Surface Jetting Induced by Explosion in Liquid Below an Immersed Bubble

Y. Zhu, G. Zhang, and J. Yang

Abstract The surface jets induced by an explosion below an immersed gas bubble in water are investigated experimentally. Typical phenomena including the bubble evolution and the jet formation are observed through high-speed photography. It is found that the inner jet resulting from the shock bubble interaction is the main cause of the surface jet. The velocity of the surface jet decreases with the initial depth of the bubble, and there exists a maximum bubble depth above which no surface jet occurs.

1 Introduction

An impact loading on a bulk of condensed matter may cause ejection of the matter in the case that defects exist on the surface of or inside the bulk. A typical example is the microjetting phenomenon which constantly occurs as a strong shock wave that reflects from a free surface [1]. The defects can be cavities or dopants. Many have been devoted to studying the jetting phenomenon due to surface defects [2] or surface curvature [3]. The jetting phenomenon due to inner defects is much less recognized, however. To extend the knowledge of the latter, we use a near-surface bubble immersed in water to mimic a single cavity defect in condensed matter and investigate the surface jetting phenomenon originating from it under the load of an underwater explosion.

As a significant part of the phenomenon, the interaction of the shock wave with the bubble, as well as the asymmetrical collapse of the bubble, has drawn plenty of attention for a long time. The collapse of the bubble is generally characterized by the formation of a small but strong inner jet in the direction of the shock wave [4]. The inner jet then penetrates the bubble, whereby the bubble turns into a toroidal shape in the later stage of development. Further impingement of the jet on

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a nearby object surface was found to be a key mechanism of cavitation erosion [5] and extracorporeal shock wave lithotripsy [6]. With such engineering backgrounds, the interaction of the shock-induced collapse with a certain boundary or interface was also of great interest. Varied materials were tested, such as rigid walls [6, 7], thin aluminum films [6, 8], gelatin blocks [6, 9, 10], organic tissues [6], and so on. However, the response of the bubble near a free surface, which is the main concern of the present study, was barely reported. The features of the bubble evolution in this layout and the correspondence between the bubble evolution and the formation of surface jet are still unclear.

The current paper focuses on the interfacial phenomenon induced by an underwater explosion below a shallowly immersed bubble. Sequential images of the flows in development are captured, and the influences of the bubble depth are examined.

2 Experimental Method

The ideal of the experiments is to create a gas bubble in water in a straight vertical tube and then to generate an explosion at the bottom of the tube.

The experimental setup is illustrated in Fig. 1. The main test section is a round glass tube with an inner diameter of 32 mm mounted on a flat, acrylic base. Along the axis of the tube is a small capillary which connects to an empty piston syringe. Bubbles are generated by slowly injecting air into the water. The explosion is generated by an electrical discharge through a thin wire, where the current is sufficiently high to cause the wire to explode. The electrical supply is basically a series circuit which consists of a bank of capacitors, an electric relay controlled by outer signals, and two copper electrodes installed on the base plate for connecting to the exploding wire. In preparation of a test, we charge the capacitors to a certain voltage. Explosion takes place when the relay contacts. The current experiments use a total capacitance of 2000 μF and an initial charging voltage of 200 V.

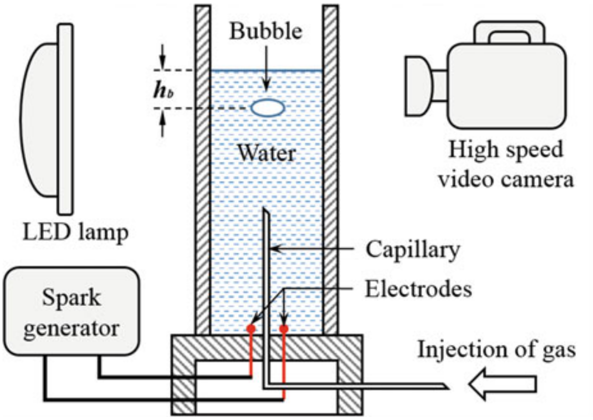

Fig. 1 Schematic of experimental setup

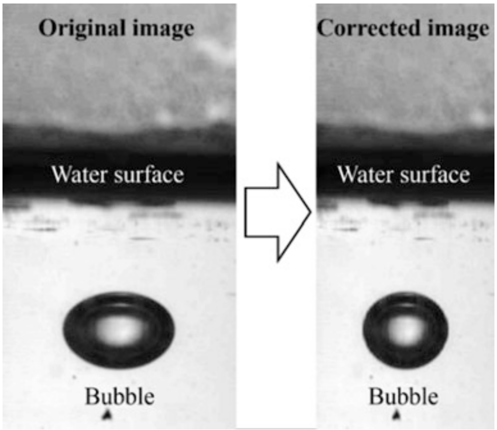

Fig. 2 An example of image correction

The tube is partially filled with water. The total height (or depth) of the water column is fixed as 70 mm for all tests. The head of capillary is about 20 mm below the water surface. In order to suppress the random drifting of the rising bubble, water solution of sodium dodecyl sulfate (SDS) instead of pure water is applied. The signal to trigger the relay is sent by a photodiode which detects the arrival of the bubble. The initial bubble depth, h_b, i.e., the distance between the water surface and the center of the bubble at the moment of explosion initiation, can be varied by adjusting the vertical position of the photodiode. An LED lamp is used to illuminate the test section, and a high-speed camera with a framing rate up to 20,000 fps is used to record the flow.

Because of the optical refraction of the round tube filled with water, the images of the bubbles in water are distorted. The distortion is calibrated using a flat plate with grids on it, based on which the images are corrected. An example of the images before and after the correction is shown in Fig. 2. One may find from the corrected image that the bubble is almost spherical. The diameters of the bubbles are about 2.0 mm.

3 Results and Discussion

The results with different bubble depth are presented. Figures 3, 4, and 5 show the high-speed sequential images of the three typical flows.

A representative case with a medium bubble depth, $h_b = 4.1$ mm, is shown in Fig. 3. When the explosion takes place, it emits light which illuminates the tube (0.1 ms). The whole water column rises at first due to the impulse of the explosion. In the first 0.2 ms, the bubble rises even faster because of the buoyancy caused by the acceleration of the water bulk, after which the main bubble migrates accordingly with the water column. At the same time, the disturbance of the explosion causes the bubble to oscillate periodically with alternative expansions and contractions. This phenomenon is evident in the horizontal direction, whereas, in the vertical direction,

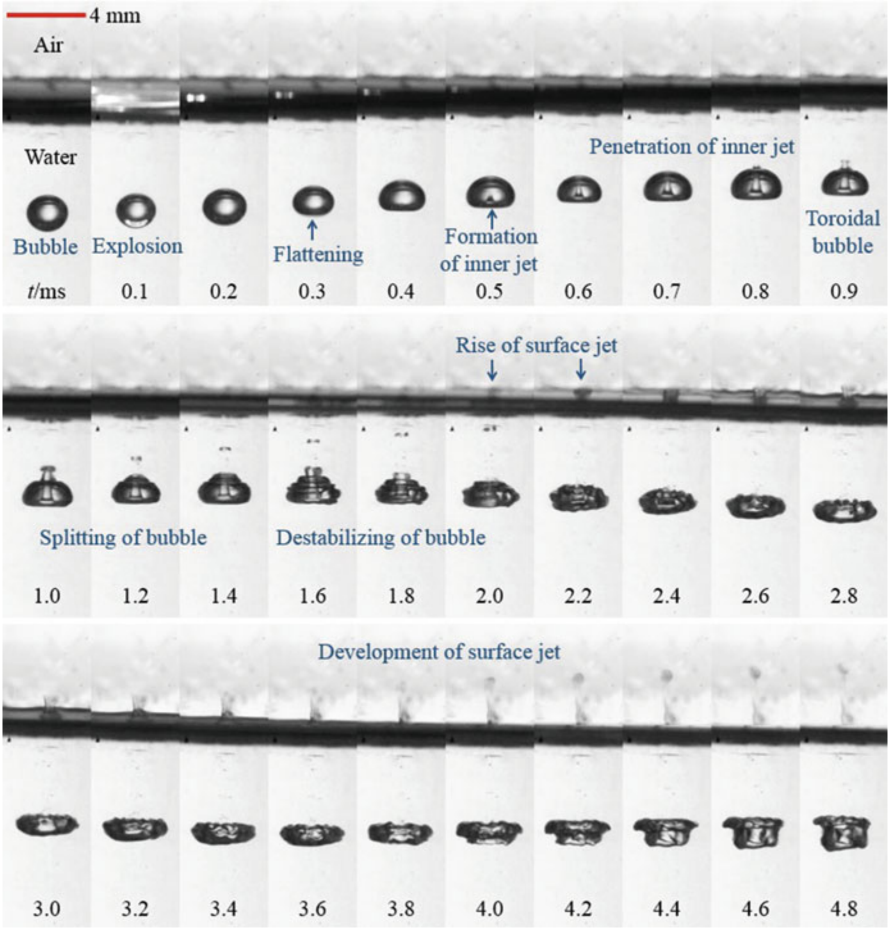

Fig. 3 High-speed sequential images showing the bubble evolution and the development of surface jet with an initial bubble depth of 4.1 mm

it is overwhelmed by the much severer bubble collapse process. The water surface rises to the maximum height at about 2.0 ms and then falls back. The main bubble follows a similar trend.

The vertical collapse of the bubble starts from the side facing the explosion, i.e., the bottom of the bubble in this study. As described in previous investigations [7, 8], the bottom of the bubble flattens at first and then develops an upward inner jet (0.5–0.7 ms). The inner jet is sharp and fast. Penetration of the inner jet further transforms the bubble into a toroidal shape (0.8–1.4 ms). The jet maintains a relatively high speed as it reenters the upper water. A part of the main bubble is entrained by the jet which then rolls up and splits from the main bubble to form a small ring bubble. The ring bubble can be roughly seen as a delayed marker of the jet frontier. When the jet flow reaches the free surface, a surface jet develops (2.0 ms). In this case, the velocity of the surface jet is about 1 m/s.

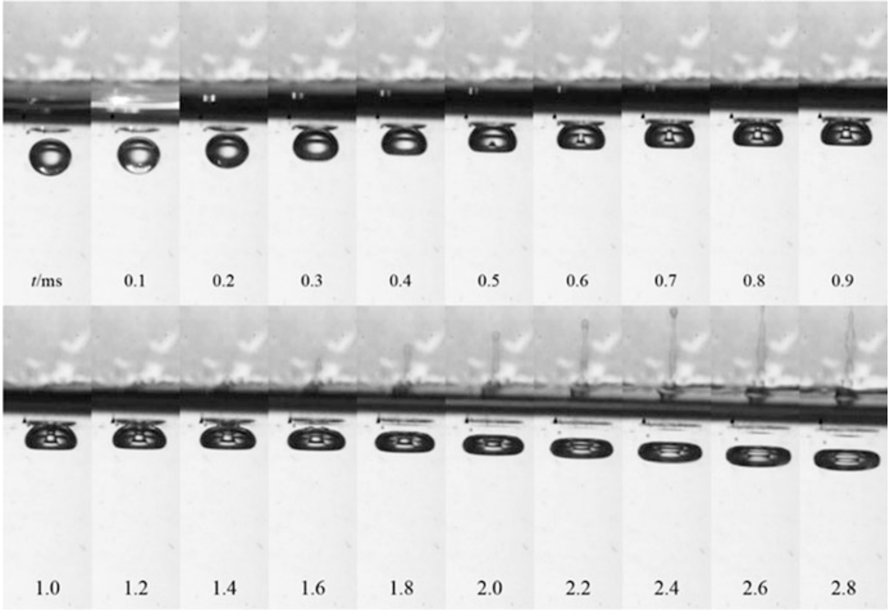

Fig. 4 High-speed sequential images showing the bubble evolution and the development of surface jet with an initial bubble depth of 1.3 mm

Reducing the bubble depth leads to a similar phenomenon. Figure 4 shows the result obtained with an extremely small depth, $h_b = 1.3$ mm. The initial bubble is almost attached to the free surface. After the explosion interacts with it, it actually floats to the surface, as shown in the frames after 0.3 ms. The formation of the inner jet takes place at about 0.5 ms, the same time as the former case. For the distance to the surface is smaller and there is less water in the way of the jet, the surface jet comes into forth earlier than the former case, and the jet velocity is much larger.

Increasing the bubble depth may lead to a different situation on the other hand. Because the strength of the jet flow attenuates when the jet pierces through the rest of the water, there must exist a maximum bubble depth higher than which the jet may not penetrate. Figure 5 shows the result with a bubble depth of 5.2 mm. Although the evolution of the overall water column and the bubble remains similar to the first case, the inner jet seems to fail to reach the free surface, and no surface jet is developed. The separated ring bubble which roughly marks the jet frontier stalls in the middle eventually, despite of the fast rising stage before 2.0 ms.

The experimentally obtained velocities of the surface jets with different bubble depths are summarized in Fig. 4. It shows that the velocity of surface jet decreases with the bubble depth. The critical bubble depth is about 4.5 mm. When the bubble depth is larger than the critical value, the inner jet may not penetrate the free surface, and hence no surface jet occurs (Fig. 6).

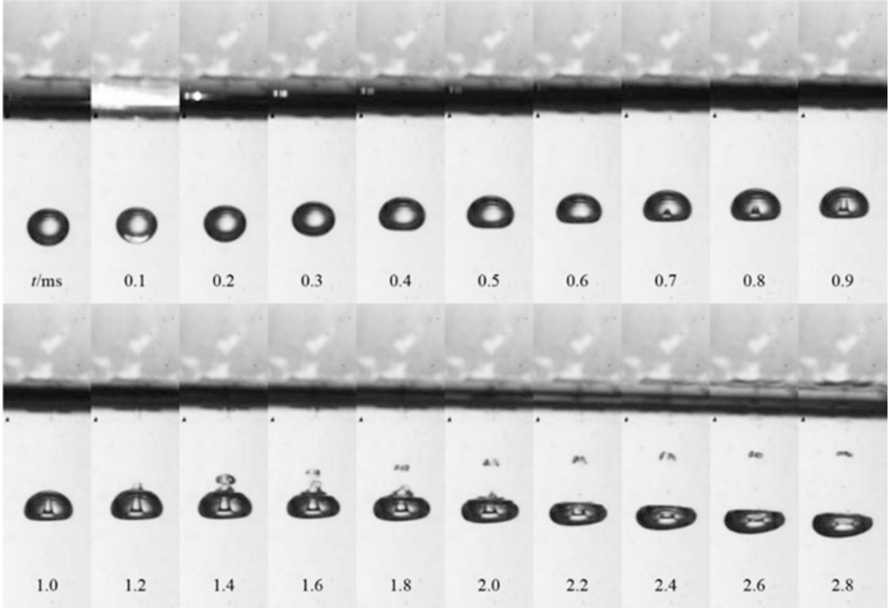

Fig. 5 High-speed sequential images showing the bubble evolution without surface jet with an initial bubble depth of 5.2 mm

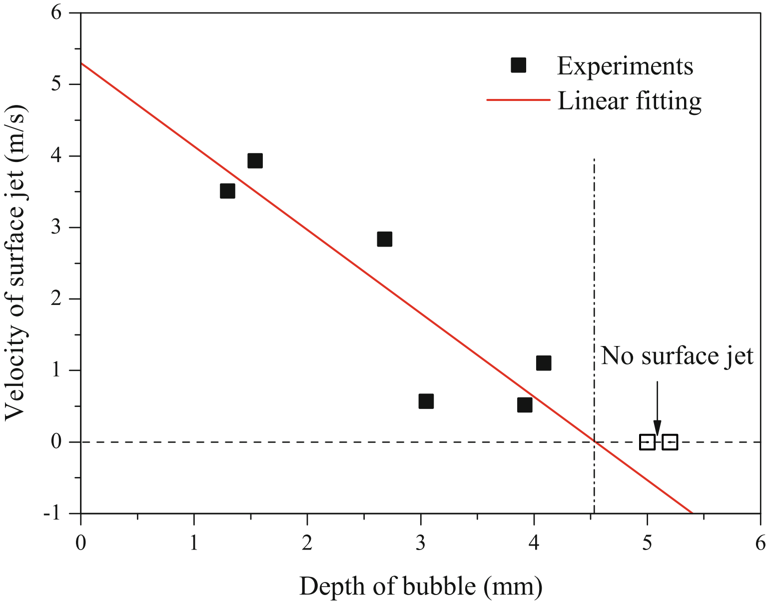

Fig. 6 Velocity of the surface jet varying with the bubble depth

4 Conclusion

The surface jets induced by the interaction of an explosion with a near-surface gas bubble in water were investigated experimentally. The interfacial flow including the bubble evolution and the jet formation was observed by the method of high-speed photography.

It is found that the bubble subsequent to the interaction of an underwater explosion may develop a small but strong jet inside the bubble. It is this inner jet that penetrates through the water column above the bubble and causes a jet on the surface. The velocity of the surface jet decreases with the depth of the immersed bubble, given the bubble size and the explosion energy are fixed. When the bubble is deeper than a certain depth, the inner jet cannot break up the free surface to cause a surface jet.

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