmetry at the middle of the gap is much higher than that near the walls; the bubble gets constricted in the middle (\(t^* = 1.172\)). The constriction develops and the bubble surface at the tip of the constriction collides at the axis of symmetry, and the bubble is split in two for the upper and lower sides (\(t^* = 1.362\)). The split bubbles continue to shrink with the translation toward the nearer walls and collapse in the vicinity of the walls (\(t^* = 1.407\)). This splitting collapse have been reported by the previous study [6] when \(w^*\) takes a value of slightly larger than 2, although the phenomenon in case of smaller \(w^*\) was not investigated. In the case of \(w^* = 1.25\) (figure 2 (b)), the bubble takes the flattened hourglass shape and reaches the maximum expansion (\(t^* = 0\)). Once the bubble surface near the walls changes its motion from the expansion to the shrinkage, the surface velocity toward the axis of symmetry is accelerated and gets higher than that around the middle of the gap where the surface started to shrink earlier (\(t^* = 0.917\)). After that, surface collisions occur near the walls in first (\(t^* = 1.331\), the bubble is left at the middle of the gap as a single bubble and neutrally collapses without translation (\(t^* = 1.452\)).

The above mentioned bubble behaviors in the experiments are successfully simulated in figure 3. When \(w^* = 1.61\) with the initial bubble shape of the disc-like shape, the convex part around the middle of the gap shrinks faster and becomes cylindrical shape with a constriction in the middle at \(t^* = 1.295\). After that the surface collision occurs at the tip of the constriction (\(t^* = 1.340\)) and the bubble is split in two. At this moment, a shock wave is emitted where the surface collision occurs. The split bubbles collapse with the translation toward the nearer walls and the small liquid jets are formed along the axis of symmetry toward the walls (\(t^* = 1.364\)). These liquid jets penetrate the bubble near the walls and the bubbles become a toroidal shape (\(t^* = 1.407\)). The liquid jet impingement causes the shock wave emission near the wall. This liquid-jet related shock wave is actually observed in the shadowgraph image in figure 4 (a). The toroidal bubbles continue to shrink and collapse just before \(t^* = 1.451\), the shock wave is emitted again due to the rebound of the bubble volume. On the other hands, in the case of the flattened hour glass (\(w^* = 1.25\)) in figure 3 (b), the convex parts near the walls of the bubble surface prominently shrinks and the bubble shape becomes cylindrical (\(t^* = 0.954\)) while the constriction initially existing around the middle of the gap does not develop so much. At this moment, the surface instability occurs near the wall, which leads to the further acceleration of the flow concentration toward the axis of symmetry. Subsequently, surface collisions occur and the main body of the bubble is

![Figure 2](image2.png)

**Figure 2.** Typical snapshots of the collapsing bubble at (a) \(w^* = 1.61\) and (b) \(w^* = 1.25\).

![Figure 3](image3.png)

**Figure 3.** Numerical schlieren images with bubble shapes of the numerical simulation at (a) \(w^* = 1.61\) and (b) \(w^* = 1.25\). The bubble shape at \(t^* = 0\) represents the initial shape in computation.
remained at the center of the gap as a single bubble ($t^* = 1.336$). These surface collisions cause the shock wave emissions near the wall. The remained bubble collapses neutrally at the center of the gap without translation; the corresponding shock wave is generated and propagates spherically ($t^* = 1.526$). The rebound shock wave is observed in the experiments as evident in the shadowgraph image in figure 4 (b). It should be noted that the collapse times in figures 3 (a) and (b) are in good agreement with those in the corresponding experiments.

We also investigate the pressure on the solid walls in the simulations. It is found that in the case of the splitting bubble collapse ($w^* = 1.61$), the pressure increases suddenly at $t^* = 1.40$ and takes the maximum value. This pressure rise is found to be caused by the shock wave emission due to the jet impingement on the split bubble near the wall. On the other hand, in the case of the neutral collapse of the initially flattened hourglass shaped bubble ($w^* = 1.25$), two characteristic pressure peaks are observed; former pressure peaks are caused by the surface collisions near the wall and latter one by shock wave emission due to the rebounding motion of the collapsing bubble at the center of the gap. It is confirmed that the maximum value of the pressure peak in the case of the splitting collapse becomes much higher than that in the case of the neutral collapse.

4. Conclusion

The collapsing behavior of a bubble generated at the center of two rigid walls and its effect on the wall was investigated experimentally and numerically. We demonstrated two typical bubble behaviors depending on $w^*$ which was the ratio of the maximum bubble radius and the gap width: one was a spilling bubble collapse and the other was a neutral bubble collapse. In the splitting bubble collapse where the bubble becomes ellipsoidal shape at its maximum volume, the liquid-jets occurred toward both the upper and lower walls from the split bubbles. The shock wave associated with these jets were observed both in the experiments and simulations. In the neutral bubble collapse where the bubble shape became flattened hourglass shape at its maximum volume, the liquid-jets did not occur and the bubble collapsed at the center of the gap without translational motion; the rebound shock wave was emitted there. These collapsing behaviors were successfully simulated by using the ghost fluid method. It was shown that the magnitude of wall pressure by the shock waves was much higher in the splitting bubble collapse than that in the neutral bubble collapse.

Acknowledgment

This work was partly supported by JSPS KAKENHI Grant Number 25289034.

References

[1] Brennen C 1995 Cavitation and bubble dynamics (Oxford University Press)
[2] Futagawa M, Kogawa H, Hasegawa S, Naoe T, Ida M, Haga K, Wakui T, Tanaka N, Matsumoto Y and Ikeda Y 2008 J. Nucl. Sci. Technol. 45(10) 1041
[3] McClintock D A, Riemer B W, Ferguson P D, Carroll A J and Dayton M J 2012 J. Nucl. Mater. 431 147
[4] Riemer B, Haines J, Wendel M, Bauer G, Futakawa M, Hasegawa S and Kogawa H 2008 J. Nucl. Mater. 377 162
[5] Gonzalez-Avila S R, Klaseboer E, Khoo B C and Ohl C-D 2011 J. Fluid Mech. 682 241
[6] Ishida H, Nuntadusit C, Kimoto H, Nakagawa T and Yamamoto T 2001 Proc. CAV 2001: Fourth Intl Symp. on Cavitation (Pasadena, CA) CAV2001:sessionA5.003
[7] Kobayashi K, Kodama T and Takahira H 2011 Physics in Medicine and Biology 56 6421