

# Experimental Study on Multi Bubble Ice Breaking Under Layer Ice Boundary Conditions

Wenqi Guo<sup>1</sup>, Fulin Yu<sup>1,2,a</sup>, Chao Su<sup>1</sup>, Zhanquan Li<sup>1</sup>, Fengguang Jia<sup>1,2</sup>,  
Yueying Gong<sup>1</sup>

<sup>1</sup> College of Ship and Port Engineering, Shandong Jiaotong University, Weihai;

<sup>2</sup> Key Laboratory of Fluid Solid Coupling Dynamics in Weihai City, Weihai.

<sup>a</sup> yufulin@sdjtu.edu.cn

**Abstract.** Under certain conditions of bubble spacing and bubble to ice distance, the motion state and ice breaking effect of horizontal and vertical bubbles under ice plate boundary conditions were studied. Bubbles are generated through underwater discharge, and the generating device is placed horizontally or vertically below the ice plate, and the experimental phenomenon is observed through an ultra-high-speed camera. Firstly, the motion characteristics and ice breaking ability of two horizontal bubbles under an unperforated ice block were demonstrated. Then, the motion characteristics of two horizontal bubbles and two vertical bubbles under a porous ice block, the breaking effect of the ice block, and the water mound phenomenon on the free surface were observed. The experiment observed unique bubble behavior, including bubble fusion, bubble collapse, and oblique jet, as well as the influence of bubble-bubble and bubble-ice interactions on the morphology evolution and ice breaking effect of bubbles. The results indicate that the ice breaking effect of the interaction between bubbles and perforated ice plates is weaker than that of non-perforated ice plates, which may be more helpful for subsequent bubble ice breaking research.

**Keywords:** bubbles; ice board; ice breaking effect; jet

## 1. Introduction

As an emerging field, the use of bubble assisted icebreaking systems can effectively increase the icebreaking ability of icebreakers. Exploring the influence of bubble motion states and characteristic parameters on ice blocks is of great significance. Cui Pu[1-3] recorded the experimental process of the interaction between electric spark bubbles generated by underwater discharge and floating ice plates using a high-speed camera. Using shadow image method, he observed the propagation process of waves in the ice plate and explored the characteristics of shock waves that occur when the ice plate ruptures, bubble jets, and bubbles collapse. He found that the mode of crack formation on the ice plate is related to the thickness of the ice plate and the distance from the position where the bubbles are generated to the ice plate, And the mechanism of ice plate cracking under bubble loading was analyzed. The unique characteristics exhibited by bubbles were observed, including bubble fusion, bubble splitting, non-spherical collapse, and jet directed towards each other. The analysis shows that the destructive effect of bubbles is influenced by the interactions between bubbles, bubbles, and bubble boundary.

The main focus of this experiment is to study the ice breaking effect of multiple bubbles on layer ice. Two bubbles arranged vertically and horizontally will have different ice breaking effects under different bubble spacing, distance between bubbles and the bottom of the ice block, and free liquid surface joint boundary conditions. Therefore, the main content of this article is to explore the damage effect of shock waves and pulsating loads generated by multiple bubbles on ice under different arrangement conditions.

## 2. Experimental method

### 2.1 experimental apparatus

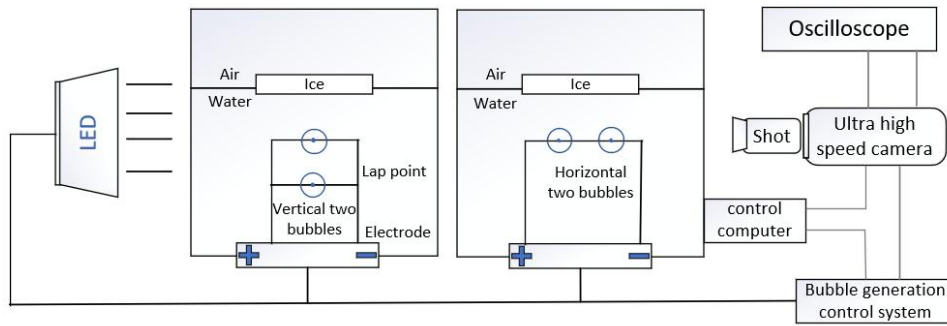


Fig. 1 Schematic diagram of experimental device

The experimental setup is shown in Figure 1. This experiment was conducted in a 600mm cubic glass water tank, with a floating ice plate on the water surface, and pulsating bubbles will be generated below the ice plate. Due to the rapid formation and collapse of bubbles, ultra-high-speed camera was used to record the process.

## 2.2 Principle of bubble generation

Bubbles are generated by an electric spark bubble generation device. The electrode made of copper wire (0.6mm) is connected to the positive and negative electrodes of the capacitor. In order to generate bubbles, the positive and negative electrodes are connected to form a short circuit. When the electrode is triggered, the capacitor discharges, and the electrode quickly heats up and evaporates nearby water. Therefore, bubbles are generated, accompanied by luminescence and electrode combustion and melting[4-5].

## 3. Experimental study on ice breaking under multi-bubble fusion

For two bubbles, bubbles can also serve as a special boundary, and the interaction between bubbles and the coupling between bubbles and ice will affect their ice breaking ability. Therefore, this section investigates the bubble fusion and ice breaking effects under horizontal layout conditions. Under this condition  $\gamma_{bb} = 0.68$  (distance between two bubbles)  $\gamma_{bi} = 1.02$ . Define non dimensional bubble ice block bottom distance and bubble spacing:

$$\gamma_{bi} = \frac{d_{bi}}{R_{\max}} \quad (1)$$

$$\gamma_{bb} = \frac{l}{2R_{\max}} \quad (2)$$

Among them,  $d_{bi}$  is the distance from the center of the bubble to the bottom of the ice block,  $l$  is the distance between the centers of two bubbles, and  $R_{\max}$  is the maximum equivalent radius of the bubble.

The bubble motion diagram is shown in Figure 2, where two bubbles are generated below the ice block. In the expansion stage of bubbles, two bubbles will come into contact with each other and expand towards each other due to their close proximity (b). The bubbles continue to expand until they completely merge into one bubble (c). Subsequently, the bubble entered the collapse stage, and the far ends on both sides of the bubble began to contract (d). Due to the Bjerknes force exerted by the ice on the bubble, two oblique jets towards the ice block were generated at the location of the far end contraction, as shown by the red arrow in Figure 2 (d) (which is similar to the movement of the bubble near the wall). Subsequently, the two jets collide with each other (f), merging the bubbles into circular bubbles, and releasing shock waves from various positions of the circular bubbles[6-10]. The shock waves propagate to the lower surface of the ice block and produce reflections. As mentioned earlier, shock waves also propagate into the ice and generate reflections on the upper surface of the ice, resulting in tension in the ice and causing the ice to rupture. Then

the crack gradually extends downwards with the propagation of the wave, as shown in Figure (h-i). Subsequently, the bubbles generate a jet that collides with the bottom of the ice, accelerating its rupture. It can be observed that the cracks caused by the jet are generated from the bottom, as shown by the red arrow in Figure 2 (j), and gradually extend upwards to cause the ice to break, ultimately resulting in a through crack.

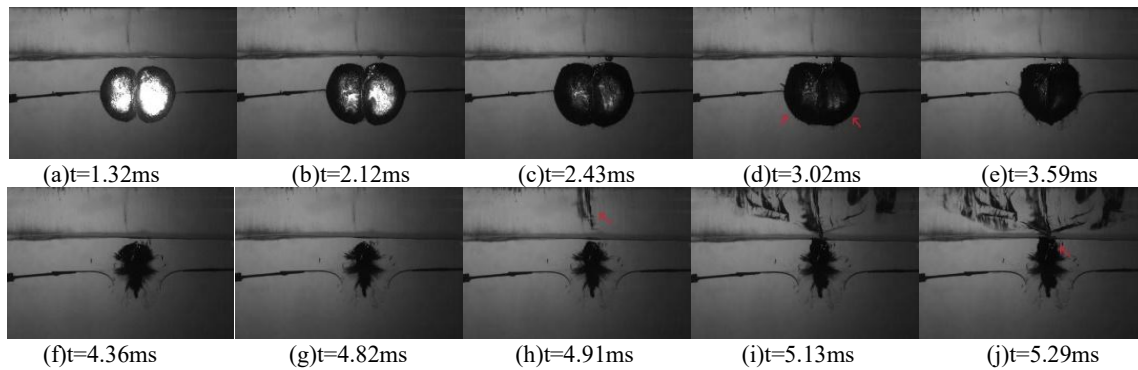


Fig. 2 High speed image of two horizontally arranged bubbles collapsing under an ice block

$$(\gamma_{bb} = 0.68, \gamma_{bi} = 1.02)$$

This experiment measured the radius after bubble fusion. During the expansion stage and the early stage of collapse of the bubble, the radius of the fused bubble changes relatively steadily. After a period of time, the decrease rate of the radius of the fused bubble accelerates. This may be due to the effect of ice on the bubble and the interaction between the two bubbles, which results in a greater Bjerknes force on both sides, leading to an accelerated collapse rate of the bubble.

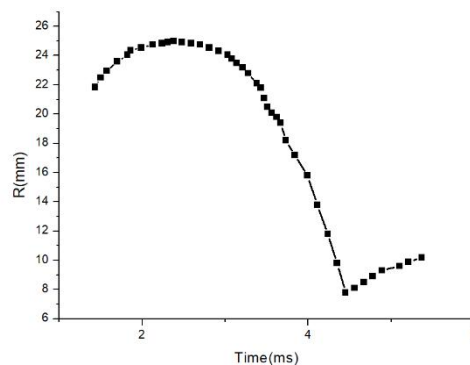


Fig.3 Horizontal fusion bubble radius variation chart

## 4. Analysis of Coupling Characteristics of Bubbles Near Perforated Ice

For the motion characteristics and ice breaking effect of the fusion of two bubbles below a perforated ice block, there will not only be the influence of the interaction between the two bubbles, but also the influence of the ice block and the free liquid surface. Therefore, this section will explore the ice breaking effect of the fusion of two bubbles under horizontal and vertical layout conditions, the motion characteristics of bubbles, and the water mound phenomenon generated by the free liquid surface. The thickness of the ice block is 20mm, and the diameter of the hole is 65mm.

### 4.1 Horizontal arrangement condition

Firstly, the fusion phenomenon, ice breaking effect, and water mound phenomenon of two horizontally arranged bubbles under a perforated ice block are studied under the working condition of (distance from the center of the bubbles to the free liquid surface). Two horizontal bubbles are located directly below the hole. Due to the close spacing between the bubbles, during the expansion stage, the near ends of the two bubbles come into contact with each other and become flattened, while the far end is hemispherical (a). The upper part of the two bubbles, due to their distance from

the free liquid surface, has a relatively small interaction, so the bubbles are basically spherical. Subsequently, the fused bubbles continued to expand to their maximum volume (b). Due to the action of ice and free liquid surface, bubbles tend to have an oblique jet, as shown by the red arrow in Figure 4 (d). Afterwards, the bubble entered the collapse stage, and a downward oblique jet was generated on both sides of the upper half of the fused bubble, and the two jets collided with each other (Figure e), generating shock waves, and the fused bubble became a ring-shaped bubble. After the jets collide with each other, the fluid moves from the inside to the surroundings, causing the surface area of the annular bubble to begin to shrink and eventually become hollow inside. Subsequently, the ice began to break, as shown by the red arrow in Figure 4 (f). After that, the ice cubes broke off from the red marked position (Figure g). Due to the distance between the bubbles and the free liquid surface, as well as the thickness of the ice blocking the view, the water mound was only observed after a period of time. It may be due to the collision between the water mound and the interior of the ice block hole that a thinner water film is formed (Figure h). Due to inertia, the liquid will continue to rise, and a series of water droplets will form at a faster top speed. At the same time, some water droplets will detach from the water mound, eventually forming a higher water column.

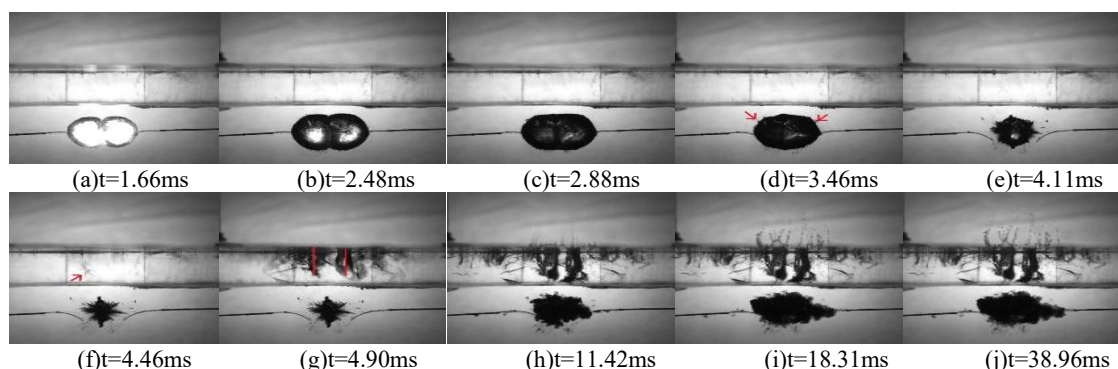


Fig.4 High speed image of two horizontally arranged bubbles collapsing under a perforated ice block ( $\gamma_{bb} = 0.78$ ,  $\gamma_{bi} = 0.86$ ,  $\gamma_{bf} = 2.44$ )

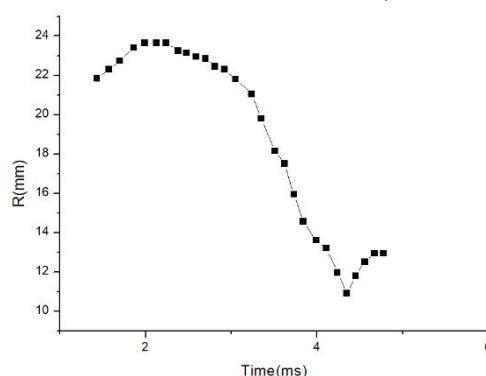


Fig.5 Changes in the radius of horizontally fused bubbles near perforated ice blocks

This working condition is due to the fact that the ice block has holes and the radius of the holes is greater than the radius of the fusion bubbles, resulting in the fusion bubbles being counteracted by the action of the free liquid surface and the ice block. Compared with the radius change chart of the fused bubble in Figure 3, it can be seen that the radius change rate of the fused bubble in Figure 5 during the collapse stage is smaller than that in Figure 3.

## 4.2 Vertical arrangement working condition

The study on the fusion phenomenon, ice breaking effect, and water mound phenomenon of vertically arranged two bubbles under perforated ice blocks is shown in Figure 6. The two bubbles are located directly below the hole. Due to the small spacing between the bubbles, during the bubble expansion stage, the two bubbles will come into contact with each other, and the contact ends will gradually flatten until they merge at their maximum volume (b). Subsequently, the bubbles begin to

collapse, and the upper part of the fused bubbles will gradually become flattened due to the action of the free liquid surface (c). At the same time, the lower sides of the fusion bubble begin to contract, and the entire fusion bubble will appear as a biconical shape (c-d). Due to the presence of a free liquid surface, the upper part of the fusion bubble contracts rapidly, resulting in the formation of a downward jet, as shown by the red arrow in Figure 6 (d), which becomes a ring-shaped bubble. This is similar to the phenomenon of two vertical bubbles in near free liquid surface conditions. Subsequently, the jet penetrates the fused bubbles, as shown in red in Figure 6 (e). The jets collide with each other, causing a "water hammer effect" and generating shock waves. Then, the bubble continues to collapse to its minimum volume and emits a series of shock waves. In the subsequent process, two reflected waves will be generated, one from the lower surface and the other from the upper surface of the ice block, as mentioned earlier. The generated shock wave can cause the rupture of ice, as shown by the red arrow in Figure 6 (g). In the following period of time, it can be observed from Figure (h-j) that a water mound was formed, which is basically similar to a hill shaped water mound[11]. At the same time, a water skirt was also observed, and due to the presence of inertia, it gradually contracted into a water column.

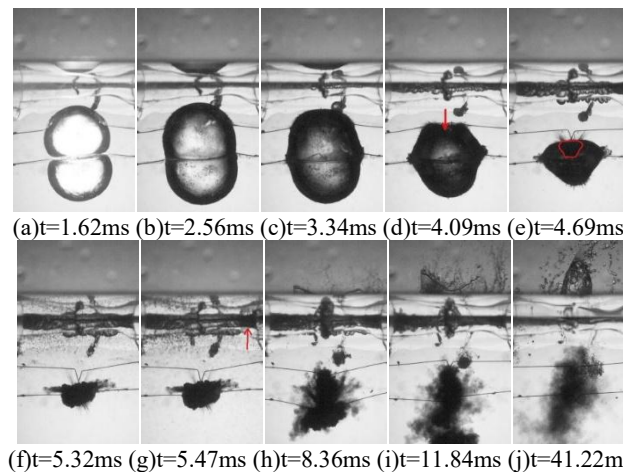


Fig.6 High speed image of two vertically arranged bubbles collapsing under a perforated ice block  
( $\gamma_{bb} = 0.72$ ,  $\gamma_{bi} = 0.82$ ,  $\gamma_{bf} = 2.19$ )

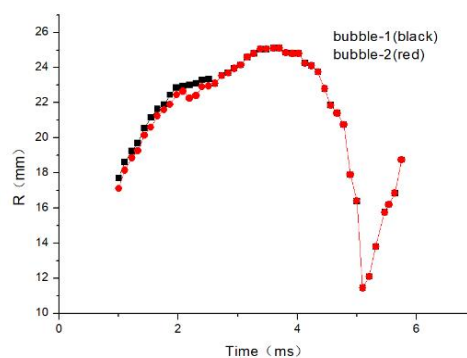


Fig.7 Changes in the radius of horizontal and vertical fusion bubbles near perforated ice blocks

Under this working condition, the radii of the upper and lower bubbles are basically the same during the expansion stage, and the measured radius after fusion is the length of the transverse axis of the fused bubbles. By comparing the horizontal fusion bubble radius variation chart in Figure 5, it can be seen that the time it takes for the vertical fusion bubble radius to reach its maximum value is greater than the horizontal working condition. The main reason is that the upper part of the fusion bubble is subjected to the action of the free liquid surface to generate a downward jet, while the lower sides of the fusion bubble move upwards, resulting in a biconical shape of the fusion bubble. When the jet penetrates the annular bubble, the bubble radius rapidly decreases, indicating that it may be driven by high pressure that increases the collapse speed of the fused bubble.

## 5. Summary

(1) When two horizontally arranged bubbles are located below an ice block, a jet flows towards the ice block. However, due to the interaction between the two bubbles and the suppression effect of the ice block on the bubbles, an oblique jet flows towards the ice block are ultimately formed; Ice cubes rupture from top to bottom, and the secondary jet of bubbles can also cause damage to the ice cubes.

(2) When two fused bubbles are located directly below the center of a perforated ice block, the effect of the ice block on the bubbles is less than that of the free liquid surface, resulting in bubble pulsation characteristics that are basically similar to the pulsation effect of bubbles on the free liquid surface; The shock wave generated by the collapse of bubbles can also lead to the rupture of ice blocks, but the effect is not as good as the rupture effect of ice blocks without holes. The energy of bubble fusion is mainly used for the interaction with the free liquid surface.

## Acknowledgements

This research was supported by the funds of Shandong Province Youth Entrepreneurship Technology Support Program for Higher Education Institutions, China (2022KJ211).

## References

- [1] CUI P, ZHANG A, WANG S, et al. Ice breaking by a collapsing bubble. *Journal of Fluid Mechanics*, 2018, 841: 287-309.
- [2] CUI P, ZHANG A, WANG S, et al. Experimental study on interaction, shock wave emission and ice breaking of two collapsing bubbles. *Journal of Fluid Mechanics*, 2020, 897.
- [3] CUI P, ZHANG A, WANG S. Shock wave emission and ice breaking effect of multiple interacting bubbles. *Ocean Engineering*, 2021, 234: 109175.
- [4] Zhang Aman, Wang Shiping, Bai Zhaohong, et al. Experimental Study on Bubble Pulsation Characteristics in Different Environments. *Journal of Mechanics*, 2011, 43(1):71-83.
- [5] Zhang Aman, Wang Chao, Wang Shiping, et al. Experimental Study on the Interaction between Bubbles and Free Liquid Surface. *Journal of Physics*, 2012, 61 (8): 300-312.
- [6] Liu Jinghan, Tang Ting, Wei Zhuobin, et al. Research on the Load Law of Shallow Water Explosion Shock Wave near a Column. *Journal of Weapon Equipment Engineering*, 2021, 42 (01): 168-173.
- [7] Qin Jian, Wen Yanbo, Meng Xiangyao, et al. Research on Underwater Explosion Bubble Jet at the Bottom of a Fixed Supported Square Plate. *Chinese Science: Physics, Mechanics, Astronomy*, 2021, 51 (12): 118-128.
- [8] Wen Yanbo, Hu Liangliang, Qin Jian, et al. Experimental and Numerical Simulation Study on Bubble Pulsation and Water Jet in Near Field Underwater Explosion. *Explosion and Shock*: 1-22 [2021-11-30].
- [9] Gu Bin, Liu Liangtao, Wei Mingli, et al. Research on Bubble Collapse and Jet Load Characteristics in Near Surface Explosion. *Journal of Sichuan University of Light Industry and Chemical Technology (Natural Science Edition)*, 2020, 33 (05): 35-43.
- [10] Yu Jun, Liu Guozhen, Wang Jun, et al. A New Method for Calculating the Load of Underwater Explosion Bubble Jet. *Journal of Computational Mechanics*, 2021, 38 (01): 120-125.
- [11] Han Rui. Research on Nonlinear Coupling and Fusion Characteristics of Multiple Bubbles (Bubble Groups). Harbin Engineering University, 2017.