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Comparisons of spark-charge bubble dynamics near the elastic and rigid boundaries

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ABSTRACT

The objective of this paper is to apply experimental methods to investigate the dynamics of spark-induced bubbles in the vicinity of the elastic and rigid boundary. In the experiment, the temporal evolution of the bubble is recorded by the high-speed camera at the 25,000 frames per second, as well as corresponding data such as normalized collapse position, the time of bubble collapse, and the velocity of the high-speed liquid jet. Results are presented for a single bubble generated over the elastic and rigid plates, under a wide range of normalized standoff distance from 0.5 to 3.0. The results show that the high-speed jet emitted by non-spherical bubble collapse near the boundary is one of the important factors to cause the destructive erosion pit. With the increase of the standoff distance, the expansion, shrink, jet formation, and rebound of the bubbles vary evidently adjacent to the different boundary conditions. Compared with the rigid boundary cases, the normalized first collapsed position and the time of bubble collapse are much smaller near the elastic boundary. The formation of the high-speed liquid jet in the neighborhood of the elastic/rigid boundary is founded in two different mechanisms. Furthermore, the normalized maximum velocity near the rigid plate is always larger than that near the elastic plate.

1. Introduction

Energetic bubble dynamics in the vicinity of different boundaries is a classical problem. In the traditional studies, much attention is paid on the mechanism of the cavitation bubble collapse near the rigid boundary and its formation of destructive erosion [1]. Because the occurrence of excessive cavitation bubbles in many industrial systems, such as ship propellers [2], turbines [3] and cryogenic pumps [4], not only cause structural damages [5,6], vibration [7] and noise [8], but also lead to a dramatic decline of operating efficiency [9]. To prevent and even control the cavitation bubbles and its fateful consequences, the materials of the fluid machinery are further developed to the one with significant elasticity, i.e. the composite materials (carbon or glass fiber), which is proved to have an evident effect on the bubble dynamics [10]. In recent years, the investigation of bubble dynamics near the elastic boundary is also significantly motivated by an important role of cavitation bubbles in various medical applications for cancer cell treatment, ultrasonic lithotripsy [11], and targeting drug delivery [12]. However, the challenges about the implementation of the bubbles near rigid/elastic boundary still stand, since its mechanism has not yet been fully elucidated.

The initiation of cavitation bubbles typically begins that the local pressure is below the saturated one. Due to the pressure variations between the inner bubble and surrounding liquid, the cavitation bubble presents a series of behaviors with harmfulness, such as expansion, shrink, collapse, and rebound. Rayleigh was the first one to theoretically analyze the cavitation phenomenon occurred on the ship propellers with the spherical bubble hypothesis, namely Rayleigh equation [13]. Then, a great deal of work is performed to perfect the theory, including the efforts provided by Plesset et al. [14]. However, massive numerical and experimental investigations demonstrate that bubbles stay the main feature of a non-spherical collapse, especially, affected by acoustic wave [15,16], shock wave [17] and gravity [18,19], near rigid/elastic boundary [20], and adjacent to the free surface [21]. The asymmetrical bubble collapse and formation of a jet are proposed by Kornfeld and Suvorov [22], who considered that asymmetrical collapse is a result of a pressure gradient around the bubble. Due to a different direction of pressure gradient near the various boundaries, the high-

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speed jet of the bubble is founded to impact directly towards the rigid boundary and be repelled away from the free surface. As for the elastic boundary, Brujan et al. [23,24] employed the high-speed camera technique to experimentally investigate the interaction of a laser-induced cavitation bubble with an elastic membrane. They found that bubble presents the "mushroom-like" bubble during the stage of the shrink phase, caused by the deformation and rebound of the elastic boundary.

Due to having the same direction with high-speed jet, the bubble migration is demonstrated that they also migrate towards rigid boundaries and away from free surfaces [25]. To quantitatively describe the relationship between bubble migration and boundary condition, Blake et al. [26,27] first developed the theory of Kelvin impulse by using potential flow and the image method, which can well predict the bubble motion near the rigid boundary, free surface and inertia wall. However, the theory is not a good predictor for elastic boundary condition, because it does not include the elastic modulus for boundary. In the research about bubble migration vicinity of the elastic boundary, a valuable and interesting phenomenon was founded that bubble present neutral collapse, which do not move towards or away the boundary. Because the neutral collapse of bubble does not cause extremely destructive action, many researchers paid their attention to neutral collapsing bubbles by changing the flexible material coated on the surface of the fluid machine to prevent the cavitation erosion. Shima et al. [28] and Tomita et al. [29] investigated the behaviors of neutral collapsing bubbles in the neighborhood of the sandwich structure, which is considered as a kind of elastic composite material. Their works further verified the validity of the research thought discussed above, and broaden the knowledge of bubble dynamics near the composite boundary.

Extensive experiments on dynamic behaviors of bubble collapse near the different boundary have been reported in the works of Blake et al. [30], Zhang et al. [31], Lauterborn et al. [32] and Klaseboer et al. [33]. In those works, they usually adopted focused laser light or electric sparks to generate a bubble and high-speed photography to record temporal evolution of bubble shape. Historically, dynamical properties of the bubble is founded to be significantly influenced by a normalized standoff parameter γ, defined as the distance between the initial location of the bubble and the boundary scaled by the maximum bubble radius. As for the measurements of the boundary, Brujan et al. [23,24] used the elastic modulus to describe the elastic membrane (the mixture of PAA and water). On the other hands, boundary inertia m^* and boundary stiffness k^* are introduced as the quantitative elastic factors to describe an elastic boundary, and the latter one is first employed in the works of Gibson & Blake. Besides, the environment factors, such as the combination of Bjerknes force and buoyancy force, are also considered by Zhang et al. [34].

In present work, a systematic investigation of the effect of elastic/rigid boundary on the dynamics of spark-charged bubbles is carried out for a range of normalized standoff $\gamma = 0.5$–3.0. The detailed shape variations about bubble oscillation, as well as high-speed liquid jet, is analyzed. The objective of this paper is to (1) demonstrate the energetic and destructive behaviors of the bubble near the boundary, especially for the high-speed jet; (2) compare the dynamic characteristics of the bubbles near the different boundaries, namely the rigid and elastic plates.

2. Experimental setup

2.1. Bubble generation apparatus

The experiment is carried out in cuboid-shaped water tank with a height of 1000 mm and a square bottom for length of 500 mm, as shown schematically in Fig. 1(a). To get better photography and illumination, the water tank is made of transparent glass, which is partially filled with sufficiently degassed water. The temperature of water in the tank is maintained at 25 °C. The bubble is generated by Joule heating at the connect point of the electrodes by the discharge of a 6600 μF charge to 800 V, as shown in Fig. 1(a). Upon discharging, the copper electrodes with 0.25 mm diameter, evaporate the water at the connect point, emit extremely high temperature, and create a bubble with rapid expansion, namely a spark-induced bubble. The main cause of bubble generation results from vapor gas caused by high temperature, rather than the hydrogen and oxygen bubbles caused by ionization of water. In addition, the time span of DC voltage discharge is so short that the time about ionization of water can be ignored, compared with the heat transfer. To quantitatively describe a bubble in infinite fluid, the maximum radius of a bubble is defined as

$$R_m = \sqrt{A/\pi} \tag{1}$$

where parameter A is the maximum area of the bubble. It is found that the center of initial bubble is always located at the connected point. So it is possible to precisely control the initial position of the bubble. In present experiment, the bubble is generated over the boundary, and the detail information about the relative position between a bubble and boundary is shown in Fig. 1(b). The both ends of the boundary are tensely clamped by a holder, and the boundary is completely immersed in water during the experiment. As shown, the dimensionless standoff distance between a bubble and boundary is defined as

$$\gamma = \frac{L}{R_m} \tag{2}$$

where parameter L is the distance from the bubble center to the boundary at inception.

2.2. High-speed photography

The temporal evolution of the bubble dynamics is recorded with a high-speed camera (Phantom V12.1) operating at 25,000 frames per second. To ensure the sharpness of bubble outline and its inner structure, the exposure time of each frame is set as 30 μs. Diffusive illumination is provided by a continuous light source at one side of the water tank, which is opposite to the high-speed camera, as shown in Fig. 1(a). In order to get a better light distribution around the bubble, a piece of glass is placed between the camera and the light source. The high-speed camera and copper electrodes are almost synchronously triggered, and the maximum error in delay time for both is approximately 0.067 ms, which is small enough compared to the bubble periods.

2.3. Elastic/Rigid boundary

In the experiment, two kinds of materials are investigated, namely, carbon fiber composite and standard aluminum samples, as shown in Fig. 2. They are processed with the same length of 120.0 mm and width of 80.0 mm, but not the height. In order to make the carbon fiber composite to be easily yielding, it is machined with the height of 0.5 mm, which is considered as an elastic boundary. And the aluminum sample is about 20.0 mm in height, which is considered as a rigid boundary referred from classic work of Brujan et al. [23,24] and Hung et al. [35]. The elastic properties of the elastic boundary samples are strained by a universal test machine. The boundary is quantified by determining the stress-strain relation and calculating the elastic modulus, E, as the slope of the stress-strain curves. Under compression, the boundary sample brakes at a stress value of 2750 N. The detailed information including size, elastic modulus, and density can be founded in Table 1.

3. Results and discussion

3.1. Typically behavior of the individual bubble

Fig. 3 shows the typically temporal evolution of individual bubble