Experimental evidence of thermodynamic effects in columnar cavitation bubble dynamics

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Abstract: We perform experiments of cylindrical cavitation bubbles by controlled tube-arrest method at different temperatures. The generation, growth, and collapse of the bubbles in a water column are observed by a high-speed camera, and the internal temperature changes of the bubble are directly measured by an unarmoured T-type thermocouple. Our results show that the maximum length and collapse time of the bubbles both decrease as the temperature increases. A temperature drop is observed at the beginning of the cavitation growth, indicating the thermodynamic effects in the bubble evolution. Stronger thermodynamic effects are observed with experiments at a higher temperature.

Keywords: cylindrical bubble, thermodynamic effects, temperature measurement, tube-arrest method

1. Introduction

Cavitation is a phenomenon in which rapid pressure change in a liquid leads to the formation of cavities in places where the local pressure is lower than the saturated vapor pressure. It occurs widely in fluid machinery (centrifugal pumps, nozzles, etc.) and sometimes brings negative impacts such as structural vibration and pressure fluctuations. Phase change and heat transfer exist when cavitation occurs, which reduce the temperature at the bubble wall and generate a thermal boundary layer around the bubble. The decrease in temperature reduces the saturated vapor pressure of the surrounding liquid, thereby affecting the subsequent growth and collapse of cavitation bubbles and changing the cavitation flow. This process describes the thermodynamic effects of cavitating flow [1-2] and it is too strong to be ignored for fluids working under thermal-sensitive conditions [3]. Therefore, the thermodynamic effects of cavitation must be considered in many applications.

To estimate the degree of the cavitation thermodynamic effects and its influence on cavitation characteristics, many researchers have carried out research on the quantitative parameters of measuring the degree of thermodynamic effects. Stepanoff [4] proposed a dimensionless parameter B-factor based on the energy balance between the cavitation region and the external liquid during the phase change. Brennen [5] introduced two assumptions to the Rayleigh-Plesset equation: (1) the thickness of the thermal boundary layer around the cavitation bubble is sufficiently thin, (2) the wall of the cavitation bubble is always in a thermal equilibrium. Then combined with the Clausius-Clapeyron relation, parameter Σ (m/s²) is proposed to quantify the thermodynamic effects under flow conditions. On this basis, Franc et al. [6] transformed the equation from time-dependent to space-dependent and obtained dimensionless scaling parameter $\Sigma^* = \Sigma\sqrt{C/U^3}$. In addition, Franc et al. [7] further expanded and replaced the heat transfer process with the convective heat transfer process, and obtained a dimensionless parameter $\tau/\tau_T = \tau\big/\left(Nu\sqrt{\alpha_l}/\Sigma\right)$. However, the internal temperature T_B of the cavitation region needed in B-factor and the Nusselt number needed in τ/τ_T are both hard to obtain, which makes the practical application of B-factor and τ/τ_T difficult. The parameters in $\Sigma = \dfrac{\rho_v^2 L^2}{\rho_l^2 c_{pl} T_\infty \alpha_l^{0.5}}$ (m/s²) are relatively easy to obtain and Σ has gradually been widely used, but the validity and practicability of two assumptions applied in the

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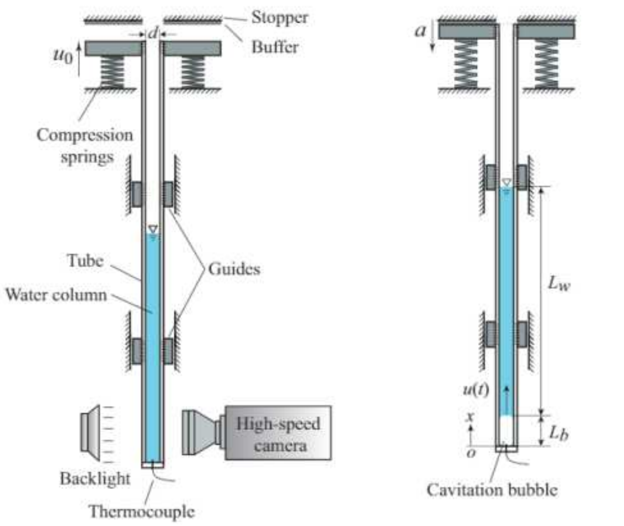
process of deriving Σ have not been fully verified. Experimental research on the cavitation thermodynamic effects needs further development.

At present, only a few experimental studies have been conducted on the thermodynamic effects in single bubble dynamics. In some studies cavitation bubbles have been induced with a high-intensity pulsed laser to study the thermodynamic effects, making the source of the temperature change of the liquid unclear [8-9]. Also, the common temperature measurement method is to use an armoured temperature sensor, whose response time is too long (~s) to record the temperature change during the growth and collapse process of cavitation bubbles (~20ms). Dular et al. [10] used tensile pulse to generate single cavitation bubbles in water and used a high-speed camera and an infrared (IR) high-speed camera to observe the morphological evolution of cavitation bubbles and changes in the temperature distribution of the surrounding liquid simultaneously. However, the experiment was only carried out at room temperature and did not provide the influence law of the thermodynamic effects. Besides, since water is an opaque medium to infrared rays, the result only represented the temperature field on the wall.

In view of the above difficulties, this paper uses the tube-arrest method to generate a single cylindrical cavitation bubble with controllable size and position, and an unarmoured thermocouple (with a response time of about 1 ms) to measure the temperature of the surrounding fluid. By the above methods, this study provides experimental evidence of thermodynamic effects in columnar cavitation bubble dynamics.



(a) (b)

Figure 1. Schematic diagram of the tube-arrest principle. (a) Tube moves upward with velocity u_0 before impact with stopper, (b) Cavitation bubble occurs immediately upon tube impact with acceleration

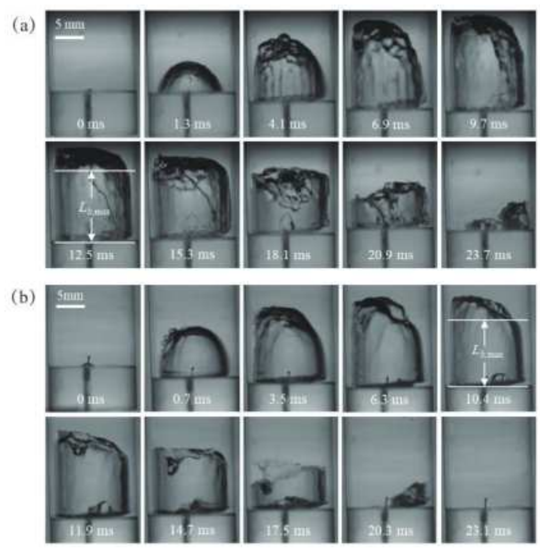


Figure 2. High speed images of cylindrical cavitation bubbles at different temperatures. (a) T = 24.0 ℃. (b) T = 42.5 ℃.

2. Methods

The method of generating cavitation bubbles by the tube-arrest method was first proposed by Chesterman [11] in 1952, and its major principal has been applied in this research. As schematically shown in Fig.1, a plexiglass tube with an inner diameter d=14.0 mm and a length of about 1.0 m is vertically installed. It is filled with deionized and degassed water at designed temperatures (in range 20.0~55.0 ℃) to a height L_w=450.0 mm. The uncertainty of tube inner diameter and liquid column length are less than 0.5 mm and 10 mm, respectively. The movement of the tube is restricted by pairs of guides to the vertical direction. After the tube is provided with an initial upward speed u_0 (by releasing 4 pre-compressed springs), it is then arrested when colliding with a stopper. As the liquid continues to move up due to inertia, single cavitation bubbles occur at the bottom of the tube. Both the movement of the tube and the growth-collapse process of the bubbles are recorded with a high-speed camera (Phantom v711) at 10,000 fps.from the side view.

The impact velocity of the tube u_0 is regulated by the stiffness and the compression of the springs, and the displacement between the stopper and the mobile platform holding the tube. The acceleration of the tube upon impact a is modified by applying buffers of different materials (e.g., rubber) and thickness to the stopper. Both u_0 and a are evaluated by image post-processing. u_0 and a are reconstructed by tracking the tube displacement with the last 5 measurements, as the motion of the tube is almost an accelerated rectilinear motion before impact. In the present study, u_0 = 2.67m/s with an uncertainty of 0.03 m/s, and a = 217.1m/s^2.

As the oscillation period of a single bubble is ~20ms in this research, a temperature measurement with a response time of $O(1)$ ms is required during the growth-collapse process of the cavitation bubble. We thus mount an unarmoured T-type thermocouple (measurement range 0~200 ℃, accuracy 0.01 ℃) with a diameter of 0.3mm at the bottom of the tube (Fig. 1), with its tip immersed in the liquid to 1~2 mm. A thermal response time of about 1.1ms of the thermocouple has been verified. The temperature measurement is then synchronized with the high-speed photography during the experiments.

3. Results

3.1. Cylindrical cavitation bubble dynamics

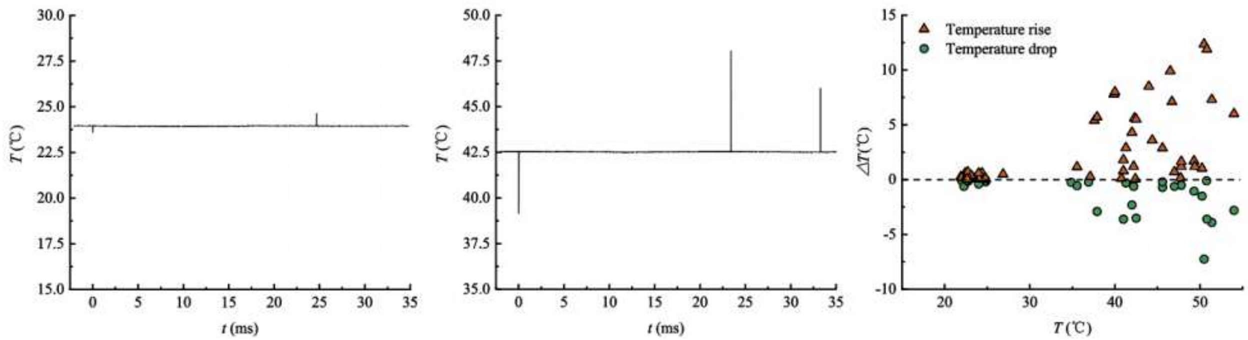
Typical high-speed images of the cavitation bubbles at 24.0 ℃ and 42.5 ℃ are shown in Fig.2. The bubbles are generated at the bottom of the tube upon tube impact (t=0 ms). They then undergo growth, collapse, and subsequent decaying oscillations until vanish completely. The growth of the bubbles is characterized by an initial radial growth until they reach the tube's inner wall and most of the time is a one-dimensional cylindrical growth. When the moving speed of the interface becomes zero (12.5ms for T=24.0 ℃ and 9.1ms for T=42.5 ℃), the length of the cavitation bubble reaches the maximum and the bubble begins to contract. As the cavitation bubble shrinks, the downward moving speed of the interface gradually increases, and a microjet directed to the bottom occurs. In the following rapid shrinking process, the diameter of the cavitation bubbles gets smaller than the inner diameter of the tube, and shrink in the axial and radial directions until the bubble collapses. The lifecycle of the first cavitation bubble at 24.0 ℃ (24.1ms) is longer than that (21.1ms) at 42.5 ℃. Since the non-condensable gas always exists in the cavitation bubble, the bubble experiences several rebound and collapse processes before it disappears completely.

The length of the cavitation bubble L_b is obtained by the image processing. It can be found that the maximum length of the cavitation bubble at 24.0 ℃ is 16.37 mm, which is longer than that (14.56 mm) at 42.5 ℃. Since the temperature is the only variable in the experiments, these changes can be attributed to the temperature. The maximum length and the lifecycle of the cavitation bubble decrease with the increase of cavitation thermodynamic effects.

3.1. Direct temperature measurement

Results of the thermocouple are shown in Fig.3. The cavitation bubble contacts the thermocouple when it is born. The measured value which now represents the temperature of the internal bubble has a sudden decrease and returns quickly. The drop is 0.4 ℃ at 24.0 ℃ (Fig.3(a)) and 3.5 ℃ at 42.5 ℃ (Fig.3(b)). After the cavitation bubble collapses, there is still a certain distance between the collapse position and the thermocouple, therefore the rise of the measured value occurs several milliseconds after the collapse. It should be noted that the measured value here does not represent the collapse temperature, it only represents the liquid temperature near the thermocouple. Not every experiment occurs rebound and second collapse. In Fig.3(b) 9.7ms after the first collapse at 42.5 ℃, a second rise results from the second collapse occurs and it is reduced compared with the first rise.

Results of temperature drops and rises at other conditions are shown in Fig.3(c). ΔT represents the change of the measured value, and the positive value change indicates temperature rise. It can be seen that the temperature rise is greater than the drop in each experiment. It should be noted that the temperature rise and drop will be underestimated if the cavitation bubble is far away from the thermocouple when it occurs or collapses. Therefore, some dots in Fig.3(c) are smaller than the actual condition. But in all, both the temperature rise and drop caused by the cavitation increase as the water temperature increases.



(a) (b) (c)

Figure 3. Measured results of the thermocouple. (a) 24.0 ℃. (b) 42.5 ℃. (c) Temperature drop and temperature rise of the first collapse under different temperature conditions.

4. Conclusions

In this paper, we generate single cylindrical bubbles with the tube-arrest method at different temperatures. The internal temperature change during the growth and collapse of the cavitation bubble is directly measured for the first time. As the temperature increases, the degree of cavitation thermodynamic effects of the liquid increases. The maximum length and life cycle of cylindrical cavitation bubbles are both decrease, and the temperature rises and drops increase.

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References

1. Brennen, C. E., *Hydrodynamics of pumps*; Cambridge University Press, New York, 2011; pp. 114.
2. Franc, J.P.; Michel, J.M., *Fundamentals of cavitation*; Springer science & Business media, Berlin, 2006; pp. 10.
3. Stahl H. A.; Thermodynamic aspects of cavitation in centrifugal pumps, *Trans. Am. Soc.Mech. Eng* 1956, 78, 1691.
4. Stepanoff, A., Cavitation properties of liquids, *J. Eng. Power* 1964, 86, 195.
5. Brennen, C. E., The dynamic behavior and compliance of a stream of cavitating bubbles, *J. FluidsEng* 1973, 95, 533.
6. Franc, J. P.; Rebattet C.; Coulon A., An experimental investigation of thermal effects in a cavitating inducer, *J. Fluids Eng* 2004, 126, 716.
7. Franc, J. P.;Pellone, C., Analysis of thermal effects in a cavitating inducer using Rayleigh equation, *J. Fluids Eng* 2007, 129, 974.
8. Tomita, Y.; Tsubota, M.; Nagane, K.; An-naka N., Behavior of laser-induced cavitation bubbles in liquid nitrogen, *J. Appl. Phys* 2000, 88, 5993.
9. Sun, C.; Can, E.; Dijkink, R.; Lohse, D.; Prosperetti, A., Growth and collapse of a vapour bubble in a microtube: the role of thermal effects, *J. Fluid Mech* 2009, 632, 5.
10. Dular, M.; Coutier-Delgosha, O., Thermodynamic effects during growth and collapse of a single cavitation bubble, *J. Fluid Mech* 2013, 736, 44.
11. Chesterman, W., The dynamics of small transient cavities, *Proc. Phys. Soc.* 1952, B65, 846.