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The impact of particles on the collapse characteristics of cavitation bubbles

Weilin Xu[a,*], Yalei Zhang[a], Jing Luo[a], Arong[b], Qi Zhang[a], Yanwei Zhai[a]

[a] State Key Laboratory of Hydraulics and Mountain River Engineering, Sichuan University, Chengdu 610065, China
[b] School of Civil Engineering, Hefei University of Technology, Hefei 230000, China

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ABSTRACT

Water-sand two-phase flows often pass through the water passages of hydraulic and hydropower projects. Aided by high-speed photography, the impact on the collapse characteristics of the cavitation bubbles of particles was researched at the mesoscopic level in this paper. The experiments yielded the following results. (1) Particles impact the form and direction of collapse of cavitation bubbles. The significance of the impact increases as the particle size increases. (2) The impact of the dimensionless distance and size ratio between the particle and the cavitation bubble on the direction of collapse of the cavitation bubble has a quantitative relationship. (3) The impact of the dimensionless distances between the particle and the wall and the cavitation bubble on the direction of collapse can be divided into five regions. Particles alleviate cavitation and protect the wall by changing the direction of collapse of the cavitation bubble under some conditions. These conclusions are theoretically important for controlling cavitation damage in water-sand two-phase flows.

1. Introduction

Cavitation erosion damage extensively occurs in hydraulic projects and seriously threatens the security of the hydraulic projects themselves and the downstream life assets. Therefore, research on cavitation erosion is extremely important. At present, there has been a large amount of research on cavitation erosion, which has mainly centered on the mesoscopic level, and a few scholars have focused on the interactions between cavitation bubbles, the particles and the wall. Arndt (2012) and Kawakami et al. (2008) conducted an overview of cavitation erosion at the meso-level and discussed numerous aspects such as numerical modeling, hydrofoil shape, surface quality characteristics and water quality. Jet formation and shock waves (Lauterborn and Ohl, 1997) in the region are the main causes of cavitation damage. A detailed experimental study had been made to clarify the mechanism of impulsive pressure generation from a single bubble collapsing in a static fluid, this is the most essential and important research task concerned with cavitation damage (Tomita and Shima, 1986; Vogel et al., 1989; Philipp et al., 1998). The maximum amplitude and the duration of the shock wave emitted during bubble cloud rebound increase with increasing the maximum radius of the cloud and, at equal maximum radius, are larger than the corresponding values obtained in the case of individual spherical bubbles (Brujan, 2012). Both the velocity of the liquid jet developed during bubble collapse and the maximum pressure of the shock wave emitted during bubble rebound show a minimum for $\gamma=1$ and a constant value for $\gamma > 3$ (Brujan, 2012). Li et al. (2013) found that a cavitation bubble did not collapse in the region near the wall until the ratio of the water head loss over the convex body height was greater than 20.

At the macroscopic level, research has mainly examined the critical condition of cavitation erosion (Zhang et al., 2015), the number of water stream cavitation (He et al., 2015), cavitation noise and cavitation damage (Paik et al., 2011). The avoidance of cavitation erosion is mainly based on optimizing the shape of the water passage (Xu et al., 2015), air entrainment (Qin et al., 2006; Wu and Chao, 2011), controlling the flatness (Kumar et al., 2014) and increasing the intensity of materials (Hattori and Ishikura, 2010). At the meso-level, the interactions among the cavitation bubble, the free fluid surface and air bubbles (Li and Rong, 2011) have recently become the focus of new research. An oblique jet (Zhang et al., 2009) will be formed when a cavitation bubble close to an inclined wall collapses. Aghdam et al. (2012) found that a bubble in its collapse stage takes on a ‘mushroom’ shape and then splits into two small bubbles. Chahine (1982) found that the formation of a reentering region (microjet or constriction) occurs on the part of the bubble which has the most freedom of motion. The motion of a cavitation bubble might be impacted by an air bubble and a rigid boundary. In addition, the impacts of an air bubble and a boundary (Xu et al., 2010) might combine with one another. Air entrainment is the most frequently used method for alleviating cavitation bubbles. Luo et al. (2013) found that the low pressure formed in the opposite direction to the cavitation bubble micro jet caused the air bubble in the low pressure field to be stretched into a

* Corresponding author.
E-mail address: xuwl@scu.edu.cn (W. Xu).

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step-like shape. Considering that a cavitation bubble's life cycle is extremely short and its size is extremely small, research on pressure changes, temperature effects and the distribution of flow fields can hardly be tested experimentally. Therefore, many researchers use numerical simulations to reveal the mechanisms of cavitation erosion phenomena (Lauer et al., 2012; Peters et al., 2015; Kim and Lee, 2015). In ultrasonics, cavitation erosion and cavitation pits (Bai et al., 2009; Franc et al., 2012; Momma and Lichtarowicz, 1995; Dular et al., 2013) in materials are accorded widespread attention.

Water-sand two-phase flows often pass through the water passages of actual projects. Considering the existence of particles, research on the collapse characteristics of cavitation bubbles is extremely rare. Huang and Li (1992) researched still and flowing water that contained particles and found that two cavitation bubbles will induce a particle when they collapse. Particles can lower a cavitation bubble's collapse pressure on a solid wall (Huang and Li, 1993). In moving water, the life cycle of the cavitation bubble is shortened as flow velocity increases (Tian et al., 1999). Those studies of water-sand two-phase flows employed macroscopic concepts. In this study, the impact on the collapse characteristics of the cavitation bubble of particles with different sizes and distances was researched.

2. Experimental approach

The experimental systems included a high voltage pulse bubble generation system, a high-speed dynamic acquisition and analysis system and a light source. The high voltage pulse bubble generation system was constructed by the high voltage laboratory of Sichuan University. The power supply was connected to 220 V alternating current. After the voltage was increased by the voltage regulator and the transformer and was changed by the protection water resistance and silicon stacks, the charge energy was stored in a 0.25 μF capacitor. When the energy stored in the capacitor reached a certain value, the discharging needle plate in the air was punctured. In addition, the electrodes connected to the needle plate and placed in twice deionized water also broke down. This was a single-pulse high-energy discharge, the puncturing energy of which formed a cavitation bubble in the center of the electrodes. By regulating the values of the changeable graphite resistance in the circuit, the sizes of the cavitation bubbles were adjusted. A MotionPro Y3-classic (Integrated Design Tools Inc., USA) high-speed recorder was used, which was matched to a Nikkor Lens. An LED light with even luminance was used as a supplemental light source. The arrangement of the experiment systems is shown in Fig. 1(a).

The research mainly focused on the meso-mechanism of the collapse of a cavitation bubble when particles of different sizes exist at different distances. A cavitation bubble is generated in a glass container (30 cm*15 cm*5 cm), with a temperature of 20 ℃ and atmospheric pressure of 101.5 kPa. Furthermore, deionized water was used in this experiment so as to reduce the impurity as low as possible. Container was cleaned with ultrasound beam before the experiment so as to reduce the gas trapped in crevice. The sizes of the cavitation bubbles were regulated by changing the values of the resistances in the circuit and the gap between the discharge needle plates. The spherical particles used in the experiment, the roughness of which was 0.0079. Four particle radii were used: 1.0 mm, 1.5 mm, 3.0 mm and 5.0 mm. The positional relationship between a cavitation bubble and a single particle are shown in Fig. 1(b).

The dimensionless distance between a cavitation bubble and a particle is defined as

$$\gamma = L/(R_C + R_P)$$

In the above formula, L is the shortest distance between the cavitation bubble and the particle's surface; R_C is the largest radius of the cavitation bubble; R_P is the particle's radius. For the dimensionless distance between the bubble and the particle, the particle's radius R_P is introduced because of the different curvatures of the particles with different sizes. However, in the experiments where cavitation bubbles and the particles keep close, cavitation bubbles completely develop along the surface of the particles.

To study the impact of the particle and the wall on the cavitation bubble, a particle with a radius of 1.5 mm was placed on the left side of the cavitation bubble, and a wall was erected on its right side. The spatial relationships of the positions of the particle, wall and cavitation bubble are shown in Fig. 1(c). Similarly, the dimensionless distance between the particle on the left side and the cavitation bubble is defined as

$$\gamma_P = L_P/R_C$$

The dimensionless distance between the wall on the right side and the cavitation bubble is

$$\gamma_W = L_W/R_C$$

In the above formulas, L_P is the shortest distance between the cavitation bubble and the particle's surface; R_C is the largest radius of the cavitation bubble; R_P is the particle's radius; and L_W is the distance between the cavitation bubble's center and the wall. The units of the parameters are mm.

The actual size and pixels in the picture were determined using a photographically calibrated ruler. The actual distance represented by the unit pixel was calculated to determine the characteristic parameters of the cavitation bubbles in the picture.

3. The impact of particles on the collapse characteristics of the cavitation bubble

3.1. The impact of particles on the collapse characteristics of cavitation bubbles of different sizes

Three groups of cavitation bubbles of different sizes were selected to discuss the impact of particles on the collapse characteristics. In Fig. 2, the particles' radii are 3.0 mm. In groups A, B and C, the maximum radius of the cavitation bubble increased in turn.

In group A, the cavitation bubble's size was very small, with a radius R_C=2.33 mm, and the cavitation bubble expanded, contracted, collapsed, and rebounded again in the original place. In group B, the size of the cavitation bubble's size increased, and the radius was R_C=3.08 mm. There was a slight transformation on the end closer to the particle. In the contraction stage, it was pulled to form an oval under the attraction of the particle. In the end, it collapsed towards the particle. In group C, the size of the cavitation bubble continued to increase, and the radius was R_C=3.80 mm. At that time, when the cavitation bubble expanded to the maximum radius, it came into contact with the particle. Later, in the contraction stage, it remained in contact with the particle. Before collapse (C8), the cavitation bubble was attracted and pulled into a tabular shape. Later, the cavitation bubble formed a water drop shape that was large on the left side and small on the right side. It then collapsed towards the particle (C9).

The experimental results of increasing the radius of cavitation bubbles in Fig. 2 show that particle of the same size shows stronger attraction to cavitation bubbles of larger radius, while the attraction will be alleviated with the decrease of the maximum radius of cavitation bubbles. The expansion of cavitation bubble drives the surrounding water to flow outward and its contraction makes the surrounding water quickly fill the released space by it. The more the radius of cavitation bubble expands, the bigger the space that the surrounding water needs to fill than the less expanded radius of the bubble. However, in condition of the same distance around the particle of the same size, water outside bubbles of the less expanded radius is weakly blocked by particle than water outside bubbles of more greatly expanded radius that also need more water to fill the released space. Meanwhile, water away from the particle shows a remarkable asymmetry when the