Experimental study of bubble dynamics in the neighbourhood of a vertical incomplete boundary

Jie Cui, Tao-Ran Zhou, Xiao Huang, Zi-Chao Li

Abstract

The bubbles have been widely used in biomedical field, military and chemical industry. The liquid jet generated by the bubble collapse through an orifice is utilized in needle-free injections and inkjet printing. In this paper we devised synchronized triggering equipment, experimentally investigated the mechanism in the interaction of an electric-spark generated a single bubble and a vertical wall with an air-back opening. Detailed observations were recorded and described for bubble oscillation, migration, jetting, as well as the high-speed water spike penetrating through the opening. The results revealed that there was a critical value of the bubble-wall distance, below which the bubble was directed away from the incomplete boundary, while the bubble may tear from the middle for larger distance. As the distance varied, we studied the volume of the water that rushed through the opening, the velocity at the tip of the water spike, and the center of the bubble as well as the migration of the bubble boundary. This work reveals that the high-speed water spike caused by the bubble may be a potential threat to the structures, specifically for cases with a small opening size and short bubble-boundary distance.

Keywords: Bubble dynamics, Underwater explosion, Incomplete boundary, Inrushing water

1. Introduction

Bubbles are a common hydrodynamic phenomenon and play an important role in natural and social activities. The collapse of bubbles often causes negative effects like high-speed jets and shock waves [1–4]. However, the dynamic characteristics of bubbles have been widely utilized in various engineering fields for applications, such as ultrasonic cleaning [5–7], shock lithotripsy [8,9], and air-gun detection [10]. The interaction between bubbles and incomplete boundaries is a complicated problem worthy of investigation [11–14]. In the field of underwater explosions, an oscillating bubble may induce high speed inrushing water through the opening and impact the inner structures of the ship, causing secondary damage [15]. Researchers have made efforts to reveal the complicated mechanism behind this strong non-linear multiphase interaction problem.

Numerical studies of the dynamics of air bubbles have been carried out for decades [16–23]. In the case of interactions between the bubble and opening, Liu et al. [24] and Khoo et al. [25] used the axisymmetric boundary element method to study bubble dynamics and water spikes at the opening, which is related to the application of needleless injection and ink-jet printing. Dadvand [26], Huang [11], respectively, studied bubble behavior near a broken water-backed plate and an air-backed plate with an opening. In these numerical simulations, the bubble-induced breakout water spike characteristics were vastly different from the normal flooding morphology without the influence of a bubble [27–29]. However, due to the limitations of the numerical method itself, only part of the process can be revealed, and a more complete evolution must be observed experimentally.

The experimental studies help to investigate field of numerical simulation [30–32]. In experimental studies, researchers used laser focusing or electric spark discharge to trigger a bubble in the glass tube to induce high-speed water jets to eject from the orifice as a mechanical study of needleless injection in the medical field. Lew [37], Kari et al. [38] further considered the effect of distance and opening radius on the jet. With the application of inkjet printing, Wang et al. [39] used a bubble generation device to study the pulsation and jet characteristics of bubbles near the discontinuous boundary. We found that, when the bubbles were generated at concentric positions of the opening, the presence of the break caused the bubbles to form a cavity.

However, it is difficult for laser and spark bubbles to create powerful
shock waves, like underwater explosions, which may cause initial damage to a ship structure. Therefore, previous researches have been limited to the coupling behavior of the bubbles to the incomplete boundary in the case of double-sided immersion of the opening by the water. Cui [40] conducted an experimental study of incomplete bilge boundaries with breakouts to analyse the bubble pulsations and loading characteristics. These experiments may be different from an actual underwater explosion; thus, we innovatively improved our experimental setup. By creating an opening at the moment when the bubble is triggered, we investigated the complex pulsating properties of the oscillating bubble near the gas–liquid interface as well as the water spike phenomena and the large deformation of the inrushing water spike surface.

The optimized experimental setup is presented in Section 2. In Section 3, parametric studies are described concerning the distance between the bubble and the opening as well as the opening size, in order to explore the dynamic behavior of expansion, collapse, rebound, re-collapse, and migration of the bubble, along with the characteristics of jetting and water spike, etc. Finally, conclusions, including the bubble tearing phenomenon and the large deformation of the inrushing water spike surface, are given in Section 4.

2. Experimental set-up

2.1. Experimental equipment

The initial condition for this study is that the shock wave from the blast causes the initial damage of the structure. At this moment, the water flooding has not begun, and the bubble is triggered near the vertical incomplete boundary. This incomplete boundary is idealized as a vertical flat plate with an opening. The experimental set-up is shown in Fig. 1. The optical observation device used in the experiments consisted of a VRI-Phantom V611 high-speed camera and Phantom analysis software, with a high-speed camera providing a rate of 7900 fps at a resolution of 1280 × 800. The experiment used an electronic delay circuit to adjust the photographic time, and the interval between two image frames was 126.58 μs, which is much smaller than the oscillation period of a single bubble (about 6 ms). The tank was illuminated by a continuous light source (280 lamp beads).

The shock wave induced by the electric spark is much weaker than that from the detonation; hence, we made an opening on the water tank to simulate the local damage from the underwater explosion shock wave. The difficulty in previous work is that the synchronization of the bubble and the flooding cannot be guaranteed. To solve this problem, we designed a synchronized triggering equipment for use in bubble dynamics experiments as shown in Fig. 2. For the water tank, we devised an active cabin door controlled by a motor, which is shown in Fig. 3. The main function is to turn on the door synchronized with the generation of the bubble. The door is well closed to prevent flooding before the bubble is triggered. A very thin paper is squeezed by the door on the opening to prevent the disturbance of the cabin door to the gas–liquid surface at the opening. The paper is thin enough so that it scarcely absorbs the energy from the bubble. Thus, the interaction between the bubble and the flooding water was well reproduced.

Experiments were carried out in a cubic glass water tank of 0.5 m in length. The water tank was made of highly translucent acrylic material with a thickness of 5 mm, the air–liquid surface was located on the inner side of the water tank, and the movement of the bubbles and water spike was not affected by the wall thickness. The light transmittance of this material was higher than 92% to ensure the clarity and accuracy of image acquisition. The vertical wall was equipped with a square opening with a length of 60 mm. Three types of plate with different sizes of the opening were prepared to match the opening, as shown in Fig. 4. Hence, circular openings with a radius of 7, 14, and 20 mm, respectively, can be switched conveniently during the experiment. The water level in the tank was maintained at 400 mm, the vertical distance between the free surface and the center of the opening (D) was set at 200 mm. The center of the opening was on the same level as the initial center of the bubble. As 200 mm is much larger than R_{max}, the free surface and the bottom of the tank hardly affect the bubble.
2.2. Non-dimensional parameters

The bubble motion is often significantly influenced by boundary conditions and buoyancy effects. The experimental results showed that the bubble was sensitive to two parameters during pulsation: the dimensionless distance $\gamma_w$ from the initial bubble center to the boundary, and the radius of the opening $R_h$. The parameter setting of the bubble is also shown in Fig. 5.

1. The dimensionless distance $\gamma_w$, a parameter describing the influence of the boundary on the bubble, is calculated as follows.

$$\gamma_w = \frac{D_w}{R_{\text{max}}}$$

where $D_w$ denotes the dimensional distance from the bubble center to the wall and the maximum equivalent radius $R_{\text{max}}$ of the bubble is typically chosen as the length factor. In the free field, we consider the maximum area of the bubble in the photography image in its first cycle to be $A$. Then, the maximum equivalent radius of the bubble is calculated as $R_{\text{max}} = (A/\pi)^{1/2}$.

2. In addition, $\delta$ is a dimensionless parameter that represents the influence of buoyancy, and, in this study, the buoyancy parameter $\delta$ can be approximated to zero due to the small bubble size.

| Table 1: Experimental parameter settings. |
|------------------------------------------|
| Size of the opening $R_h$ | $D_w$ (mm) | $\gamma_w$ |
|---------------------------|-----------|------------|
| $R_h = 0.5R_{\text{max}}$ | 2.86      | 0.20       |
|                           | 13.22     | 0.95       |
|                           | 21.27     | 1.52       |
| $R_h = 1.0R_{\text{max}}$ | 2.03      | 0.15       |
|                           | 13.24     | 0.95       |
\[ \delta = \sqrt{\frac{p_g R_{\text{max}}}{p_w}} \]  

(2)

Two control groups were set up in this study (distinguished by different circular opening radius \( R_h \): \( R_h = 0.5 R_{\text{max}} \) and \( 1.0 R_{\text{max}} \)); each group took the dimensionless distance \( \gamma_w \) from the center of the bubble to the center of the circular opening on the vertical wall as the only variable, and the parameter arrangement is shown in Table 1.

3. Experimental results

In this section, we discuss the typical bubble characteristics to reveal the mechanical mechanism of the interaction between the bubble and the complex boundaries. We aim to explore the potential damage to the ship structure during bubble motion, and reveal a novel type of bubble collapse near the broken boundary to provide theoretical support for ship structure protection. In terms of the bubble pulsation characteristics, the main focus is on the bubble collapse and jet dynamics; for the incomplete boundary, the main concern is the behavior of the water flooding through the opening.

3.1. The bubble on the side of the opening (\( R_h = 0.5 R_{\text{max}} \))

This subsection gives a vertical plate with a circular opening (\( R_h = 0.5 R_{\text{max}} \)) to investigate the evolution of the bubble and the gas–liquid boundary at typical times as the dimensionless distance \( \gamma_w \) varies from 0.20 to 1.52.

The distance between the center of the bubble and the vertical wall equals 0.2 times the maximum radius of the bubble (\( \gamma_w = 0.20 \)) as shown in Fig. 6. The bubble in the initial stage of expansion is in contact with the circular opening. A part of the bubble boundary near the rigid wall protrudes out of the opening and disturbs the quasi-static state of the gas–liquid boundary. A portion of the fluid near the circular opening shoots out and directs upwards, due to the violent expanding bubble. After the bubble reaches its maximum radius (frame 1), the boundary of the bubble near the opening begins to depress inward, which symbolizes the beginning of the collapse phase of the first cycle of the bubble.

Then, the fluid on the left side of the bubble flows into the interior of the bubble as the bubble collapses (frame 2) forming a jet with a slender shape. This indicates that a high pressure area appeared at the root of the inrushing water spike. Due to the small \( R_h \) and \( \gamma_w \) (\( R_h = 0.50 R_{\text{max}}, \gamma_w = 0.20 \)), the bubble is in contact with the vertical wall at the beginning of the expansion; hence, the circular opening is blocked by the bubble, and, for some time, the water in the tank is unable to flood out, as shown in frames 2–5.

When the jet penetrates from the right side of the bubble (frame 4), the fluid domain around the bubble evolves into doubly-connected. The jet brings gas into the bubble, forming a turbulent gas–liquid mixture, i.e., the jet trace. As the toroidal bubble continue continues shrinking, the center of the bubble moves away from the rigid wall due to the high

Fig 6. Interaction of a bubble in the neighborhood of the incomplete vertical boundary for \( \gamma_w = 0.20 \) (\( R_h = 7 \text{ mm}, D_w = 2.86 \text{ mm} \)).

Fig 7. Interaction of a bubble in the neighborhood of the incomplete vertical boundary for \( \gamma_w = 0.95 \) (\( R_h = 7 \text{ mm}, D_w = 13.22 \text{ mm} \)).
The flooding through the opening becomes more violent (frames 5–10) with a significant increase of the depth and scope. Gas–liquid boundary instability appears early in the collapse stage of the toroidal bubble: the bubble boundary diffracts from smooth (frames 1–3) to a rough and opaque state. The toroidal bubble shrinks to its minimum volume at frame 7, and re-expands (frame 8), making the opening fully exposed; hence, the flooding spike reaches a depth of $1.8R_{\text{max}}$ in the $\times$ direction due to the high water pressure near the opening.

Fig. 7 and Fig. 9 present the cases with $\gamma_w = 0.95$ and $\gamma_w = 1.52$, respectively, where frames 1–4 are the collapse phase of the first cycle of the bubble, and frames 5–8 show the second cycle. When the dimensionless distance $\gamma_w \geq 1.0$, the vertical wall gives less influence on the

![Image](image_url)

**Fig. 8.** Bubble dynamics during splitting.

**Fig. 9.** Interaction of a bubble in the neighborhood of the incomplete vertical boundary for $\gamma_w = 0.95$ ($R_h = 7$ mm, $D_w = 21.27$ mm).
bubble during its first cycle.

During the collapse stage of the bubble, as the case in Fig. 7, the bubble is split from the center into two unequal sub-bubbles, both of which produce high-speed jets toward and away from the opening. This is because the attraction from the solid wall and repulsion from the gas–liquid interface both act on the bubble, and thus the tearing phenomenon is presented. After the bubble separation, a high pressure area forms between them, resulting in opposite bubble jets. When the attraction and repulsion forces are equal, a symmetric tear from the center of the bubble will appear. This critical case requires $\gamma_w$ to be slightly less than 1 as shown in Fig. 7.

Fig. 8 (a) gives the time history of the translation of the bubble center from the maximum equivalent radius to the end of the second cycle, where $t' = R_{\text{max}} \left( \frac{\Delta P}{\rho \Delta P} \right)^{\frac{1}{2}}$ is the dimensionless time and $x_{\text{cen}}*$ is the dimensionless displacement of the bubble center. The center of the bubble moves slightly away from the opening during the first cycle of collapse, but points on the top and bottom as well as the left and right side of the bubble present symmetrical behavior, as shown in Fig. 8 (b), which means that the bubble translates spherically in the first collapse stage. At the end of the first cycle, the bubble tears into two sub-bubbles, and the one that is close to the opening translates rapidly towards the opening, as shown in Fig. 8 (a), and collapses onto the incomplete boundary. This finally intensifies the flooding.

When the size of the bubble and the opening is fixed, the bubble splitting can be classified into three patterns according to some certain range of $\gamma_w$, as shown in Table 2.

### Table 2

| Dimensionless distance parameter $\gamma_w$ | Sub-bubble shapes       |
|-------------------------------------------|-------------------------|
| $\gamma_w = 0.89-1.0$                     | Big left and small right|
| $\gamma_w = 1.0$                         | Equal volume            |
| $\gamma_w = 1.0-1.12$                    | Small left and big right|

#### 3.2. The bubble on the side of the opening ($R_h = 1.0R_{\text{max}}$)

In this sub-section, the effect of a larger opening is presented, i.e., $R_h = 1.0R_{\text{max}}$. Fig. 10 shows the evolution of the bubble and the flooding water ($\gamma_w = 0.15$ or 0.95).

In Fig. 10(a), for the case of $\gamma_w = 0.15$, which may correspond to

Fig 10. Interaction of a bubble in the neighborhood of the incomplete vertical boundary for $R_h = 14$ mm.
Fig. 11. Time histories of the translation of the bubble center with different $\gamma_w$.

3.3. Inrushing water under the influence of $\gamma_w$

This section details the properties of rushing water for different distances $\gamma_w$. Fig. 14 gives three sets of parameters $\gamma_w = 0.20, 0.95,$ and $1.52$. With the same opening size and bubble energy, the volume of water rushing out of the opening is governed by two parameters: gravity and the distance from the center of the bubble to the opening.

Clearly, for the same opening size, the volume of inrushing water is constant under the influence of gravity. The expanding bubble will occupy the fluid space, fluid may be pushed out of the opening by the bubble, and the bubble draws the fluid back from the opening as it contracts, which means that the bubble in the expanding phase will accelerate the velocity of the inrushing water, and the contraction phase is the opposite.

When $\gamma_w$ is small enough ($\gamma_w = 0.20$), the fluid near the opening is suddenly accelerated by the ignition of the bubble, and an anti-gravity “splashing water” appears, as shown in Fig. 14(a) frame 1. The incomplete boundaries impede the flow of water and reflect a portion of the pressure radiated during the movement of bubbles. The inrushing water undergoes violent splashing before being continuously elongated, as shown in Fig. 14(a). As the $\gamma_w$ increases, this splashing phenomenon gradually disappears, the splashing water exists only in the form of the liquid drop with $\gamma_w = 1.52$, as shown in Fig. 14(c) frame 4.

As the distance from the bubble to the opening increases, the depth of the inrushing water into the chamber decreases in the same dimensionless time, which means that the smaller the distance $\gamma_w$ is, the higher velocity the inrushing water has, and this is shown by the larger slope of
Fig 12. Time histories of the dimensionless displacements of the top $z_{\text{top}}^*$, bottom $z_{\text{bottom}}^*$ and the left $x_{\text{left}}^*$, the right $x_{\text{right}}^*$ of a bubble surface for different $\gamma_w$ ($R_h = 1.0R_{\text{max}}$).
suffer attacks by underwater weapons. For ships that are already structurally damaged, the presence of an opening affects the dynamic behavior of the inrushing water and bubble.

3.4. Interaction of a bubble with inrushing water already existed

In actual naval warfare, the hull plate may sometimes repeatedly suffer attacks by underwater weapons. For ships that are already structurally damaged, the presence of an opening affects the dynamic behavior of the inrushing water and bubble.

When the distance between the initial center of the bubble and the wall boundary exceeds $1.5R_{\text{max}}$, as shown in Fig. 13 ($\gamma_w = 2.06$), the boundary effect is greatly weakened, the incomplete boundary interferes less with the dynamic behavior of the bubble, the surface stability of the bubble is enhanced significantly, and the bubble expands and collapses like a sphere (frames 1–5).

In this case, the water spike rushing out of the opening remains highly stable until the end of the second cycle of the bubble, and it surges into the cabin (Segment A) only under the effect of gravity. When the $t^* = 8.95$, the wave pressure radiated by the expansion of the bubble acts on the root of the water column, as shown in the first frame of Fig. 17.

Under the influence of the bubble motion, the water column appears in an unstable state, which is defined as segment B. The head and root of the B part present a “necking” effect. The instability of segment B is due to the bubble expansion. The fluid around the bubble is accelerated towards the opening. At the same time, the bubble translates away from the opening continuously. The effect of the bubble on the flooding spike is also gradually decreased with time. We noted point A at the head of the segment B and found that the velocity of point A was gradually weakened. The dimensional speed or the depth of inrushing water (point a) is shown in Fig. 18. We found that the water reached through the opening at different speeds and surged into the chamber.

4. Concluding remarks

The complexity of the interaction between an electric-spark-generated bubble and the incomplete boundary was much greater than for the intact boundary. We designed synchronized triggering equipment between the bubble and a circular opening to investigate the effect of an incomplete boundary with that opening. We found that the dynamics of the bubble and the inrushing water were sensitive to $D_w$ (the center of the initial bubble to the center of the opening) and $R_h$ (the circular opening radius). Our concluding remarks are as follows.

1. When the distance between the initial bubble center and the opening is smaller than the maximum bubble radius (e.g. $D_w = 0.5R_{\text{max}}, R_h = 1.0R_{\text{max}}$), the air–water interface at the opening is disturbed by high pressure between the bubble and the opening at the bubble collapse phase. The resultant accelerated high-speed flooding water spike may gain the velocity of 21.4 m/s and reach the depth of 5.5 times of the maximum bubble radius, for small opening sizes. This type of water spike with large momentum and depth will be a potential threat for the inner structures inside the cabin.

2. For the same bubble-opening distance, the flooding at a large opening becomes wide and tends to splash outside, while the flooding at a small opening converges and shoots fast. As for the effects of the bubble-opening distance, since the bubble is under the effect of repellence of the air–water interface and attraction from the solid plate, it will split into two daughter bubbles during the collapse. The bubble-opening distance decides the final result of the two types of forces and the final characteristics of the bubble splitting.

3. If the boundary has been broken, inrushing water may already exist, and it is only affected by the gravity. When the pressure from bubble compression acts on the inrushing water, the “necking” phenomenon will appear with the instability of the surface. The inrushing water velocity first increases and then decreases, until the bubble translates away from the boundary.

In summary, we conducted an experimental study by adjusting some important parameters($D_w, R_h$). This work may provide a valuable reference for a deeper understanding of this new damage mode.

CRediT authorship contribution statement

Jie Cui: Methodology. Tao-Ran Zhou: Writing - original draft, Visualization. Xiao Huang: Conceptualization, Supervision, Writing - review & editing. Zi-Chao Li: Conducting experiment.
Fig 14. Dynamic characteristics of the inrushing water column with different $\gamma_w$.

(a) $\gamma_w=0.20$, $R_0=7$ mm, $D_0=2.86$ mm

(b) $\gamma_w=0.95$, $R_0=7$ mm, $D_0=13.22$ mm

(c) $\gamma_w=1.52$, $R_0=7$ mm, $D_0=21.27$ mm.
Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Fig 15. Time history of the depth in x direction of the splashing water spike.

Fig 16. Dynamics of a bubble in the neighborhood of the existing inrushing flooding water ($R_h = 14$ mm, $D_w = 28.55$ mm).

Fig 17. Evolution of the inrushing water after two cycles of the bubble in the case shown in Fig. 16.

Fig 18. Time histories of the dimensional speed of the point a.
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