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Production of large size single transient cavitation bubbles with tube arrest method*

Chen Qi-Dai(陈岐岱)† and Wang Long(王 龙)

Institute of Physics, Chinese Academy of Sciences, Beijing 100080, *China*

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Large size single transient cavitation bubbles of maximum diameter up to 3 cm with sonoluminescence have been generated in water by the 'tube arrest' method. A simplified one-dimensional model of bubble growing and water column motion is proposed. The results of numerical simulation are compared with the experimental data of the bubble size and oscillation period as the key parameters.

Keywords: sonoluminescence, transient cavitation, bubble
PACC: 7860M

1. Introduction

Periodic compression and expansion of gas and vapour bubbles in liquids occur during cavitation, this highly nonlinear bubble motion is accompanied by the emission of light, i.e. the sonoluminescence.[1] This phenomenon has a long history, starting from the multibubble sonoluminescence in water cavitated by strong acoustic field,[2] to the more recent discovery of single-bubble sonoluminescence (SBSL).[3] In this paper we study another kind of cavitation, the transient cavitation, which was first named by Flynn.[4] Different kinds of equipment to generate transient cavitation have been proposed since the 1950s, such as conical bubble in U-tube [5] and cavitation generated by water hammer [6]. Another experimental method was developed to create a single gas bubble in water or other liquids by Chesterman in the 1950s. In his design, a moving glass tube filled with liquid was arrested, and then a cavity was created in the tube. It was referred to as the 'tube arrest' method.[7] In that work the expansion and collapse of single spherical cavities in water and certain organic liquids was observed and the relation between the lifespan and the maximum diameter of a cavity was analysed.

Wang and Zhang made the observation of sonoluminescence using the 'tube arrest' method in the 1960's [8]. These authors used high-speed camera, Mie-scattering, and photomultiplier as means of diagnostics in their experiment, and observed more than one optical flash in synchronization with the bubble's afterbounces following the first collapse. The phase of sonoluminescence with respect to the bubble dynamics was investigated with special attention to check the validity of the hypothesis on cavitation mechanism proposed by Frenkel in 1940.[9] Sonoluminescence during the bubble collapse was also reported in Ref.[8]; however, their results have not been widely known as they were published in Chinese. We have attempted to repeat the above experiment with a number of technical improvements. For instance, in Ref.[8], the bubble was set in a kettle placed at the bottom of the tube and the diameter of the kettle should have exerted important effect on the bubble's luminescence according to theoretical analysis. In this work, the liquid container has been changed to a straight glass tube, and a physics model describing the motion of liquid column and the expansion and collapse of bubbles has been put forward.

The arrangement of the paper is as follows. The experimental results are presented in Section 2. A theoretical model is described in Section 3 and the results of numerical analysis are compared to the experimental data in Section 4. Conclusions are drawn

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†E-mail: chenqd@aphy.iphy.ac.cn

in Section 5.

2. Experimental set-up and results

The experimental set-up of the present work is shown in Fig.1. A glass tube sealed at the bottom and open at the top is filled with water for the most part. The water used has been distilled and pumped for 15min with a mechanical pump to diminish the surface bubbles. The tube diameter is usually 26mm while the water height in the tube is around 60cm. A rod with a small dent of diameter of roughly 1mm at its lower end is inserted vertically into the water so that an air bubble nucleus is formed in the dent. The rod hangs down along the centerline of the tube. The tube with its water content is fastened to a spring pinned at one end. For the generation of a cavitation bubble, the tube is pulled downward for certain length and locked, the spring thus being stretched. The tube is then released, to be quickly pulled upward by the spring, and then suddenly arrested by a stopper after shooting up for a short distance. We showed experimentally that during the sudden arrest, a tension wave is produced in the water column, starting from the tube bottom and travelling upward.

The bubble nucleus in the dent of the rod, which is fixed in space, is monitored with a high speed CCD camera (Delta CA-D6). The image-capture rate was adjusted to be ~1.2ms/frame with an exposure time of ~0.1 ms.The bubble is observed to grow, collapse, rebound and become fragmented. To some surprise, the growing bubble can be remarkably large, up to 3cm or more in diameter, and robust. Figures 2 and 3 present two photo illustrations.

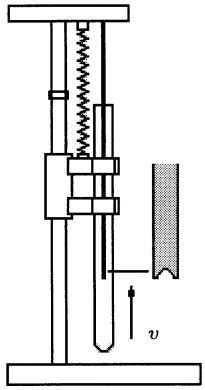


Fig.1. Experimental arrangement for the investigation of light emission from transient cavitation bubbles.

Figure 2 shows a relatively small bubble generated when the end speed of the glass tube was about 1.3m/s. The oblate sphere shaped bubble measures, at its maximum size, 17mm laterally and 1.0cm in height. The photos at consecutive instants show the entire process of the bubble's growth and collapse. The interval between two sequent pictures is ~2.4ms, and the total lifetime of the bubble is 13ms. Clouds of broken fragments were observed during the afterbounce after the collapse phase (not shown in the figure).

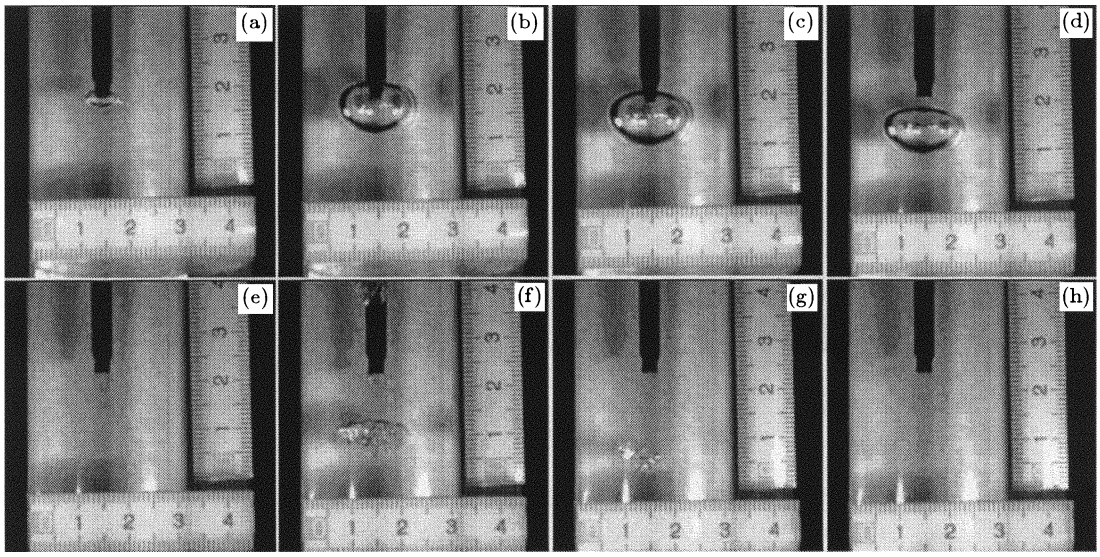


Fig.2. Photograph of one cycle of the oscillations of a transient bubble in water. The end speed of tube is about 1.3m/s, the interval between two sequent images is 1.2ms.

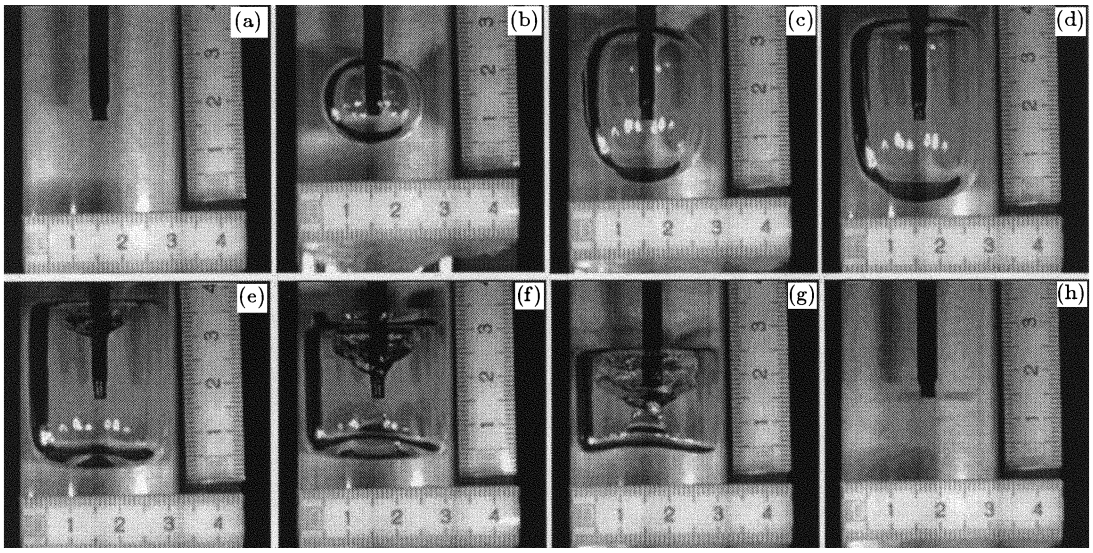


Fig.3. Photograph of one cycle of the oscillations of a transient bubble in water. The end speed of tube is about 2.8m/s, the interval between two sequent images is 2.4ms.

Figure 3 shows a large cavitation bubble generated when the end speed of the glass tube was ~2.8m/s. The bubble grew so large that the tube wall squeezed it to become roughly cylindrical in shape, so its diameter was the same as the inner diameter of the glass tube, i.e. 26mm. The length of the bubble was approximately 32mm. The time interval between two sequent pictures was ~3.6ms and the lifetime from its initiation to its first collapse lasted 26.4ms. It can be seen in the last picture that the bubble collapsed into several small bubbles. Here again, a cloud of broken fragments consisting of large amount of small bubbles was observed during the first afterbounce.

A photo multiplier tube (PMT) (Hamamatsu R212) was used to monitor the light emission. It is also used to detect the scattering light from the bubble from around 60° from the forward direction; the bubble was illuminated with a 1-mW semiconductor laser. A piezoelectric (PZT) cylindrical crystal mounted on the end of the tube was used to measure the tension waves in water. Because of their different ambient light requirement, the PMT and camera system could not be deployed simultaneously. However, instrumentation to measure the pressure of the liquid could be used simultaneously with the PMT or camera.

A set of typical measurement results obtained with PMT and PZT is shown in Fig.4. The broad negatively going peaks in the PMT signal are due to the increase in scattering light as the bubble expands to maximum. The sharp spikes, which follow the drops of the broad peaks, are due to light emission from the bubble. The PMT signal also shows that after the collapse of the bubble, there are a few afterbounces with light pulses at their ends. The behaviour of pressure measured with PZT has similar periodic feature. Each light pulse corresponds to a pressure peak.

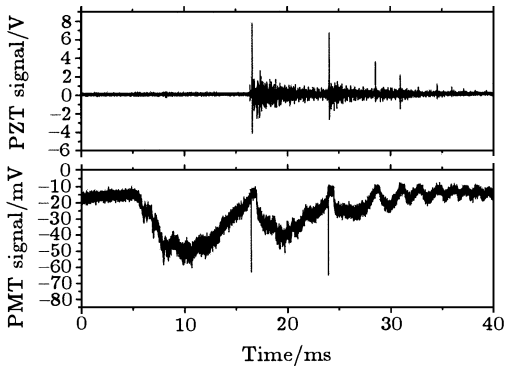


Fig.4. The pressure signal measured by a PZT at the bottom of tube (up), and the intensity of light recorded with a photomultiplier tube (down) as functions of time. The light signal is composed of the scattered laser light and the emitted SL.

3. Model of motion of liquid column

The analysis of the bubble's motion in SBSL adapts to the formulation of Rayleigh.[10] Rayleigh considered the collapse of an empty cavity that remains spherical at all times. In this experiment, since the bubble can grow to large size comparable with the diameter of the glass tube, it is not suitable to adapt to Rayleigh's model and it is difficult to construct an accurate analytic model. Therefore, in the present paper, a simplified model is suggested to describe the

motion of the liquid column in the glass tube, which determines the growth and collapse of the gas bubble.

Let us consider the process of bubble expansion and collapse. At the beginning of the experiments, a small bubble of air was injected into the water via a rod. The tube remains open to atmosphere all the time. The ambient pressure (comprising atmosphere, hydrostatic and Laplace components) and the gas pressure inside the bubble are in equilibrium. Then the glass tube with filled water is accelerated to a speed of v_0. When the glass tube stops suddenly, the water column tends to continue the motion. Since water is almost incompressible, only the water column above the gas bubble can continue to move, and then the bubble starts to expand. Under the action of gravity and atmosphere pressure, the motion of water column is gradually reduced and at last comes to rest. When the water column attains its maximum height, the bubble expands to its maximum size. In the next phase, the water drops, and compresses the gas bubble and causes it to collapse. When the bubble attains its minimum size, the motion of water column starts the next motion period. If the dissipation is ignored in these processes and the bubble do not break into fragments, the periodic motion of the water column would repeat endlessly.

Therefore, the bubble dynamics would become simple and clear if only the motion of water column above the bubble is considered. In this simplified one-dimensional model, the bubble is regarded as a thin gas column of a height z and the same diameter of the internal diameter of the glass tube, which lies between two water columns. The initial value of z is given so that the volume of the gas column is equal to the real volume of the bubble at the start of the expansion. The water column below the bubble is regarded as incompressible and at rest with respect to the glass tube. Its motion is not taken into account in this model. Obviously, the model is invalid when the bubble size is small, while it is a good approximation for most part of the whole periodic process, especially for a large initial size of the bubble.

The analysis considers the motion of the water column under the force of gravity mg, ($m = \rho_{\mathrm{w}} Sh$ is the mass of the water column, ρ_{w} the density of water, S the cross section area of the glass tube, h the height of water column), atmospheric pressure $p_0 S$ and the gas pressure $p_{\mathrm{g}} S$ inside the gas column. So the motion of the liquid column can be described by the following equation:

$$\rho_{\mathrm{w}} Sh \frac{\mathrm{d}^2 z}{\mathrm{d}t^2} = -p_0 S + p_{\mathrm{g}} S - \rho_{\mathrm{w}} Shg. \tag{1}$$

It is assumed that the expansion and collapse of the gas bubble is adiabatic: it then follows

$$p_{\mathrm{g}} z^{\gamma} = p_{\mathrm{g}0} z_0^{\gamma}, \tag{2}$$

where $p_{\mathrm{g}0} = p_0 + \rho_{\mathrm{w}} gh$ is the initial pressure in the gas column, γ is the ratio of the specific heat of the gas at constant pressure to that at constant volume. Substituting p_{g} of Eq.(2) into Eq.(1) and integrating (1), we can get an expression for the velocity the water column as a function of height of gas bubble z:

$$\begin{aligned} v^2 =& \left(\frac{\mathrm{d}z}{\mathrm{d}t}\right)^2 \\ =& v_0^2 + 2\left[\frac{(p_0 + \rho_{\mathrm{w}} gh) z_0}{(1-\gamma)\rho_{\mathrm{w}} h}\left(\frac{z^{1-\gamma}}{z_0^{1-\gamma}} - 1\right)\right. \\ & \left. - \left(\frac{p_0}{\rho_{\mathrm{w}} h} + g\right)(z - z_0)\right], \end{aligned} \tag{3}$$

where $v_0 = v(0)$ is the initial velocity of the liquid column. The maximum and minimum values of z, $z_{\max}$ and $z_{\min}$, can be numerically computed for $v = 0$. And the period of the column oscillation is obtained by time integrating of (4) from $z_{\min}$ to $z_{\max}$.

Equation (3) is also an energy conversation equation of the water column. The v_0^2 term represents the initial kinetic energy of the liquid column. Since $p_{\mathrm{g}0} = p_0 + \rho_{\mathrm{w}} gh$ represents the initial pressure of the gas, the corresponding terms in Eq.(3) represents the work done by the gas on the liquid. The third term in Eq.(3) represents the work done by the atmosphere pressure and the gravity on the liquid.

As described earlier, when the gas column expands to the maximum height $z_{\max}$ the water column velocity is zero. The velocity is also zero at the minimum radius $z_{\min}$, where the pressure and temperature of the gas in the bubble would be at their maxima, $p_{\mathrm{g,max}}$ and $T_{\max}$, respectively. Assuming no break-up, the bubble will then rebound to the same maximum size of $z_{\max}$. The values of maximum and minimum heights can be found by setting $v = 0$ in Eq.(3), such that

$$\begin{aligned} & v_0^2 + 2\left(\frac{p_0}{\rho_{\mathrm{w}} h} + g\right) z_0 \\ & \times \left[\frac{1}{(1-\gamma)}\left(\frac{z^{1-\gamma}}{z_0^{1-\gamma}} - 1\right) - \left(\frac{z}{z_0} - 1\right)\right] = 0. \end{aligned} \tag{4}$$

Simple estimation of $z_{\min}$ value for $z_{\min} \ll z_0$ can be

made by simplifying Eq.(4), i.e.

$$z_{\min} = z_0 \left(\frac{2\left(\frac{p_0}{\rho_{\rm w} h} + g\right) z_0}{(\gamma - 1) v_0^2} \right)^{1/(\gamma-1)} . \qquad (5)$$

The maximum pressure reached in the collapse when $z = z_{\min}$, can be found from (2) and (5),

$$\begin{aligned} p_{\rm g,max} =& p_{g0} \left(\frac{z_0}{z_{\min}} \right)^{\gamma} \\ =& \left(\frac{(\gamma - 1)\rho_{\rm w} h v_0^2}{2(p_0 + \rho_{\rm w} g h) z_0} \right)^{\gamma/(\gamma-1)} (p_0 + \rho_{\rm w} g h). \end{aligned} \qquad (6)$$

Also, the maximum temperature reached in the bubble can be expressed as

$$\begin{aligned} T_{\rm g,max} =& T_{\rm g0} \left(\frac{z_0}{z_{\min}} \right)^{\gamma-1} \\ =& \frac{(\gamma - 1)\rho_{\rm w} h v_0^2}{2(p_0 + \rho_{\rm w} g h) z_0} T_{\rm g0}. \end{aligned} \qquad (7)$$

If the initial volume of bubble is $1{\rm mm}^3$, the initial gas column height should be $z_0 = 1.9 \times 10^{-6}$m. We also take experiment values: the initial gas temperature $T_{\rm g0} = 293$K, the water column height h=0.55m, and the initial water column velocity v_0=2m/s. Then we can obtain the estimation values: the minimum size $z_{\min} = 8.4 \times 10^{-15}$m, maximum gas pressure $p_{\rm g,max} = 5 \times 10^{11}$atm and temperature of the bubble $T_{\rm g,max} = 6.4 \times 10^5$K by using Eqs.(5)–(7). As discussed above, the value obtained at minimum size would be an approximation as the one-dimensional model is invalid for small bubble. Furthermore, the liquid is assumed to be incompressible and the vapour in the bubble is ignored; these will have played a role in damping the sharp high temperature. There is no energy dissipation effect and the total kinetic energy of the water column is converted to the internal heat of the bubble in our calculation. The inner parameters of the bubble would not be so extreme if the dissipation effect is considered.

4. Comparison with experiment

It is difficult to conduct an experimental observation to compare the real inner parameters in the bubble in its minimum size with the theoretical predictions. However, the above equations deduced from the simplifying model can be checked with experiment observation when the bubble size $z \gg z_0$ as direct visual observations are possible of both growth and collapse. Figures 2 and 3 show that the maximum volume of the bubble is much larger than the initial bubble volume. Assuming $z_{\max} \gg z_0$, Eq.(4) can be simplified as

$$z_{\max} = \frac{v_0^2}{2\left(\frac{p_0}{\rho_{\rm w} h} + g\right)}. \qquad (8)$$

Equation (8) gives the maximum height of the water column, which is independent of the initial gas column height z_0 under the approximation. The v_0 square law relation can be experimentally demonstrated.

The oscillation period (comprising the expansion and collapse phases) of the column can be obtained by time integrating of (4) from $z_{\min}$ to $z_{\max}$,

$$t = 2 \int_{z_{\min}}^{z_{\max}} \frac{{\rm d}z}{v}. \qquad (9)$$

The integration can be done numerically as it has not an analytic expression as Rayleigh obtained for a spherical cavity. However, if we assume $z_{\min} \approx 9$ and in most part of the period $z \gg z_0$ in Eq.(9), the oscillation period can be approximately expressed as

$$t \cong 2 \int_0^{z_{\rm mzx}} \frac{{\rm d}z}{\sqrt{v_0^2 - 2\left(\frac{p_0}{\rho h} + g\right) z}} = \frac{2 v_0}{\frac{p_0}{\rho h} + g}; \qquad (10)$$

it is also independent of the initial height z_0 and its minimum value $z_{\min}$.

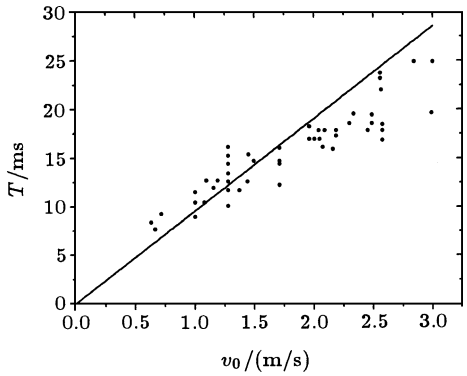


Fig.5. Dependence of first oscillation period of bubble on initial velocity of water column. The symbols stand for experimental data and the straight line stands for the calculation result. The height of the water column h=0.55m. The initial value of z_0 is about $10^{-5}{\rm m}^3$. The diameter of the glass tube is 0.26m.

Figure 5 shows the experiment data of the first oscillation periods T for different initial velocities v_0 obtained from camera photos under the following experiment conditions. The height of the water column

above the bubbles h is 0.55m. The effective initial value of z_0 is about $10^{-5}\mathrm{m}^3$. The diameter of the glass tube is 0.26m. The initial velocity of the water column is 2.5m/s. Comparing to a straight line in the figure calculated from (10), the experimental data slightly deviate from the theoretically predicted values, as the energy loss due to friction of water column on the tube surfaces has not been taken into account in the calculation model.

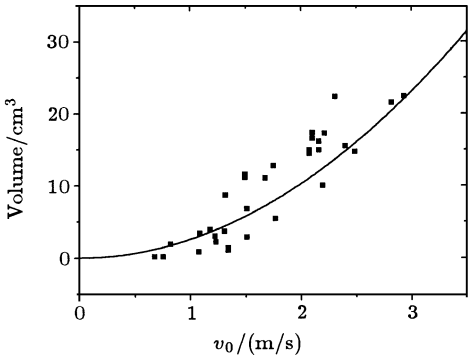


Fig.6. Dependence of maximum volume of bubble on initial velocity of water column. The symbols stand for experimental data and the curve stands for the calculation results. The experiment conditions are the same as that shown in Fig.4.

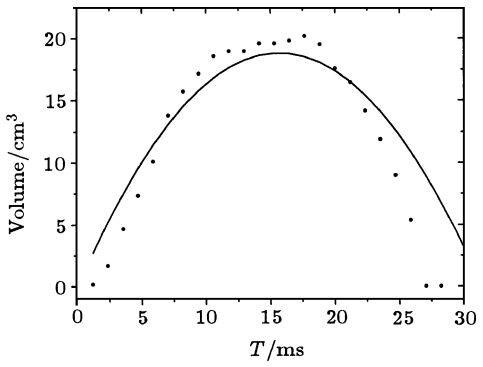


Fig.7. Temporal evolution of bubble volume. The initial velocity of water column is 2.5m/s. The symbols stand for experimental data and curve stands for the calculation results.

Figure 6 shows the experiment data of maximum bubble volume for different initial velocity obtained from the camera photos under the same experimental conditions as those of Fig.5. The theoretically predicted value from (8) is also shown in the same figure. Figure 7 shows the volume of a bubble as a function of time calculated from the above model and is compared with experimental data. In these figures, the calculation results from the proposed model agree well with the experimental data.

5. Discussion and conclusion

In this paper, we have analysed the motion of water column and proposed a simplified one-dimensional model, in which only the motion of water column above the gas bubble was taken into account. In order to exactly describe the expansion and collapse of the bubble in the present experiment configuration, a complex two-dimensional model should be established.

Obviously, the proposed model is invalid in the early phase of cavity expansion or in the whole process for a small bubble as that shown in Fig.2. However, satisfactory agreement between theory and experiment is achieved even in the regions with small volumes (below $10\mathrm{cm}^3$), where the elliptical gas bubbles do not touch the tube wall at its maximum. The reason for this would be the weak dependence of the oscillation cavity period and maximum volume on the behaviour of the bubble during the phase.

If certain energy dissipation is introduced into the proposed model, the agreement of the calculated results with experiment data will be further improved. The expansion-collapse phases for the main oscillation period and subsequent afterbounces still follow the prediction from the improved model even when the single bubble becomes a fragment cloud during the afterbounce phase.

In summary, we have used the 'tube arrest' method to generate large size transient cavitation bubbles in water and observed their light emission during the collapse phases. A simplified model is proposed to describe the temporal evolution of the cavity. Only the one-dimensional motion of the water column above the cavity is taken into account in this model. The measurement results with a CCD camera are in agreement with the prediction from the model even for the cavities with maximum diameters less than that of the tube.

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