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The Pulsation Characteristics of Multiple Bubbles Under Ship Structural Boundary Conditions

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Abstract. To study the pulsation characteristics of multiple bubbles located near the wall structure, underwater low-pressure discharge bubble generation technology was used to study the coupling characteristics of multiple bubbles under horizontal and V-shaped wall conditions. Due to the Bjerknes force on the wall of the bubble, the motion state of the bubble will be affected. Exploring the pulsation characteristics of multiple bubbles under different working conditions and arrangements. The results indicate that the coupling characteristics between bubbles become completely different under boundary conditions. Analyzing the experimental results, it was found that the pulsation period of the bubbles was shortened, resulting in jet, shock wave, and jet loads on the structure, leading to wall damage and necking after fusion. Through different boundary conditions and innovative arrangements of multiple bubbles, the influence of underwater structures on the pulsation characteristics of multiple bubbles in underwater explosions was explored, providing theoretical support for the strength design of ship structures.

Keywords: Underwater explosion; Multiple bubbles; V-shaped structure; Bubble pulsation.

1. Introduction

When ships are engaged in combat or advancing in the sea, they may encounter attacks from various underwater weapons, and the periodic bubbles produced by explosions [1-2]may also cause serious structural damage to the ship. The motion characteristics of multiple bubbles formed by explosions are closely related to non-dimensional parameters such as bubble spacing[3], distance between bubbles and ship structures, and structural boundaries. The motion behavior of bubbles involved will also be more complex [4].

To study the motion characteristics of bubbles under different boundary conditions, Domestic and foreign scholars widely use small equivalent TNT explosives, electric sparks, and laser bubble generation methods to conduct mechanistic research on bubble pulsation and study the interaction characteristics between bubbles and different boundaries. Qin Jian et al.[5-6] designed underwater explosion experiments of small equivalent TNT explosives at the bottom of fixed supported square plates at different detonation distances. They analyzed and studied bubble pulsation and jet load through underwater pressure sensors and high-speed cameras. Zhang Aman [7-10]conducted experimental research on the dynamic characteristics of bubbles under various boundary conditions using underwater electric spark generation method. In summary, previous research has mostly been limited to the study of the motion characteristics of bubbles near free surfaces and the study of the motion characteristics of individual bubbles under different boundary conditions [11]. Therefore, conducting experimental research on the coupling effect of multiple bubbles under boundary conditions is very important.

This article uses underwater electric discharge to generate bubbles under horizontal and V-shaped structural wall conditions[12]. By controlling non dimensional parameters, the coupling characteristics of bubbles near the structure are analyzed, and the coupling characteristics of junction bubbles are studied. The experimental results are analyzed by bubble radius[13].

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2. Experimental equipment

The experimental equipment setup is shown in Figure 1, including a high-speed camera, water tank, bubble generation device, voltage storage device, oscilloscope, and lighting device. The water tank uses high transmittance hardened glass, with a thickness of 12mm and a length, width, and height of 600mm. In addition, there is a high-precision positioning device directly above the water tank, which is used to adjust the initial center position of the bubbles. The lighting source used is a continuous LED light source with a voltage of 400V. The pulsation process of bubbles is recorded by a high-speed camera, and the camera resolution is 512 × 512 pixels, shooting rate of 37000 frames per second, and image exposure time set to10μs.

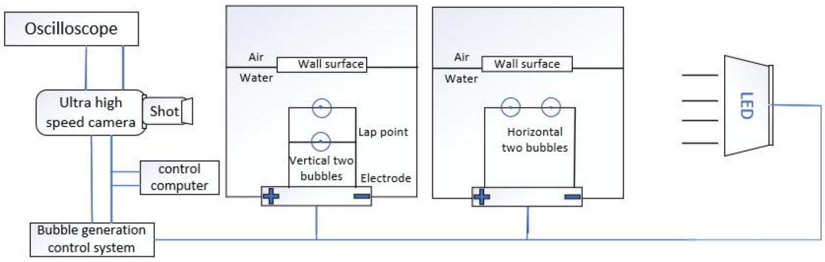

Fig. 1 Experimental Equipment Layout

3. Analysis of coupling characteristics of bubbles near wall structures

3.1 The influence of feature parameters on bubble fusion characteristics.

This section mainly studies the fusion phenomenon of two bubbles near the wall and explores the influence of different characteristic parameters on the motion state of bubbles. Therefore, the following text will discuss the situation where the bubble spacing is about $\gamma_{bb} = 1.00$, $\gamma_{bw} = 1.20$. Select the time points at which the bubble motion state changes most significantly in each stage for analysis, and discuss the impact of different arrangements (vertical and horizontal). Introducing the dimensionless bubble to wall distance parameter here:

$$\gamma_{bw} = \frac{d_{bw}}{R_{\max}} \tag{1}$$

Among them, d_{bv} is the distance from the initial center of the bubble to the wall, and $R_{\max}$ is the maximum equivalent radius of the bubble.

3.1.1 Vertical arrangement

Firstly, the fusion phenomenon of two bubbles near the wall in the vertical arrangement of bubbles is analyzed, as shown in Figure 2. Several bubble states of the fused bubbles are presented, where the black straight line above the bubbles represents the wall, with bubble 1 above and bubble 2 below. Due to the close spacing between the bubbles, the two bubbles exhibit non spherical pulsation in the first cycle as a whole. For example, during the expansion stage, the upper part of bubble 2 is suppressed by bubble 1 and becomes flattened, and the same applies to the bottom of bubble 1. Other positions are basically hemispherical. The two bubbles met the fusion condition at t=1.59ms and began to fuse. Subsequently, the bubbles began to expand and reached their maximum volume after fusion at t=2.48ms. If there were fusion bubbles near the free liquid surface, a downward jet could be seen from the upper part of the fusion bubble; The curvature of the top and bottom of the fused bubble may be relatively large, but due to the action of the wall on the fused bubble, the jet of the bubble will only face the wall. Figures 2 (e) - (g) show the motion of the fused bubble jet from start to finish, with a jet tendency appearing at the bottom of the bubble. In addition, from Figure (f), it is evident that the jet is facing upwards, with its shape circled in red. The phenomenon of "necking" of the bubble can also be observed, and the upper part of the fused

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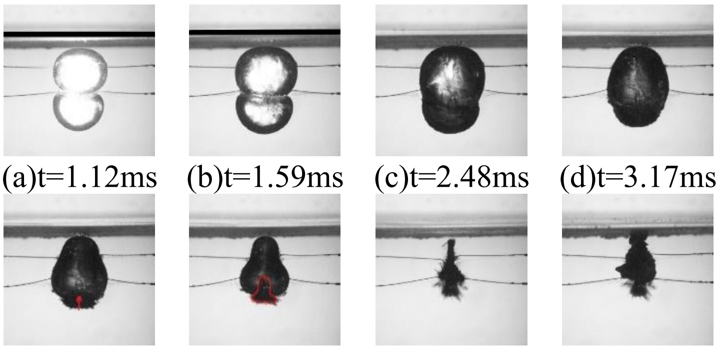
bubble becomes "gourd shaped". At t=4.56ms, the jet is about to collide with the top of the fused bubble and penetrate it. The jet generated by the fusion bubble will penetrate the bubble and impact the wall, which will be subjected to the impact force generated by the fusion jet.



(a)t=1.12ms (b)t=1.59ms (c)t=2.48ms (d)t=3.17ms

(e)t=3.86ms (f)t=4.23ms (g)t=4.56ms (h)t=5.13ms

Fig. 2 Vertical motion state of two bubbles near the wall surface($\gamma_{bb}=0.97$, $\gamma_{bw}=1.18$)

Observing Figure 3, the radius changes of the two bubbles during the expansion process are basically similar. Due to the overall elliptical shape of bubble 1 and the hemispherical shape of bubble 2, the measured lateral radius of bubble 1 is larger than that of bubble 2; The radius of bubble 2 remains relatively constant for a period of time, which may be due to the mutual cancellation of the fusion effect of bubble 1 on bubble 2 and the effect of the wall on bubble 2, causing the two bubbles to begin to merge; After the fusion of two bubbles, the upper part of the bubble experienced "necking" phenomenon. Therefore, the measurement position for this time is the spherical part of the lower part of the bubble. The measured radius change of the fused bubble is represented by a black curve. From the graph, it can be seen that the radius change of the fused bubble is faster in the later stage, indicating that the collapse speed of the bubble is faster.

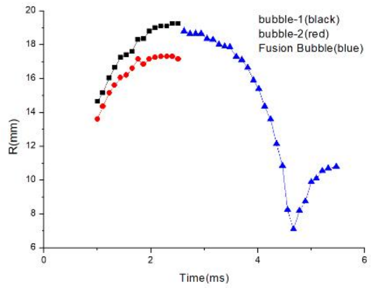


Fig. 3 Changes in radius of two vertical bubbles and fused bubbles below the wall surface

3.1.2 Horizontal layout

For the typical bubble motion moment of the fusion phenomenon of two bubbles near the wall under horizontal layout conditions, as shown in Figure 4. Due to the close spacing between the bubbles, the two bubbles exhibit non spherical pulsation in the first cycle. For example, during the expansion stage, the two bubbles suppress each other and the part facing each other becomes flattened from the middle, while the other parts become hemispherical. The two bubbles fused at t=1.42ms, then continued to expand and reached their maximum volume under fusion at t=2.51ms. However, due to the action of the wall surface, the two bubbles showed obvious asymmetry, and there was a tendency for the lower left and right positions of the two bubbles to produce jets towards the wall surface, as shown in Figure 4(d). At this point, the bubble enters the collapse stage, and a diagonal jet is generated from the lower left and right parts of the fused bubble (red arrow in Figure (e)). After a period of time, the two jets collide with each other at t=3.86ms (Figure (f)), and

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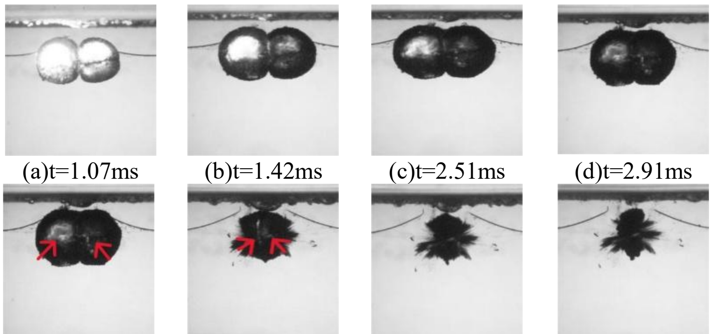
the fused bubble will transform into a circular bubble. Afterwards, the annular bubble continued to collapse, and after the jets collided with each other, the fluid moved from the inside to the surroundings, causing the surface area inside the annular bubble to begin to shrink and eventually become hollow inside. According to Figure 5, it can be seen that the radii of the two bubbles are basically the same, indicating that the two bubbles expand and collapse symmetrically along the vertical axis below the wall. In addition, the radius of the measured fusion bubble decreases faster than that of a single bubble during the collapse stage. This may be due to the gradual thinning of the water film after the two bubbles come into contact, until the fusion makes the fusion bubble a whole. The fusion bubble collapses faster in the horizontal direction, equivalent to the sum of the half diameter changes of the two bubbles.



(a)t=1.07ms (b)t=1.42ms (c)t=2.51ms (d)t=2.91ms

(e)t=2.93ms (f)t=3.86ms (g)t=4.11ms (h)t=4.23ms

Fig. 4 Motion state of two horizontal bubbles near the wall ($\gamma_{bb} = 0.98$, $\gamma_{bw} = 1.12$)

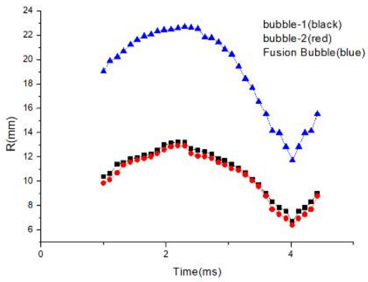


Fig. 5 Changes in radius of two horizontal bubbles and fused bubbles below the wall surface

For the two bubbles arranged vertically and horizontally below the wall, after the fusion of the two bubbles arranged vertically, they are subjected to the Bjerknes force on the wall. The bottom velocity of the fused bubbles is relatively high, and a jet will be generated towards the wall. The fused jet will directly cause an impact force caused by direct contact with the wall; When two bubbles are arranged horizontally, after the two jets collide with each other, the liquid diffuses around and causes the annular bubbles to collapse irregularly. The annular bubbles will tear apart, possibly because the lower part of the fused bubbles, which is far from the wall, is less inhibited, resulting in a faster collapse speed at that location.

4. Analysis of coupling characteristics of bubbles near V-shaped structures

Two bubbles are arranged horizontally, with the initial points of the two bubbles located directly below the V-shaped tip, and the two bubbles are located on both sides of V; In theory, bubbles are subjected to the combined action of another bubble and an oblique wall. In order to make the content universally meaningful, we introduce the dimensionless bubble and V-shaped structure distance parameter here:

$$\gamma_{bv} = \frac{d_{bv}}{R_{\max}} \tag{2}$$

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Among them, d_{bv} is the distance from the initial center of the two bubbles to the V-shaped tip, and $R_{\max}$ is the maximum equivalent radius of the bubbles.

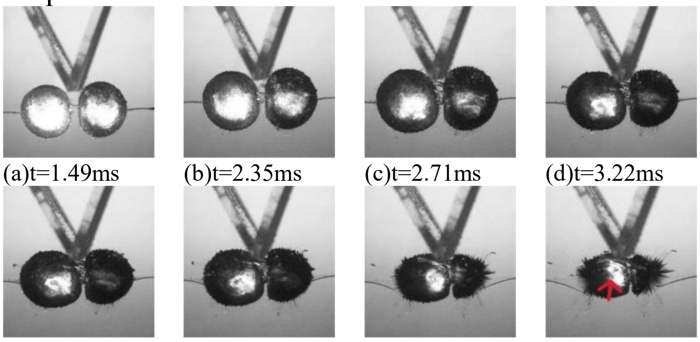
(a)t=1.49ms (b)t=2.35ms (c)t=2.71ms (d)t=3.22ms
(e)t=3.53ms (f)t=3.81ms (g)t=4.29ms (h)t=4.51ms

Fig. 6 Horizontal motion state of two bubbles near the V-shaped structure ($\gamma_{bb}=1.60$, $\gamma_{bv}=0.61$)

Under the above conditions, select the time point at which the bubble motion state changes most significantly in each stage for analysis. During the expansion stage of bubbles, due to the inhibitory effect between two bubbles, the end of the bubbles facing each other becomes flat. In addition, the structure obstructs the bubbles, and the upper part of the two bubbles near the structure also moves non spherical; By observing the process of bubble expansion, it was found that there was little change in the position near the structure, and the bubble expansion speed was slower, as shown in Figure 6 (a-c); Furthermore, as shown in Figure 7, the radius variation of bubbles indicates that under the combined action of bubble 1 and structure, bubble 2 maintains a relatively constant radius for a period of time. Subsequently, the bubble enters the collapse stage, during which there is liquid contact between the two bubbles. The collapse speed of the bubbles near the structure and facing each other is relatively small, while other positions are less affected by the structure and collapse faster, two bubbles will generate a jet towards the structure and towards each other. Therefore, the direction of the jet is inclined upwards. After a period of time, the jet of bubble 2 penetrates through two bubbles and appears inside bubble 1, as indicated by the arrow in Figure (g). Then, the jets of bubble 1 and bubble 2 collide with each other (Figure h), causing the liquid to splash everywhere and the bubble to break at that location, reduce the impact of the jet on the structure.

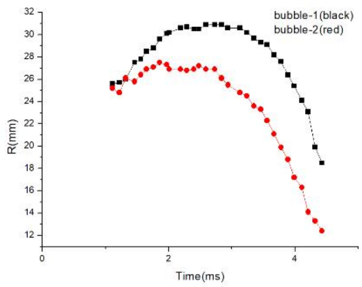

Fig. 7 Changes in the radius of two horizontal bubbles near the V-shaped structure

5. Summary

This article selects horizontal walls and V-shaped structures as ship structural boundaries to observe and explore the motion characteristics of bubbles under multi bubble fusion. Explored the influence of horizontal and vertical bubble arrangement on bubble fusion characteristics and their effects on wall surfaces; The pulsation characteristics of two horizontally arranged bubbles below the V-shaped structure were observed. Therefore, the following conclusion was drawn:

(1) For two vertically arranged bubbles on the wall boundary, the upper bubbles are suppressed by the wall, causing their pulsation period to be greater than that of the lower bubbles. Due to the increase in pressure, the upper bubbles exhibit a special "necking" phenomenon, causing the

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bubbles to tear from this position. The lower bubbles produce an upward jet, which will impact the wall and cause damage.

(2) By observing the fusion motion of two horizontally arranged bubbles near the wall and V-shaped structure boundary, it can be seen that due to the boundary conditions and the interaction between bubbles, bubbles will produce a jet towards each other's bubbles and structure under both operating conditions. When the distance between bubbles and structure is small, it is an oblique jet; After jet collision, it will cause the rupture of bubbles, reducing the impact of jet on the structure.

On this basis, the boundary conditions of the experiment can be further optimized to further explore the influence of ship boundary conditions on multi bubble pulsation.

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