

Article

Research on the Collapse Characteristics of Cavitation Bubbles near a Semi-Cylindrical Groove

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Abstract

Cavitation research is critical for anti-cavitation design of fluid machinery flow components, but the collapse dynamics of cavitation bubbles near common wall types, such as semi-cylindrical grooves, remain unrevealed. In this paper, the morphological evolution, vortex ring evolution, and bubble migration characteristics of the cavitation bubble near a semi-cylindrical groove were investigated by means of dual-view high-speed photography. The results show that (1) when the bubble is located at the symmetric position of the semi-cylindrical groove, four typical vortex ring phenomena appear during its collapse: longitudinal elliptical vortex ring, double-layer elliptical vortex ring, circular vortex ring, and transverse elliptical vortex ring. (2) Longitudinal elliptical vortex rings, the most frequently observed type, are concentrated in regions with small to moderate dimensionless distances. Double-layer elliptical vortex rings and circular vortex rings correspond to moderate and large dimensionless distance intervals, respectively. Transverse elliptical vortex rings tend to form when the bubble has a small dimensionless radius and is located near the groove center, a phenomenon strongly associated with the initial bubble position. (3) When the bubble is located at an asymmetric position, three cases are found, namely, the bubble migrates from the groove to the flat wall, the bubble impacts the flat wall vertically downward, and the bubble migrates from the flat wall to the groove.

Keywords: cavitation bubble dynamics; high-speed photography; semi-cylindrical groove; vortex ring

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1. Introduction

High-speed jets and intense shock waves released during cavitation bubble collapse are the core causes of cavitation erosion damage to flow components of fluid machinery, such as water turbines, pumps, and valves [1,2]. Semi-cylindrical grooves, such as welds, joints, and cracks, commonly exist on the surface of hydraulic flow passage components [3–5]. Such structures possess geometric features of continuous curvature and smooth transition between the groove mouth and the flat wall, which significantly alter the local flow field structure and bubble collapse behavior, making them high-incidence areas of cavitation erosion damage in hydraulic machinery. In addition, cavitation erosion also widely occurs in the field of fire engineering [6]. Therefore, investigating the dynamic

characteristics of cavitation bubble collapse near semi-cylindrical grooves has important engineering application value and scientific significance for optimizing the anti-cavitation design of hydraulic machinery and extending equipment service life. In this paper, the collapse characteristics of cavitation bubbles near a semi-cylindrical groove were studied in detail using a high-speed photography experimental system.

The collapse behavior of cavitation bubbles near various rigid walls has been widely concerned. According to the geometric structure of the wall, it can be divided into flat walls [7–12] and curved walls [13–21]. For the research on the collapse behavior of cavitation bubbles near flat walls, Li et al. [7] found, based on high-speed photography experiments, that with the increase of the bubble–flat wall distance, the collapse morphology of cavitation bubbles changes from an eccentric shape to an elliptical egg shape, and finally collapses spherically. Brujan et al. [8] found experimentally that when the cavitation bubble is far away from the flat wall, the jet penetrates the bubble to form an annular bubble that collapses radially, forming a crescent shape during the second collapse. Brujan et al. [9] combined high-speed photography experiments and numerical simulation methods, and found four typical cases of conventional jets, needle jets, and co-directional double jets by changing the bubble–flat wall distance. Lindau et al. [10] found experimentally that when the cavitation bubble is close to the flat wall, the jet passes through the bubble to form a vortex ring, and obvious splashing occurs after the jet hits the wall. With the increase of the bubble–wall distance, the formation of the vortex ring becomes more obvious. Xiang et al. [11] observed the vortex ring generated after the collapse of cavitation bubbles near the flat wall through experiments and simulations, leaving multi-focus annular damage on the wall. The results show that the higher the velocity of the bubble collapse jet, the greater the velocity and width of the vortex ring. During the rebound stage of cavitation bubble collapse, Brujan [9] and Zhang [12] also found the reflection flow, and the results show that the reflection flow will make the cavitation bubble move away from the wall.

For the research on cavitation bubble characteristics near curved walls, factors such as the geometric structure, curvature of the wall, and the distance between the bubble and the wall have a significant impact on the cavitation bubble collapse behavior. Tomita et al. [13] studied the dynamic characteristics of cavitation bubble movement, deformation, and collapse jet near a curved wall. The results show that when the cavitation bubble and the curved wall have the same scale, the movement of the cavitation bubble is significantly affected by the curvature. Cui et al. [14] found through experimental observation and numerical simulation that a single cavitation bubble near a trapezoidal pit changes from an egg shape to two drop-shaped clouds during collapse. Kim et al. [15] found experimentally that when the bubble–wall distance is small, the cavitation bubble collapses near the wall with multiple trapezoidal pits and splits into two smaller cavitation bubbles, one of which is far away from the wall and the other is close to the wall. Shan et al. [16] studied the case of small bubble–wall distance, and the results show that with the increase of pit curvature, the collapse jet velocity of cavitation bubbles gradually decreases. Shervani-Tabar and Rouhollahi et al. [17] carried out a more detailed numerical simulation study and found that with the increase of pit curvature, the collapse jet velocity of cavitation bubbles decreases, the bubble period becomes longer, and the bubble centroid movement becomes more significant. Zeng et al. [18] studied the collapse morphology and jet characteristics of cavitation bubbles near complex walls, such as plane symmetric rectangular grooves and wedge-shaped grooves, in detail by means of experiments and numerical simulations. It was found that the bubble centroid has a significant transition during the jet formation stage, and the narrowing of the groove width enhances the jet intensity and centroid movement speed. Andrews et al. [19,20] further extended the research to asym-

metric cases and studied the influence of rectangular grooves on the direction of the cavitation bubble collapse jet by using numerical simulation and experimental methods. It was found that with the increase of groove depth, the maximum deflection angle of the jet direction has no obvious change. With the increase of the distance between the bubble and the groove, the maximum deflection angle of the jet decreases. Zhou et al. [21] compared the pressure distribution of curved walls and flat walls through experiments. The results show that the existence of curvature increases the unevenness of the wall pressure, and the degree of unevenness increases with the increase of curvature.

In summary, numerous scholars have conducted extensive research on the collapse morphology and jet characteristics of cavitation bubbles near various wall structures, including flat walls, rectangular grooves, wedge-shaped grooves, pits, and slits. However, studies focusing on the collapse morphology and movement characteristics of cavitation bubbles near semi-cylindrical grooves remain relatively limited. Compared with the aforementioned structures, semi-cylindrical grooves possess two essential geometric features that may fundamentally alter bubble collapse dynamics. First, the continuous uniform curvature feature, which differs from the sharp corners of rectangular grooves and the discrete curvature changes of pits, exerts an axial guiding effect on the collapse flow field. Second, the smooth transition feature between the groove mouth and the adjacent flat wall, which avoids flow separation and pressure mutation at the groove mouth of rectangular grooves, forms a composite flow field effect of the groove curvature constraint and flat wall constraint.

Existing studies have not systematically revealed the jet directionality, three-dimensional vortex ring evolution, pressure loading distribution, and bubble migration characteristics of cavitation bubbles near semi-cylindrical grooves. In particular, there is a lack of quantitative research on the dynamic behavior of bubbles at asymmetric positions, and no mapping relationship between dimensionless parameters and collapse modes has been established. Most existing studies adopt single-view high-speed photography, which can only observe the two-dimensional planar morphology evolution of bubbles and cannot fully capture three-dimensional vortex ring structures and spatial migration characteristics. This work constructs a dual-view synchronous high-speed photography experimental system to simultaneously acquire front and top images of bubble collapse processes, systematically investigates the collapse morphology and vortex ring evolution characteristics of cavitation bubbles at symmetric positions near semi-cylindrical grooves and the migration laws of bubbles at asymmetric positions, establishes a partition map of dimensionless parameters and collapse modes, reveals the regulation mechanism of semi-cylindrical grooves on bubble collapse behavior, and provides experimental support for improving the theory of cavitation bubble collapse near complex wall surfaces.

2. Experimental System and Physical Model

Figure 1 show the schematic diagram and physical diagram of the high-speed photography experimental system, respectively. The main equipment of the experimental system includes two high-speed cameras, a delay generator, a laser generator, a focusing lens, a water tank, a concave lens, a light source, etc. Among them, two high-speed cameras are used to record the complete process of cavitation bubble dynamic behavior near the groove model. High-speed camera 1 takes a top view, and high-speed camera 2 adjusts the optical path through the installed concave lens and filter to take a front view. Two i-speed 510 high-speed cameras (iXcameras, Essex, UK) are used for synchronous recording, with an identical camera exposure time (shutter time) of 1 μ s and a frame rate of 100,000 fps. The pixel-to-length calibration coefficients (spatial resolution) are calibrated to 0.0625 mm per pixel for the front-view camera and 0.0286 mm per pixel for the top-view camera. The water tank is filled with deionized water, and the size of the water tank

is $150 \times 150 \times 150 \text{ mm}^3$. The laser generator is used to induce cavitation bubble generation, and the delay generator is used to coordinate the synchronous operation of the high-speed camera and the laser generator. The beam expander is used to amplify the laser beam, the focusing lens focuses the laser precisely on the cavitation bubble growth point, and the light source makes the picture clear. The three-dimensional displacement translation stage can adjust the position of the experimental material to carry out parametric experiments. In this paper, the shooting speed of both high-speed cameras is 1.0×10^5 frames per second. The laser energy is adjusted by changing the working voltage of the laser generator, thereby regulating the cavitation bubble size. The energy range of the laser generator is 0–100 mJ. The experimental ambient pressure is atmospheric pressure, and deionized water is used as the experimental medium. In addition, the machining precision of the groove radius is $\pm 0.01 \text{ mm}$, and the surface roughness of the groove wall and adjacent flat wall is controlled within $0.8 \text{ }\mu\text{m}$. As for the phase transition effect, under the experimental conditions of this study, the duration of the first cycle of the cavitation bubble is extremely short, and the water temperature is controlled at $25 \pm 0.5 \text{ }^\circ\text{C}$. The phase transition inside the bubbles is negligible, which exerts little influence on the overall collapse, migration, and vortex ring evolution of cavitation bubbles. According to previous work by Tomita et al., boundary confinement effects can be eliminated when the tank side length exceeds 10 times the maximum bubble radius [13], and the water tank adopted in this experiment satisfies this requirement. Furthermore, calculations based on the acoustic propagation law presented by Lindau et al. demonstrate that pressure waves reflected from the tank walls return only after the completion of the primary bubble collapse, thereby causing no interference to experimental observations [10].

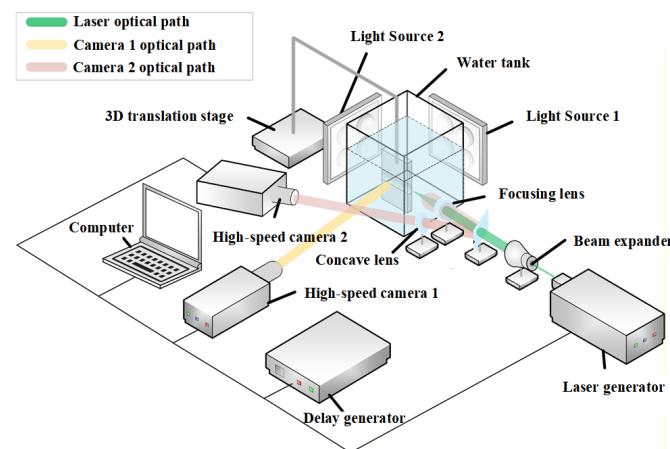


Figure 1. High-speed photography experimental system.

Figure 2 presents the physical model and parameter definitions. A Cartesian coordinate system is constructed with the initial centroid of the cavitation bubble r_0 as the origin, with the x -axis pointing horizontally to the right and the y -axis pointing vertically upward. This coordinate system serves as the unified reference frame for quantifying bubble centroid displacement, conducting error analysis, and verifying experimental repeatability. O denotes the center of the semi-cylindrical groove, l is the vertical distance from the bubble initial centroid r_0 to the groove center O , R_c is the groove radius, and $R_{\max}$ is the maximum radius of a cavitation bubble in an unbounded flow field. The bubble azimuthal angle θ is defined as the angle between the vertical symmetry axis passing through O and the line connecting O to r_0 . For the convenience of subsequent analysis, the displacement distance of the bubble centroid is denoted by S , which is defined as follows:

$$S = \sqrt{\Delta x^2 + \Delta y^2} \quad (1)$$

In the formula, Δx and Δy denote the displacement components of the bubble centroid along the x -axis and y -axis, respectively.

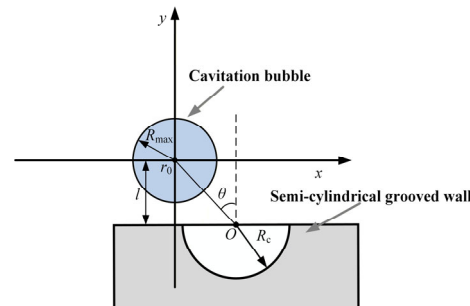


Figure 2. Diagram of physical model and parameter definition.

The error analysis of experimental results is organized as follows. The spatial resolution of the high-speed images is 0.048 mm per pixel in both the x and y directions. Therefore, the minimum error in displacement distance of the bubble centroid (ΔS_{err}) can be expressed as:

$$\Delta S_{err} = \sqrt{\Delta x_{err}^2 + \Delta y_{err}^2} = \pm 0.068 \text{ mm} \quad (2)$$

Here, Δx_{err} and Δy_{err} are the distance errors in the x -axis and y -axis directions, respectively.

To ensure the reliability of the experimental system and the reproducibility of the observed phenomena, 10 replicate validation experiments were conducted under a constant laser voltage to generate cavitation bubbles with a maximum radius of $R_{max} = 1.60$ mm, which is presented as a typical example to demonstrate the experimental consistency. Statistical data were collected for the maximum radii of the laser-induced bubbles, and their mean value and standard deviation were calculated to quantify the variability of bubble generation. The detailed measurement data and corresponding error indicators are provided in Table 1.

Table 1. Error analysis of the validation experiments.

Series	R_{max} (mm)
#1	1.64
#2	1.56
#3	1.62
#4	1.58
#5	1.58
#6	1.61
#7	1.63
#8	1.58
#9	1.57
#10	1.61
Average	1.60
Standard deviation	0.027 (1.69%)

As shown in Table 1, the maximum bubble radius shows consistently low variability across repeated experiments. Its standard deviation is 1.69% of the mean value, which

demonstrates excellent repeatability of bubble generation. These results collectively validate the reliability of the experimental system.

To simplify the mathematical model and describe the dynamic behavior of the bubble under different conditions more accurately, the dimensionless radius (R^*), dimensionless distance (l^*), and dimensionless time (T^*) are defined as follows:

$$R^* = \frac{R_{\max}}{R_c}, \quad (3)$$

$$l^* = \frac{l}{R_c}, \quad (4)$$

$$T^* = \frac{t}{T_0}, \quad (5)$$

where t is the time calculated from the inception of the cavitation bubble, and T_0 is the duration from the inception of the cavitation bubble to the end of the first collapse. In this paper, the parameter values are $l^* = 0.3\sim 3.3$, $R^* = 0.5\sim 3.0$, and $R_c = 1.5$ mm. A total of 157 sets of experimental data were obtained. Every operating condition involved in this paper was repeated no less than three times, and key representative test cases were repeated over five times to guarantee reliable experimental outcomes.

3. Cavitation Bubbles at Symmetric Positions

This section presents the high-speed photography results under different R^* and l^* and deeply analyzes the bubble collapse morphology and vortex ring evolution characteristics.

Figure 3 shows the evolution process of the bubble in the longitudinal elliptical vortex ring phenomenon from the front view (Figure 3a) and top view (Figure 3b; $R^* = 1.8$, $l^* = 1.3$, $\theta = 0^\circ$). The scale is marked in the first frame, and the serial number and time are also marked in each frame. Frames 1~2 are the first period of the growth stage, and the lower part of the bubble wall is in contact with the wall. Frames 3~7 are the first period of the collapse stage, and a long elliptical vortex ring parallel to the groove channel is formed at the end of collapse. Frames 8~10 are the second period, and secondary cavitation bubbles are formed in the bubble cloud at the junction of the groove and the flat wall.

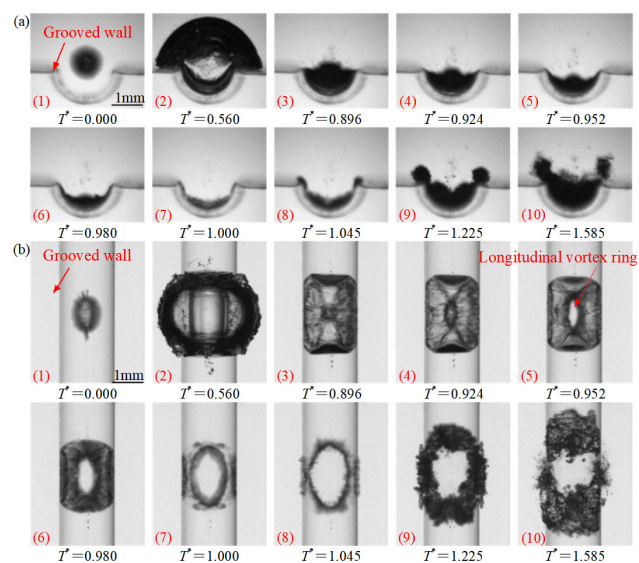


Figure 3. Evolution of the longitudinal elliptical vortex ring. (a) Front view. (b) Top view.

Figure 4 shows the evolution process of cavitation bubbles in the double-layer elliptical vortex ring phenomenon from the front view (Figure 4a) and top view (Figure 4b; $R^* = 1.1$, $l^* = 1.4$, $\theta = 0^\circ$). Frames 1~3 are the first period of the growth stage, and the lower part of the bubble wall is in contact with the wall. Frames 4~6 are the first period of the collapse stage. At the end of the first collapse period, the cavitation bubble appears as two upper and lower bubbles in the front view, with the upper bubble larger than the lower one. In the top view, they are two overlapping elliptical vortex rings. The overall length of the vortex ring perpendicular to the groove wall is larger than that parallel to the groove wall. The larger bubble is the upper vortex ring, and the smaller bubble is the lower vortex ring.

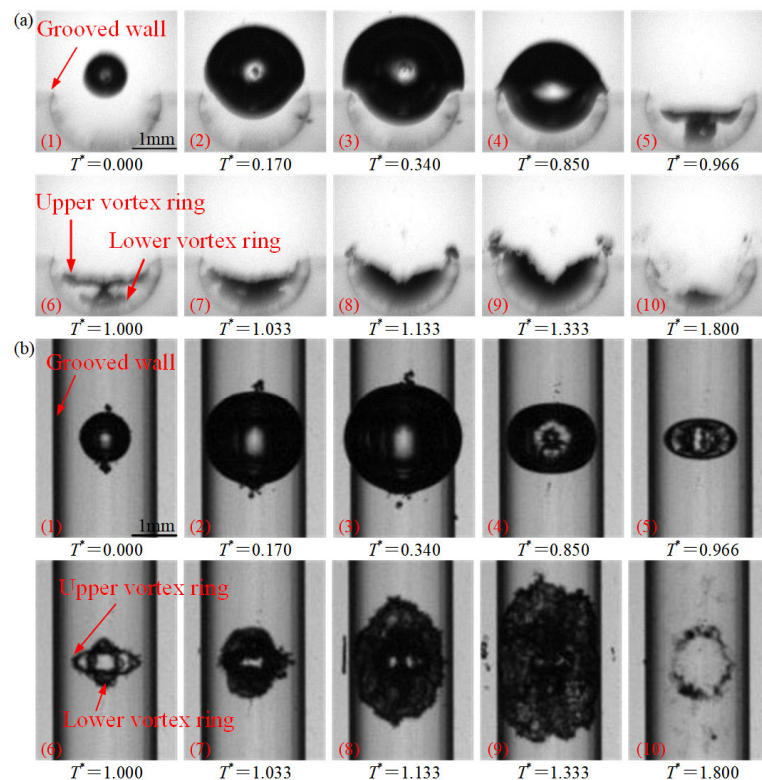


Figure 4. Evolution of the double-layer elliptical vortex ring. (a) Front view. (b) Top view.

Figure 5 shows the evolution process of cavitation bubbles in the circular vortex ring phenomenon from the front view (Figure 5a) and top view (Figure 5b; $R^* = 2.5$, $l^* = 2.1$, $\theta = 0^\circ$). Frames 1~3 are the first period of the growth stage, and the lower part of the bubble wall is not in contact with the wall. Frames 4 and 5 are the first period of the collapse stage. At the end of the first collapse period, the cavitation bubble is T-shaped in the front view, and a circular vortex ring is formed in the top view.

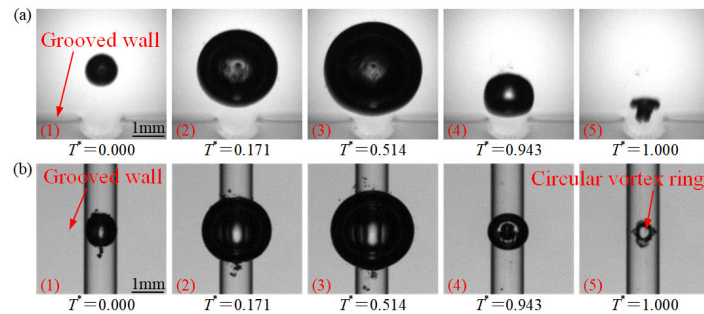


Figure 5. Evolution of the circular vortex ring. (a) Front view. (b) Top view.

Figure 6 shows the evolution process of cavitation bubbles in the transverse elliptical vortex ring phenomenon from the front view (Figure 6a) and top view (Figure 6b; $R^* = 1.2$, $l^* = 1.1$, $\theta = 0^\circ$). Frames 1~2 are the growth stage, and the lower part of the bubble wall is in contact with the wall. Frames 3~5 are the first period of the collapse stage, and a long elliptical vortex ring perpendicular to the groove channel is formed at the end of collapse. Frames 6~10 are the second period, and the vortex ring splits and moves away from each other along the groove channel.

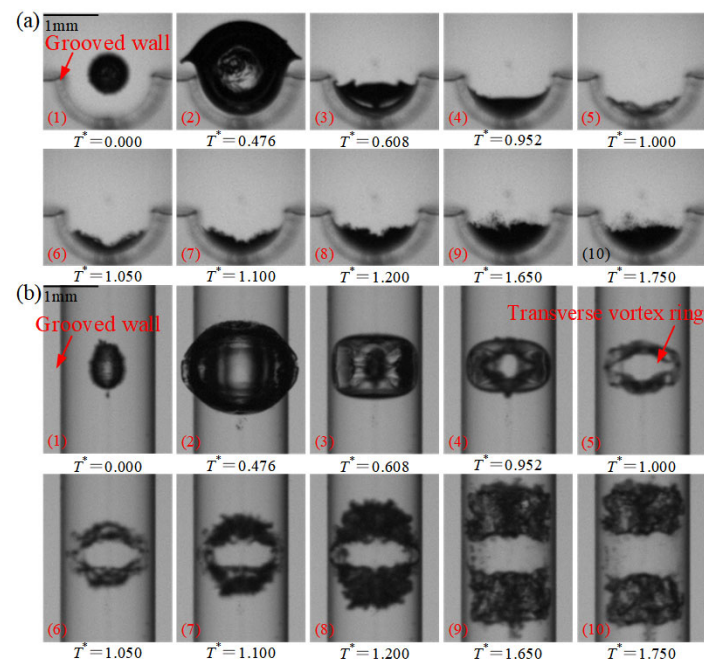


Figure 6. Evolution of transverse elliptical vortex ring. (a) Front view. (b) Top view.

Figure 7 presents the partition map of vortex ring phenomena based on R^* and l^* . Different colored squares in the figure represent different vortex ring phenomena. The longitudinal elliptical vortex ring phenomenon occurs in the ranges of $R^* = 1.1\sim 3.0$ and $l^* = 0.3\sim 1.8$, the double-layer elliptical vortex ring phenomenon occurs in the ranges of $R^* = 1.0\sim 1.6$ and $l^* = 1.1\sim 1.8$, the transverse elliptical vortex ring phenomenon occurs in the ranges of $R^* = 1.0\sim 1.2$ and $l^* = 0.7\sim 1.1$, and the circular vortex ring phenomenon occurs in the ranges of $R^* = 1.0\sim 2.5$ and $l^* = 1.6\sim 2.1$. There are no transitional morphologies between these four vortex ring phenomena. It can be seen that the longitudinal elliptical vortex ring is the most frequent and occurs in the region with small l^* . Notably, as R^* increases,

the corresponding l^* range for the longitudinal elliptical vortex ring phenomenon expands. The double-layer elliptical vortex ring phenomenon occurs in the region with medium l^* , and the circular vortex ring phenomenon occurs in the region with large l^* . When the initial centroid of the cavitation bubble is close to the center of the groove, a transverse elliptical vortex ring is often formed.

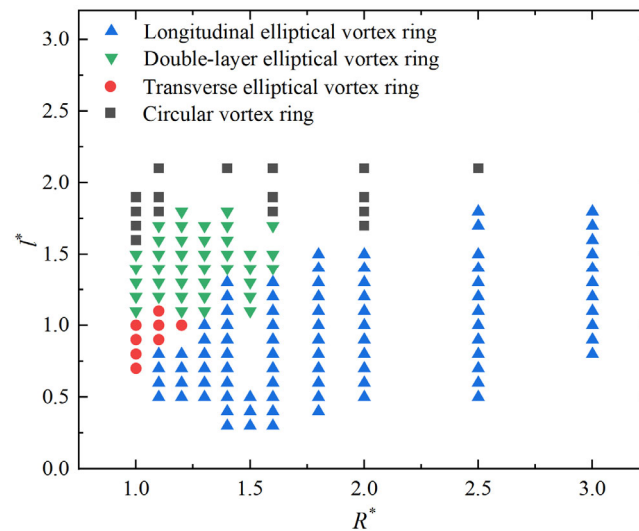


Figure 7. Partition map of vortex ring phenomena based on R^* and l^* .

The physical mechanisms of the four typical vortex ring phenomena are briefly analyzed by integrating previous research findings. For the longitudinal elliptical vortex ring, the continuous curvature of the groove imposes an axial guiding effect on the underlying flow field when the bubble is close to the wall. The pressure difference across the bubble induces a jet along the groove axis (the direction of minimum resistance), which entrains ambient fluid to form an axially elongated vortex ring after penetrating the bubble [10]. As R^* increases, the spatial range of the bubble influenced by the groove curvature expands, correspondingly widening the l^* interval for this vortex ring. For the double-layer elliptical vortex ring, at moderate l^* , the bubble is simultaneously affected by the grooved surface and adjacent flat walls. A primary jet forms along the groove axis, while the reflected flow at the groove mouth interacts with it to induce a secondary vortex ring below the primary one [9]. This structure cannot form when l^* is too small (insufficient reflected flow intensity) or too large (weakened local groove effect). When $R^* > 1.6$, the large-scale bubble covers the entire groove and adjacent flat walls, smoothing out the local groove mouth effect. The axial guiding effect of the groove's continuous curvature then dominates, leading to a transition to a single longitudinal elliptical vortex ring. For the circular vortex ring, when the bubble is sufficiently far from the groove, the local curvature disturbance to the global flow field is negligible, and the pressure field approximates that of an infinite flat wall [21]. The jet then propagates vertically downward to the wall, forming an axisymmetric circular vortex ring after bubble penetration [10,11]. For the transverse elliptical vortex ring, when the bubble is very close to the groove center and has a small size, the transverse curvature constraint of the groove exceeds the axial constraint, making the direction perpendicular to the groove channel the path of minimum resistance. The collapse jet thus develops transversely and entrains fluid to form a transverse elliptical vortex ring. This phenomenon is unique to semi-cylindrical grooves due to their continuous curvature and only occurs near the groove center.

4. Cavitation Bubbles at Asymmetric Positions

According to the variation of cavitation bubble centroid displacement (S) with dimensionless time under different R^* and l^* , the evolution of cavitation bubbles at asymmetric positions can be divided into three cases. When the cavitation bubble is located at an asymmetric position, three cases are found: the bubble migrates from the groove to the flat wall, the bubble impacts the flat wall vertically downward, and the bubble migrates from the flat wall to the groove. The bubble movement characteristics under the three cases are quantitatively analyzed below.

4.1. Case 1

Figures 8 and 9 show morphological evolution and centroid movement of the cavitation bubble during expansion and collapse in the first two periods for Case 1. The other relevant important parameters are $R^* = 0.7$, $l^* = 2.58$, and $\theta = 7.59^\circ$. As shown in Figure 8, the jet is directed to the lower left, i.e., from the groove to the flat wall. As shown in Figure 9, at the end of the secondary collapse of the cavitation bubble, the centroid of the cavitation bubble moves to the lower left and is closer to the junction of the groove and the flat wall compared with the maximum volume of the cavitation bubble during growth.

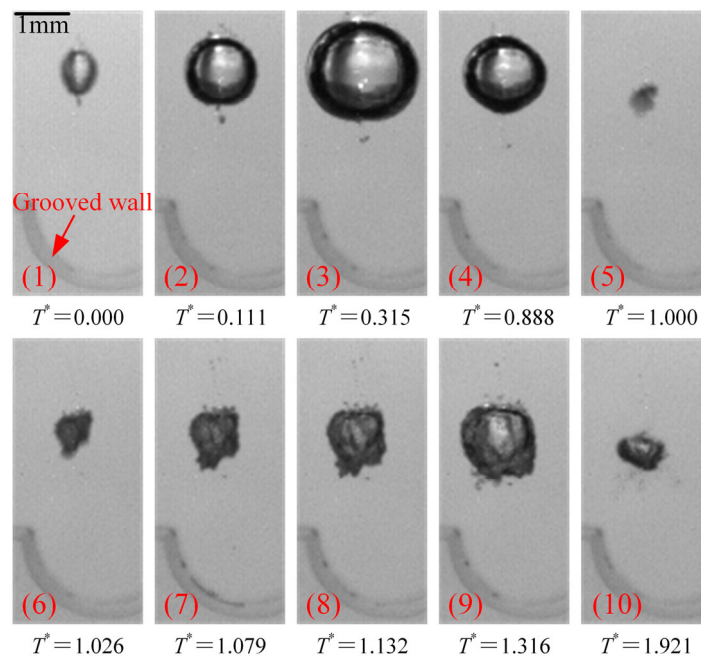


Figure 8. Morphological evolution of the cavitation bubble during expansion and collapse in the first two periods for Case 1. Frames (1)–(5) present the expansion and collapse phases of the first period, while Frames (6)–(10) present the rebound and re-collapse phases of the second period.

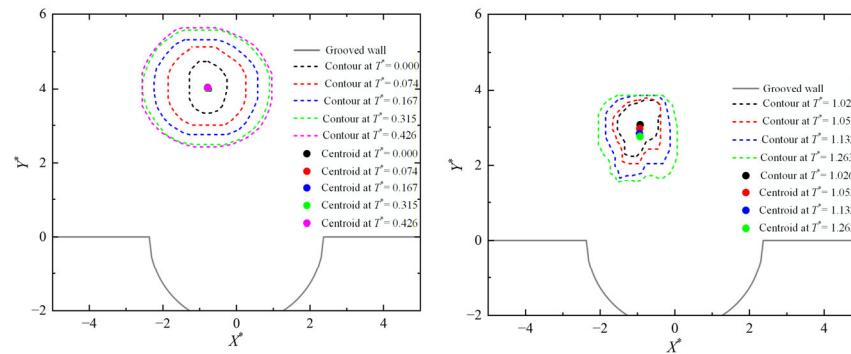


Figure 9. Variations of bubble wall position and centroid position during expansion and collapse in the first two periods for Case 1.

Figure 10 shows the variations of the displacement distance (S) of the bubble centroid with dimensionless time in Case 1. Different color curves represent different R^* and l^* . The similarity between subplot (a) and subplot (b) is that S rises sharply at the end of the first collapse and then increases slowly. The difference is that S increases with the increase of R^* , and S is not significantly affected by l^* .

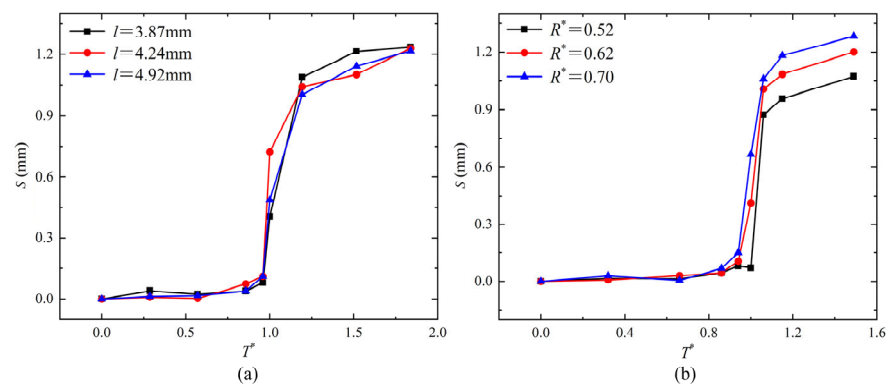


Figure 10. Variations of the displacement distance of the bubble centroids for Case 1. (a) Variations of the cavitation bubble centroid displacement distance with l^* . (b) Variations of the displacement distance of the bubble centroid with R^* .

4.2. Case 2

Figures 11 and 12 show morphological evolution and centroid movement of the cavitation bubble during expansion and collapse in the first two periods for Case 2. The other relevant important parameters are $R^* = 0.7$, $l^* = 2.83$, and $\theta = 25.01^\circ$. As shown in Figure 11, the jet is directed vertically downward to the flat wall, and the cavitation bubble contacts the wall in the second period. As shown in Figure 12, at the end of the secondary collapse of the cavitation bubble, the centroid of the cavitation bubble moves significantly downward compared with the maximum volume of the cavitation bubble during growth.

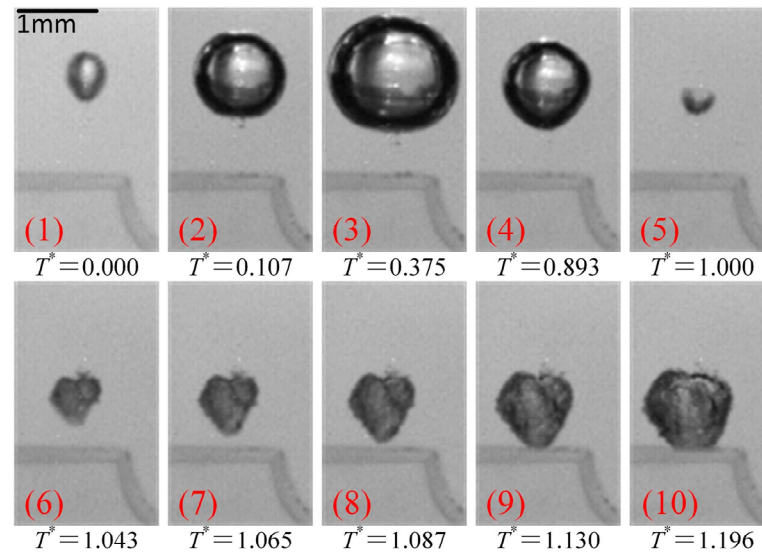


Figure 11. Morphological evolution of the cavitation bubble during expansion and collapse in the first two periods for Case 2. Frames (1)–(5) present the expansion and collapse phases of the first period, while Frames (6)–(10) present the rebound and re-collapse phases of the second period.

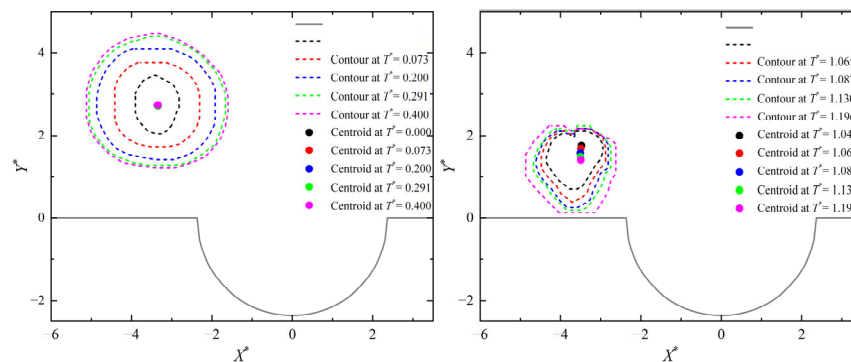


Figure 12. Variations of bubble wall position and centroid position during expansion and collapse in the first two periods for Case 2.

Figure 13 shows variations of the displacement distance (S) of the bubble centroid with dimensionless time in Case 2. Different color curves represent different R^* and l^* . The similarity between subplot (a) and subplot (b) is that S rises sharply at the end of the first collapse and then increases slowly. In addition, neither l^* nor R^* exerts a significant influence on S .

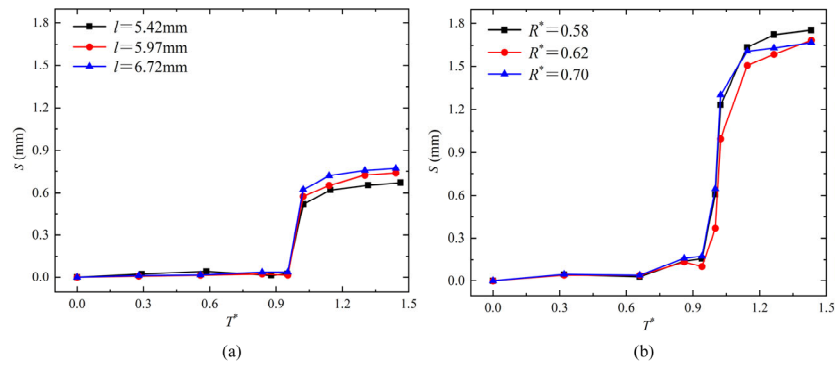


Figure 13. Variations of the displacement distance of the bubble centroids for Case 2. (a) Variations of the cavitation bubble centroid displacement distance with T^* . (b) Variations of the displacement distance of the bubble centroid with R^* .

4.3. Case 3

Figures 14 and 15 show morphological evolution and centroid movement of the cavitation bubble during expansion and collapse in the first two periods for Case 3. The other relevant important parameters are $R^* = 0.7$, $l^* = 3.28$, and $\theta = 38.66^\circ$. As shown in Figure 14, the jet is directed to the lower right, i.e., from the flat wall to the groove. As shown in Figure 15, at the end of the secondary collapse of the cavitation bubble, the centroid of the cavitation bubble moves to the lower right and is closer to the junction of the groove and the flat wall compared with the maximum volume of the cavitation bubble during growth.

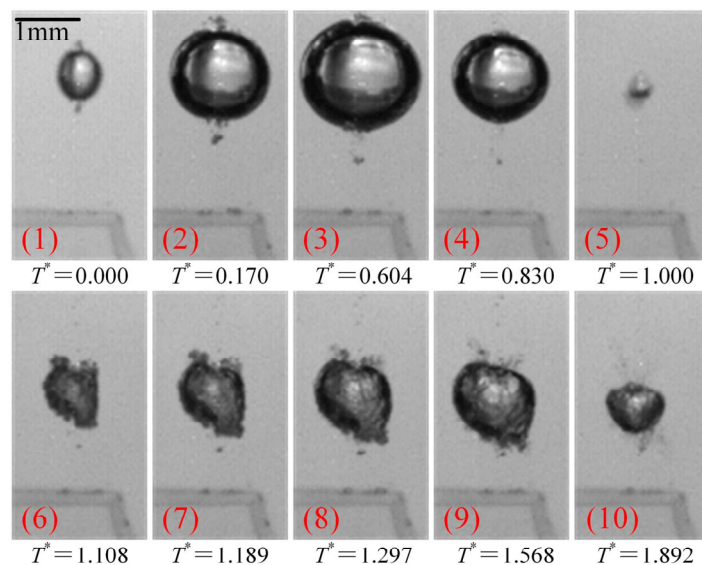


Figure 14. Morphological evolution of the cavitation bubble during expansion and collapse in the first two periods for Case 3. Frames (1)–(5) present the expansion and collapse phases of the first period, while Frames (6)–(10) present the rebound and re-collapse phases of the second period.

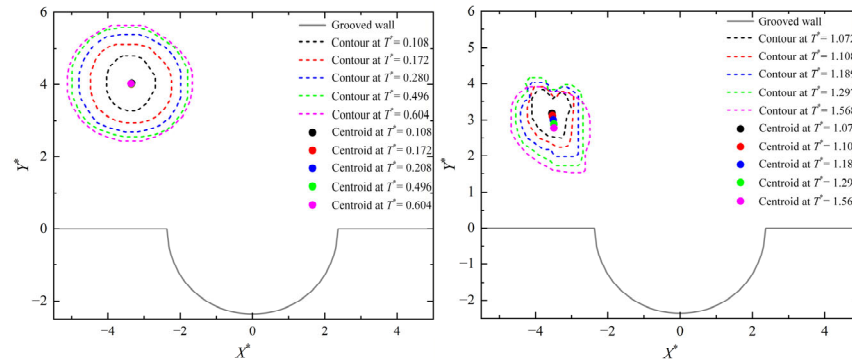


Figure 15. Variations of bubble wall position and centroid position during expansion and collapse in the first two periods for Case 3.

Figure 16 shows variations of the displacement distance (S) of the bubble centroid with dimensionless time in Case 3. The curve trends in both subplot (a) and subplot (b) are the same: S rises sharply at the end of the first collapse and then increases slowly. In addition, S increases with the increase of R^* and l^* .

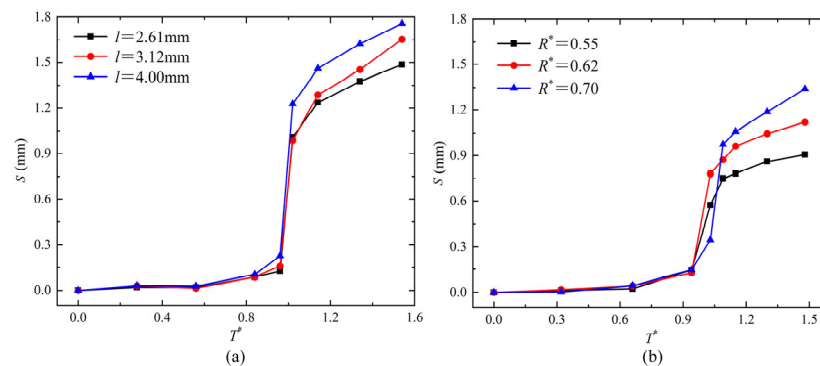


Figure 16. Variations of the displacement distance of the bubble centroids for Case 3. (a) Variations of the cavitation bubble centroid displacement distance with l^* . (b) Variations of the displacement distance of the bubble centroid with R^* .

4.4. Physical Mechanisms

Based on the concept of impulse, the Kelvin impulse of a cavitation bubble is the accumulation of the resultant external force acting on the bubble over one cycle. Therefore, investigating the Kelvin impulse of a cavitation bubble enables the determination of the resultant force acting on it, and further the prediction of its motion characteristics. When a cavitation bubble collapses in an unbounded flow field, the total Kelvin impulse of the system is zero, resulting in no overall migration of the bubble. When a rigid wall is present, to satisfy the boundary condition of zero normal velocity at the wall surface, the method of images is employed to introduce an “image bubble” to the equivalent hydrodynamic effect of the wall. All effects of the wall can be equivalent to the Kelvin impulse contribution of the image bubble to the original bubble, and the total Kelvin impulse is the vector sum of the impulses of the original bubble and the image bubble [9,13].

According to the classic study by Tomita et al. in 2002 [13], the image impulses induced by walls with different curvatures exhibit distinct quantitative differences: for a cavitation bubble near a flat wall, the direction of the Kelvin impulse is perpendicular to and pointing toward the flat wall; for a bubble near a concave curved wall, the Kelvin impulse is directed perpendicularly toward the concave curved wall. Moreover, at the

same distance, the magnitude of the image impulse generated by a concave curved wall is always smaller than that generated by a flat wall.

For Case 1, Case 2, and Case 3, the difference in azimuthal angle θ leads to different influences of the flat wall and the concave curved wall on the bubble. The resulting significant differences in the non-uniformity of the pressure distribution in the flow field surrounding the bubble cause distinct horizontal and vertical components of the Kelvin impulse, which in turn lead to differences in the migration direction of the bubble centroid. For example, in Case 2, the horizontal components of the Kelvin impulse induced by the flat wall and the grooved wall cancel each other out, so the total Kelvin impulse of the bubble is directed vertically downward, resulting in the vertical downward migration of the bubble. For Case 1 and Case 3, the differences in the migration direction of the bubbles are attributed to the opposite directions of the horizontal components of the Kelvin impulse.

5. Conclusions

Based on the high-speed photography experimental system, this paper investigated the collapse deformation characteristics, vortex ring evolution characteristics, and cavitation bubble movement characteristics near a semi-cylindrical groove, and discussed the influences of dimensionless radius (R^*) and dimensionless distance (l^*) on the cavitation bubble collapse morphology, vortex ring evolution characteristics, and displacement distance of the bubble centroid (S). The main conclusions are as follows:

- (1) When the cavitation bubble is located at the symmetric position, four typical vortex ring phenomena are found: longitudinal elliptical vortex ring, double-layer elliptical vortex ring, circular vortex ring, and transverse elliptical vortex ring. The transverse elliptical vortex ring is easy to form in the extremely small l^* region, the longitudinal elliptical vortex ring is concentrated in the small l^* region, the double-layer elliptical vortex ring is mostly found in the medium l^* region, and the circular vortex ring is formed in the large l^* region.
- (2) The distribution of the four typical vortex ring phenomena is closely related to the dimensionless parameters R^* and l^* : longitudinal elliptical vortex rings, the most frequently observed type, are concentrated in regions with small to moderate l^* , double-layer elliptical and circular vortex rings correspond to medium and large l^* , respectively, and transverse elliptical vortex rings tend to form when the bubble has a small R^* and is located near the groove center, a phenomenon strongly associated with the initial bubble position.
- (3) When the cavitation bubble is located at an asymmetric position, three cases are found. Case 1: the cavitation bubble moves from the groove to the flat wall, S increases with the increase of R^* , and S is not significantly affected by l^* . Case 2: the cavitation bubble impacts the flat wall vertically downward, S increases with the increase of l^* , and S is not significantly affected by R^* . Case 3: the cavitation bubble moves from the flat wall to the groove, and S increases with the increase of R^* and l^* .

In future work, theoretical research and numerical simulation methods will be adopted to further investigate the dynamic behavior characteristics of cavitation bubbles near semi-cylindrical grooves. A mature theoretical model describing bubble dynamics near semi-cylindrical groove walls will be developed to elaborate the internal influence mechanism of characteristic parameters in depth. Multi-cycle coupled numerical simulations combined with phase transition dynamic models will be performed to refine the relevant physical mechanism analysis. Furthermore, corresponding experimental verifications will be supplemented to fully reveal the regulatory mechanism of semi-cylindrical grooves on the morphological evolution and jet characteristics of cavitation bubbles.

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