Dynamics of cylindrical cavitation bubbles in a tube: a study using the tube-arrest approach

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Abstract: Large cavitation bubbles can cause severe damage during transient processes in hydraulic systems. Here, we summarize our recent work [1] where comprehensive criteria were proposed to predict the onset of large cylindrical cavitation bubbles in a tube. The criteria consist of two cavitation numbers and are validated by experiments using a modified tube-arrest apparatus. The findings in the current work can be useful to alleviate losses induced by large cavitation bubbles forming water column separation.

Keywords: Cavitation; Acceleration；Bubble dynamics; Tube-arrest, Water column separation

1. Introduction

The formation and collapse of cavitation in a hydraulic system can produce large pressure changes. An extreme example is the liquid column separation in a flow passage induced by intense transient processes (e.g., the rapid closure of a valve in a pipeline, and the load rejection process in a hydraulic turbine system). In such transient processes, the large acceleration of the bulk fluid and the violent pressure change potentially create cavitation. When a cavitation bubble grows to the size of its container, it is possible to separate the water column, and subsequently results in a significant transient pressure increase with the rejoining of liquid columns [2,3]. The appearance of these large cavitation bubbles in hydraulic pipelines can cause catastrophic destruction and result in casualties and substantial economic losses [4,5].

Previous studies regarding water column separation and large cavitation bubbles mainly focused on the propagation of pressure wave propagation in pipelines. It is well known that the amplitude of the pressure surge is affected by the oscillation period of the cavitation bubble and its size, which are decided by operating factors (e.g., the initial flow velocity [6] and pressure differences in the system [4]). Besides the studies on column separation based on physical and numerical models of hydraulic systems, the 'tube-arrest' method provides a low-cost equivalent approach to produce transient cavitation bubbles [7,8]. In a tube-arrest setup, bubbles with sizes comparable to the tube diameter (i.e., forming a full liquid column separation) could be produced after the liquid-filled tube is arrested by a stopper. Studies showed that the size of the cavitation bubble could be affected by the initial velocity of the tube [7,8]. However, the evolution of a large cylindrical cavitation bubble, as well as the cavitation onset criteria in a transient process still remains unclear.

In this paper, we produce large transient cavitation bubbles using a modified tube-arrest apparatus. This apparatus can decouple flow velocity and acceleration to perform systematic experiments to validate the theoretical results. Based on the setup, cavitation bubbles with various sizes have been observed and further analysis on the onset criteria of large cavitation bubbles is presented in the following sections.

2. Materials and Methods

Figure 1 shows the modified tube-arrest set-up. An acrylic tube filled with water to different heights is driven upwards by stepping on the actuator until the top of the tube is arrested by the stopper. Purified

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water used in the experiments has been degassed by boiling before injecting into the tube after cooling. The acceleration a is decoupled from the velocity u_0 by attaching different buffer materials to the bottom of the stopper. The bubble length L and impact velocity u_0 are measured from the calibrated high-speed images. The acceleration a was measured by an accelerometer attached on the tube. For all the tests, u_0 varies from 1.0 to 6.0 m·s^{-1}, and a lies in the range of from -98 to 23,906 m·s^{-2}. More details about the experiments can be found in Xu et al. [1].

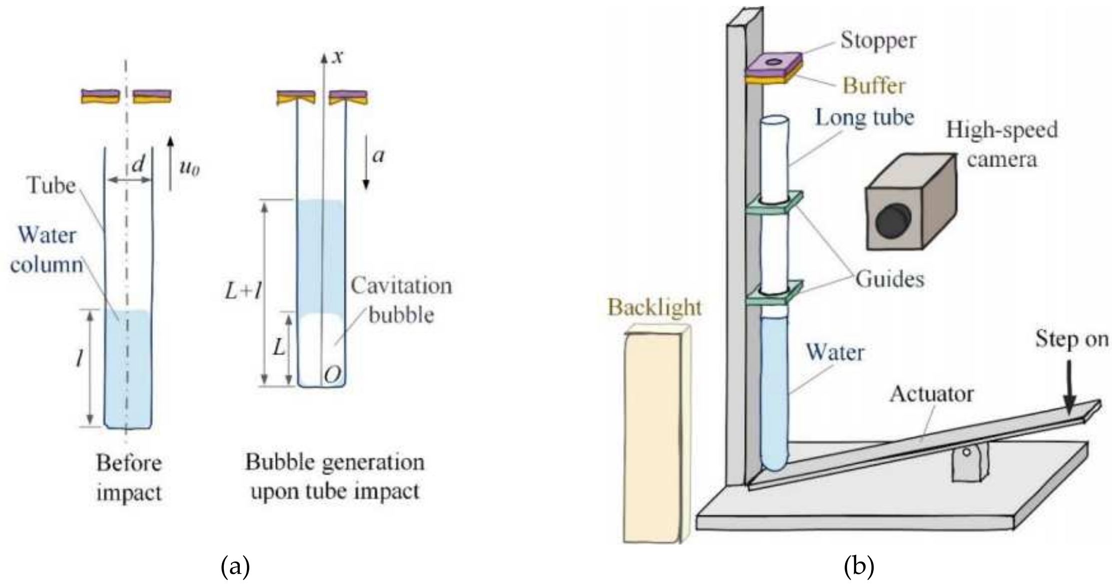

Figure 1. Experimental setup. (a) Cavitation bubble generation process by the tube-arrest principle and major parameters (dimensions not to scale); (b) Schematic of the modified tube-arrest apparatus.

3. Results

In figure 2, we show typical high-speed images of a large cavitation bubble generated at the tube bottom. Initially (0–3.38 ms), the bubble grows to a hemisphere until its diameter approaches the inner diameter of the tube. The bubble then grows along the tube and develops into a large cylindrical bubble to its maximum length $L_{max} = 31$ mm (at 3.38–18.38 ms). After the full water column separation, the bubble comes to the first collapse stage (at 18.38– 32.88 ms), and subsequent decaying oscillation lasts until the bubble eventually disappears.

We observe that $L_{max} > d$ is the condition to guaranteed water column separation for most cases and we address such a cavity 'large cavitation bubble' hereafter. Figure 3 summarizes the experimental results of nondimensional maximum bubble length $L^*_{max} = L_{max}/d$. The results are first presented in a dimensional u_0 versus a diagram as shown in figure 3(a). No distinct trend about how the bubble size are distributed can be found on this diagram. This indicates that the large cavitation bubble onset cannot be predicted directly using either u_0 or a. Instead, we show here that the onset of large cavitation bubbles is controlled by two non-dimensional parameters (as shown in figure 3(b)).

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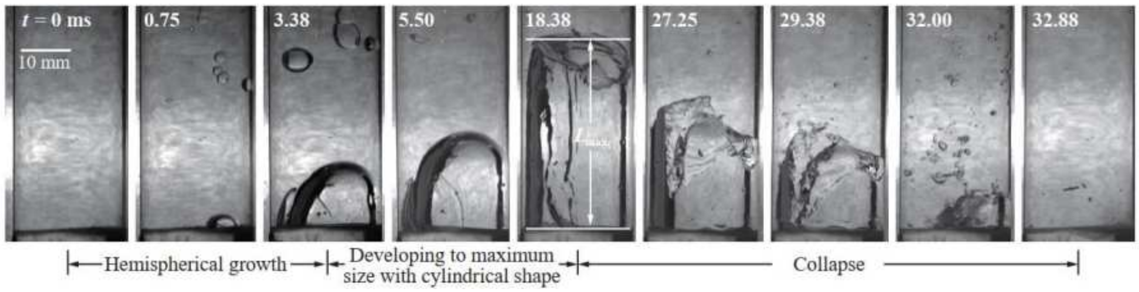

Figure 2. High speed images of a typical large cylindrical cavitation bubble formed at the bottom of the tube. $t = 0$ ms indicates the moment of tube impacting upon the stopper.

The first parameter is a cavitation number proposed by Pan et al.: $Ca_1 = \frac{p_r - p_v}{\rho a l} \approx p_\infty / \rho a l$, where p_r is the reference pressure and p_v is the saturated vapor pressure of the liquid [9]. In the current experiments, $p_\infty \approx p_r \gg p_v$ is the atmospheric pressure. This cavitation number applies to transient processes where the pressure drop due to liquid acceleration is much greater than that of the flow velocity, which is the case in our tests. By this criterion, $Ca_1 < 1$ predicts cavitation onset due to acceleration.

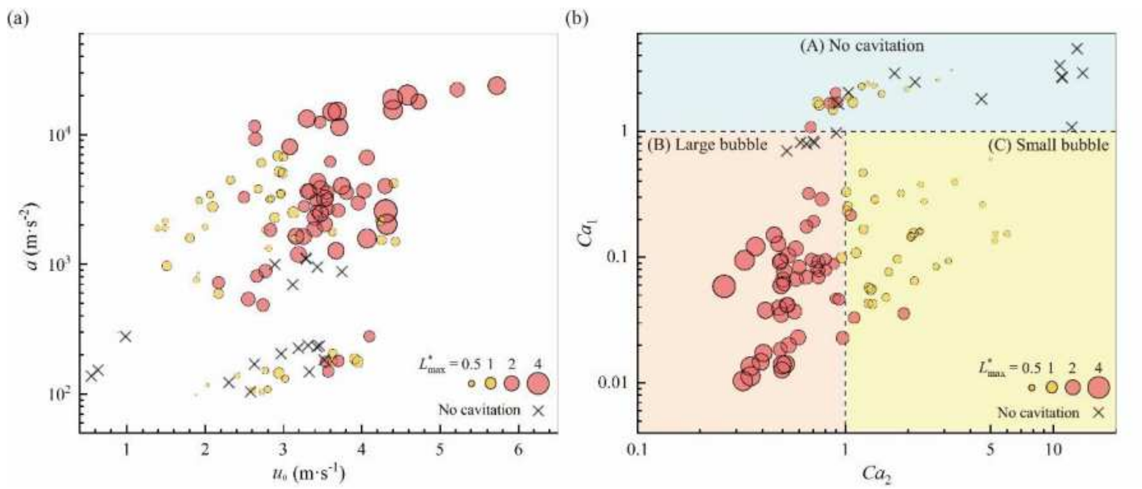

Figure 3. Dimensionless maximum bubble length L^*_{max} on (a) u_0 vs. a and (b) Ca_2 vs. Ca_1 phase diagrams, respectively. For $L^*_{max} \leq 1$ (small bubbles), the circles are filled in yellow. For $L^*_{max} > 1$, the circles are filled in red indicating large cavitation bubbles. (b) is divided into 3 regimes by $Ca_1 = 1$ and $Ca_2 = 1$. Regime A ($Ca_1 > 1$) represents the no cavitation zone. The sub-domain of $Ca_1 < 1$ indicates cavitation onset, which is separated into two regimes by $Ca_2 = 1$: onset of large cavitation bubbles (regime B, $Ca_2 < 1$) and small cavitation bubbles (regime C, $Ca_2 > 1$), respectively.

The second parameter is a modified cavitation number derived based on energy conservation: $Ca_2 = \left(\frac{d}{l}\right)\left(\frac{p_\infty}{0.5\rho u_0^2}\right) = \frac{1}{l^*} Ca_0 = \frac{d}{L_{max}}$, , where $l^* = l/d$ is the slenderness of the water column, and $Ca_0 = \frac{p_\infty}{0.5\rho u_0^2}$ is the classic cavitation number. Detailed derivation for Ca_2 is available in [1]. Note that $L^*_{max} = \frac{L_{max}}{d} = Ca_2^{-1}$ also indicates Ca_2 (Ca_2^{-1} to be more specific) is a direct measure of the non-dimensional maximum bubble size. When $L^*_{max} = Ca_2^{-1} > 1$, a large cavitation bubble is able to form.

The onset of large cavitation bubbles requires both $Ca_1 < 1$ (onset threshold for cavitation, no matter small or large) and $Ca_2 < 1$ (threshold for large bubbles) simultaneously. These comprehensive criteria are

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validated against the experimental data on the Ca_1 versus Ca_2 diagram, as shown in figure 3 (b). The whole domain is divided into three regimes by $Ca_1 = 1$ and $Ca_2 = 1$. As expected, almost all the no-cavitation events are located in regime A ($Ca_1 > 1$), blue region in figure3(b); while when $Ca_1 < 1$ (red and yellow regions in figure 3(b), cavitation bubbles are consistently observed. The sub-domain of $Ca_1 < 1$ is further separated into two regimes by the line of $Ca_2 = 1$. Regime B ($Ca_2 < 1$, red region in figure 3) represents the criterion of large cavitation bubble onset, and regime C ($Ca_2 > 1$, yellow region in figure 3) is for small cavitation bubbles, respectively. The experimental data fall in the corresponding regimes and agree well with the theoretical prediction.

4. Conclusions

In the current work, we discuss the key factors affecting the size of cavitation bubble confined in a tube during a transient process using a modified 'tube-arrest' technique. We propose comprehensive onset criteria (consisting of two non-dimensional numbers) for large cavitation bubbles in a tube, which can be useful in terms of predicting the cavitation size in a hydraulic system. The results of this research may provide guidelines in the design and operation of hydraulic systems considering safety during transient processes.

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