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On the internal collapse phenomenon at the closure of cavitation bubbles in a deceleration process of underwater vertical launching

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ABSTRACT

In a typical experiment of underwater vertical launching, cavitation bubbles are generated in the low-pressure regions of the vehicle in the water and collapse when the projectile runs through the free surface. A new internal collapse phenomenon that advances from the tail to the head of the axisymmetric projectile has been observed in an underwater launching experiment: it differs from usual collapse phenomena and is rarely observed in water tunnel tests. During this process, cavities shrink upstream quickly, producing high impact pressure, and fast re-entry jets form, inducing strong instabilities. Analysis indicates that this phenomenon is relative to rapid changes in vehicle speed and cavitation number. Thin cavitation bubbles are generated when the vehicle accelerates rapidly, and then vapor condenses rapidly and forms an additional body force at the closure of the cavity in the deceleration process. As a result, large velocity directed to the wall to the wall is generated, and the liquid water layer continues to move toward the wall and impact as an internal collapse. Numerical simulations are also performed on the decelerating effect on the cavity evolution. Results indicate that the pressure increase is a critical factor, which results in a nonlinear change in the cavity length. In proportion to the enlargement of the deceleration, the cavities shorten more quickly.

1. Introduction

When objects run in water at high speed, cavitations occur in low-pressure regions, where part of the liquid water changes into vapor. Cavitation is one of the most important and complicated phenomena in hydrodynamics. In particular, when cavitation bubbles collapse, high-pressure pulses are generated, exerting major impact and even causing damage on the structures of vehicles [1].

Bubble collapse has been intensively investigated theoretically, experimentally, and numerically in the past, including the dynamics of single sphere bubbles [2–5], non-sphere bubbles [6–9], and interaction among a limited number of bubbles [10–16]. However, very large scale computation involving the solution of Navier–Stokes equations is required to determine the behavior of many bubbles [17]. Simplified models of bubble clusters and bubbly flows have also been established and used to identify various mechanisms of flow behaviors [18–20].

In applied research on hydrodynamics and ocean engineering, the collapse of bubble clusters that involve a huge number of bubbles is also an important issue. For example, cavitation bubbles collapse when vehicles are launched through the free surface of the water to open air [21], and bubble dynamics is also an important issue in research on underwater explosion [22,23]. Moreover, the instabilities at cavitation closures are usually prominent in cloud cavitations with quasi-periodical breaking-off and shedding [24,25]. Observations show that the shedding cavitation cloud may collapse at the cavitation closure, and this kind of collapse is closely related to the instability of cavitation bubbles [26–29].

Given the strongly unsteady behavior of cavitating flows, the variation in the velocity is an important influencing factor on the evolution of cavitating bubbles. Some researchers have studied the changes in the shape of natural supercavitation under various decelerating conditions using numerical methods [30–32]. Chen et al. [33] numerically and analytically investigated the development of cavitation bubbles around submerged vehicles with decelerating navigation and indicated that the cavity is induced to collapse by the deceleration after fluctuation. These aforementioned numerical results are mostly similar in terms of their qualitative characteristics. However, the associated experimental results available in the literature are very limited because of the limitations in water tunnel and other test methods. As a consequence, numerical results are also lacking in rigorous validation.

In the present study, an internal collapse is observed in a vertical underwater launch experiment without bubble shedding. The

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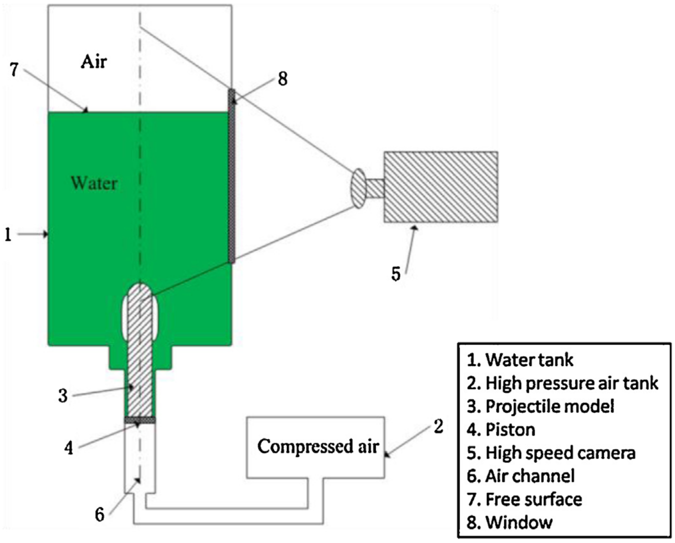

Fig. 1. Schematic of the experiment system.

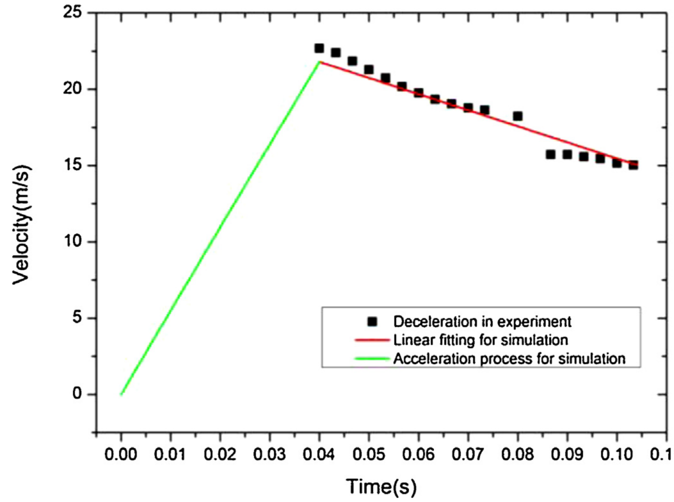

Fig. 2. Projectile speed in the launch process. The black solid squares represent the speed of the projectile by conducting pixel analysis on the experimental results. The red curve represents the linear fitting of the experiment results, while the green curve represents a linear estimate of the speed in the acceleration process. The speed values shown in the green and red curves are combined and used as the speed condition in the basic numerical simulation (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

bubble collapses at the closure and is propagated reversely and quickly upstream. The mechanisms and influence of the internal collapse are analyzed. Furthermore, numerical simulations are performed to study the effects of speed change by varying the deceleration of the projectile. The present work is organized as follows: Section 2 presents the experimental setup, numerical methods, and relevant flow parameters. Section 3 focuses on experimental observations, in which the overall evolution of the cavitation patterns in the whole launching process, the rapid cavity shortening phenomenon in the internal collapse process, and the strong re-entry jet induced by the collapse are described. Section 4 discusses the mechanism of the internal collapse. Section 4.1 identifies the fast acceleration and deceleration of the projectile as the main cause of the internal collapse, and Section 4.2 further examines the effect of deceleration on the variation of the cavity shape, along with numerical results. Section 5 summarizes the major conclusions of the study.

2. Experimental and numerical methods

2.1. Experimental setup

To investigate the underwater launch problem, a small-scale vertical underwater launch system is established, as shown in Fig. 1. The measuring equipment used includes pressure probes to obtain the air pressure after decompression by vacuum pump and temperature probes to obtain the water temperature.

In the launch experiment, the piston is pushed by compressed air and propels the projectiles to accelerate and move vertically. The cavitation bubbles generated in the low-pressure regions around the shoulder of the projectiles evolve unsteadily and collapse after exiting the water. The projectile model is hollow and made of stainless steel. The equivalent density of the model is similar to liquid water to avoid the large influence of the forces of gravity and buoyancy. The basic launch conditions of the typical experiments are listed in Table 1.

Table 1
Basic launch parameters.

Water depth	1.185 m
Air pressure	40 KPa
Water temperature	19.2 °C
Fastest measured speed of projectile	21.8 m/s
Frame rate of high speed camera	6000 fps
Projectile diameter	70 mm
Projectile length	500 mm
Projectile mass	1.9 kg

The projectile speed varies throughout the whole process. In the observed part, the speed curve can be calculated as shown in Fig. 2 by image processing and is approximately linear. For the acceleration part in the launch tube, the movement of the projectile cannot be observed. Assuming that the high-pressure gas expands uniformly, the pressure on the piston surface can be conducted by the volume ratio of the gas tank and tunnel. Subsequently, the projectile speed in the accelerating process is estimated as shown in Fig. 2.

2.2. Numerical methods

To simulate the motions and phase change of liquid water and vapor, the mixture/multiphase flow equations are adopted based on the third type of method mentioned in Section 1. The continuity and momentum equations of the mixture of liquid water, vapor, and non-condensable air are established as

$$\frac{\partial}{\partial t}(\rho_m) + \nabla\cdot(\rho_m \vec{v}_m) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho_m \vec{v}_m) + \nabla\cdot(\rho_m \vec{v}_m \vec{v}_m) = -\nabla p + \nabla\cdot[(\mu_m + \mu_t)(\nabla\vec{v}_m + \nabla\vec{v}_m^T)] + \rho_m \vec{a} + \rho_m \vec{g} \tag{2}$$

where p is the mixture pressure, ρ_m is the mixture density, $\vec{v}_m$ is the mixture velocity vector, and $\vec{g}$ is the gravitational acceleration. $\vec{a}$ is the acceleration of the flow field and is calculated by $\vec{a} = -\dot{\vec{v}}$, where $\dot{\vec{v}}$ is the acceleration of the projectile model. The laminar viscosity μ_m is defined as the density-weighted average of the three components. μ_t is the turbulent viscosity closed by the RNG k–ε model. The mixture density ρ_m is defined by

$$\rho_m = (1-\alpha_v)\rho_l + \alpha_v \rho_v \tag{3}$$

where α_v is the component volume fraction of vapor, and ρ_v and ρ_l are the component densities of the vapor and liquid components, respectively.