Dynamics of a Laser-induced Bubble Near a Convex Free Surface

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Abstract

This paper experimentally documents the behavior of a laser-induced bubble near a convex paraboloidal free surface with different vertical radius of curvatures, generated in a rotating cylindrical water flask. The shape of the free surface plays a key role on bubble behaviors when bubble collapses. Due to the strong influence of the free surface, the bubble forms a microjet outwards the free surface when it collapses. And the nondimensional bubble collapse time, T_c/T_c', is smaller than 1, where T_c is the bubble collapse time and T_c' is the Rayleigh time of bubble collapse with an equivalent maximum radius. As the relative distance between the bubble center and the free surface, h/R_{max}, decreases, T_c/T_c' decreases, which is different with the bubble behavior near a flat rigid boundary, where h is the distance between the bubble center and the flat free surface or the convex free surface center, R_{max} is bubble equivalent maximum radius. Compared with the bubble dynamics near a flat free surface, the bubble near a convex free surface presents a milder collapse behavior. T_c/T_c' increases with the nondimensional radius of curvature of the free surface center, r_s/R_{max}, decreases, where r_s is the vertical radius of curvature of the free surface, which is different from the bubble behavior near a curved rigid boundary. It implies that the convex shape of free surface reduces the Kelvin impulse, and the strength of the microjet when bubble collapses decreases with a decreasing r_s/R_{max}. Meanwhile the convex free surface provides a focusing mechanism to the splash on the free surface when bubble collapses. The splash gets a higher velocity when r_s/R_{max} decreases.

Keywords: bubble dynamics; convex free surface; micro jet strength

Introduction

Cavitation phenomena is a double-edged sword for human lives. It causes cavitation erosion ship propellers [1], pipelines [2] and turbines [3]. Meanwhile, with appropriate controlling technology, it is feasible to apply the cavitation to benefit our daily life, e.g., kidney stone fragmentation [4], surface cleaning [5] and drug delivery [6]. During these cavitation process, the collapse of the cavitation bubbles, especially near a boundary, plays a key role on the cavitation erosion or the beneficial effects. Nevertheless, bubble collapse behaviors strongly depend on the features of the boundaries. Not only the physical properties but also the geometric parameters of the boundary will greatly influence on bubble dynamics.

In the past decades, extensive research been carried out on bubble dynamics near a flat boundary. Near a flat rigid boundary, the bubble presents an aspherical collapse and develops a micro jet towards the rigid boundary [7, 8], while the bubble forms a micro jet outward the free surface [9, 10] when it collapses near a flat free surface. In 1980s, Blake *et al*. [11] applied the Kelvin impulse to analyze the strength of the micro jet at bubble collapse, and Supponen *et al*. [12] developed the Kelvin impulse and use a dimensionless pressure anisotropy parameter to scale the micro jet strength with the jet feature, e.g., jet velocity, jet volume and jet impact time, etc. Most research focused on a cavitation bubble occurring near a flat boundary. However, the bubble dynamics near a curved boundary has received less attention, and the influence of the geometric parameters of the boundary remains poorly understood.

A number of studies have been dedicated to the bubble dynamics near a curved boundary. For example, Tomita *et al*. [13] generated a laser-induced bubble near a curved rigid boundary and the experiments present that the velocity of the micro jet increases while the shape of the rigid boundary changes from concave into convex. Obreschkow *et al*. [14] study the behavior of a bubble in a droplet in micro gravity. They observed two liquid jets escaping from the drop when the bubble collapses, and a shorter bubble life time in the droplet than the bubble in an infinite fluid. Also the spike and the splash on the concave free surface are not as violent as a flat free surface. In addition, Tagawa *et al*. [15] focus a laser in a capillary to generate a bubble, and the asymmetric bubble dynamics induces a thin and focused jet (velocity up to 850 m/s) on the convex free surface due to the surface tension. They stated that the convex free surface

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is able to focus the shockwave and cause the supersonic jet on the surface. In this paper, we report an experimental study of bubble dynamics near a convex free surface and focus on the strength of the micro jet when bubble collapses.

Experimental setup

To simulate the dynamics of a cavitation bubble near a curved free surface, we designed a rotating experimental setup as in Fig. 1. The water flask (D = 150 mm, H = 350 mm) was filled with deionized and degassed water and all experiments took place at room temperature. When the cylindrical water flask is rotating, the flat free surface turns into a paraboloid due to the gravity and the centrifugal force. The vertical radius of curvature of the free surface $r_s = 900g/\pi^2 n^2$, where g is the gravitational acceleration, and n is the revolutions per minute of the water flask. And we used a Q-switched pulsed ruby laser (wavelength: 694.3 nm, maximum pulse energy: 1.5 J, pulse length: 20–30 ns) to generate a cavitation bubble with maximum radius of about 2-3 mm in the water flask. We used a signal generator (Rigol DG2021A) to trigger a laser and a highspeed camera (Phantom V711) simultaneously. The motions of the bubble and the free surface were recorded by the camera (at 79 069 frames/s with an exposure time of 1 μs) for subsequent analyses.

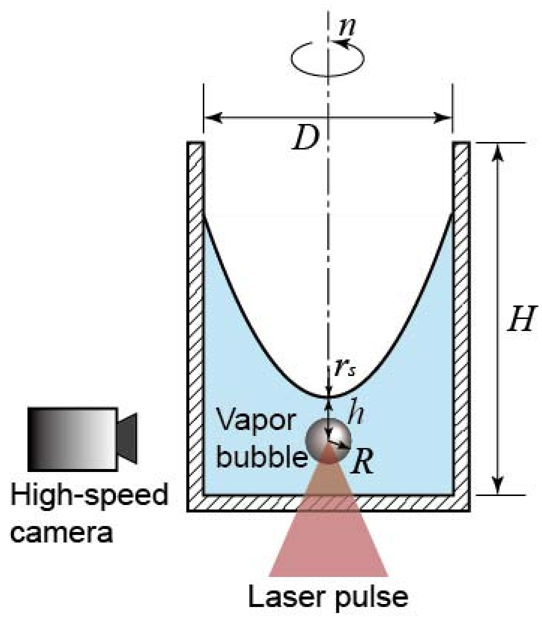

Fig. 1. Schematic of the experimental setup with a side view synchronized with the laser pulse.

Results and discussion

For the convenience of depicting the experimental results, we use three nondimensional parameters, h/R_{max}, r_s/R_{max} and T_c/T_c’, where h is the distance between the bubble center and the flat free surface or the convex free surface center, R_{max} is the bubble equivalent maximum radius, T_c is the bubble collapse time and T_c’ is the Rayleigh time of bubble collapse with an equivalent maximum radius. Figure 2 presents the bubble behaviors near the flat free surface with different h/R_{max}. Due to the strong influence of the free surface, the bubble collapses non-spherically and forms a micro jet outward the free surface. And the bubble collapse time, T_c, is much shorter than T_c’. T_c/T_c’ increases with an increasing relative distance h/R_{max} increases, which is in contrast with the bubble behavior near a flat rigid boundary [16]. The possible explanation is that it would be much easier for bubble to push the liquid away to grow and pull the liquid back to collapse due to the deformable free surface, resulting a T_c/T_c’ smaller than 1.

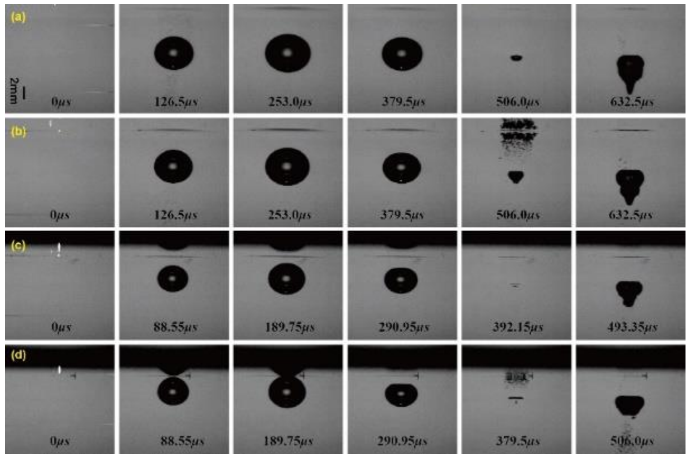

Fig. 2. Laser-induced bubble behaviors near a flat free surface with different h/R_{max}. (a) h/R_{max} =2.261, T_c/T_c'=0.916; (b) h/R_{max} =1.932, T_c/T_c'=0.904; (c) h/R_{max} =1.432, T_c/T_c'=0.862; (d) h/R_{max} =1.027, T_c/T_c'=0.846. The scale bar is only valid on the vertical direction due to the image distortion from the cylindrical water flask.

Four typical experimental results are presented when the bubble grows and collapses near a free surface with different convex shape in Fig 3. With the same h/R_{max}, T_c/T_c' increases with a decreasing r_s/R_{max}, which is different from the influence of the convex shape on the bubble behavior near a rigid boundary [13]. A more convex surface indicates more liquid to be driven into motion, especially the liquid on the bubble upper side, which would increase bubble collapse time. It implies that the Kelvin impulse and the strength of the microjet when bubble collapses near a convex free surface would be smaller than when bubble collapses near a flat free surface, because of the increasing bubble collapse time with the decreasing r_s/R_{max}, though the bubble behavior, in general, is similar with a flat free surface due to the strong influence of the free surface. It is valid to pay more attention to theoretical analysis and simulation research in the future. In the experiments, we also observed that a violent splash appears when bubble collapses, which is an important phenomenon on the bubble behavior near a free surface. The focusing of the convex free surface enhances the strength of splash. The splash gets a higher velocity when r_s/R_{max} decreases. One potential application of the high-speed and thin splash is to the development of no-needle liquid-injection systems which would be beneficial for health care worldwide.

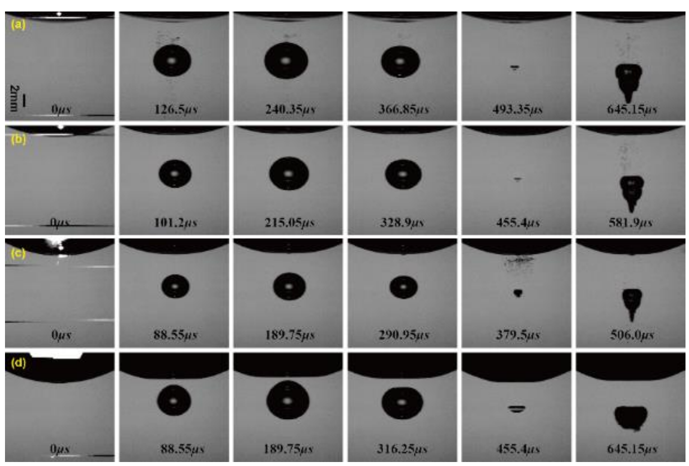

Fig. 3. Laser-induced bubble behaviors near a convex free surface. (a) h/R_{max} =1.977, r_s/R_{max} =8.292, T_c/T_c'=0.924; (b) h/R_{max} =2.125, r_s/R_{max} =5.458, T_c/T_c'=0.938; (c) h/R_{max} =2.152, r_s/R_{max} =5.710, T_c/T_c'=0.948; (d) h/R_{max} =0.977, r_s/R_{max} =4.304, T_c/T_c'=0.897. The scale bar is only valid on the vertical direction due to the image distortion from the cylindrical water flask.

Conclusions

We carried out experimental studies on the bubble dynamics near a convex free surface, which had not been studied previously. In general, the bubble presents similar collapse behavior with the bubble collapses near a flat free surface. But due to the influence of the convex shape of the free surface, some different features appear on the bubble collapse time and the jet strength. Via the bubble collapse time analysis, we found that T_c/T_c' is smaller than 1 when bubble collapses near a free surface. T_c/T_c' increases with h/R_{max} increasing and r_s/R_{max} decreasing. Compared with the bubble collapse near a flat free surface, the longer bubble collapse time near a convex free surface suggests a smaller Kelvin impulse and a milder microjet when bubble collapses. And the focusing of the convex free surface leads to a violent splash on the free surface, which would be further investigations.

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