Growth and Collapse of Cavitation Bubbles*

(Distribution Change of Cavitation Nuclei
due to the Collapse of Cavitation Bubbles)

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The growth and collapse of cavitation bubbles are observed in distilled water using a hydro shock tube which alternately generates low pressure and high pressure in the test section. The cavitation bubbles are fragmentized into numerous small bubbles (so called nuclei) after their collapse. The number of remaining nuclei increases rapidly as the gas content increases in the water. The nuclei population varies in the water during the growth and collapse of cavitation bubbles, and finally it becomes comparable with the one measured in some cavitation tunnels. The cluster of cavitation bubbles, grown from the remaining nuclei, behaves like a single bubble in the initial stage, but at the middle stage it separates into small bubbles, and they collapse faster.

Key Words: Cavitation, Nuclei, Inception, Nuclei Population,
Bubble growth, Bubble Collapse

1. Introduction

It is already understood that small air bubbles suspended in water, so-called cavitation nuclei, play an important role in the inception of cavitation. Several experimental techniques to investigate the cavitation nuclei behaviour have been proposed. For instance, a light scattering method developed by Keller [1] have been compared with a holographic technique by Billet and Gates [2]. Further, the Coulter counter method [3] and the cavitation susceptibility meter [4] have been developed. Also, many investigations have been performed on scale effects concerning the nuclei population. When hydrogen bubbles are introduced into the stream around a head form as the nuclei, the incipient cavitation number for sheet cavitation markedly decreases in scatter and converges to the maximum value in the stream without introducing hydrogen bubbles, while the desinent cavitation number does not change [5]. One of the authors [6] has experimentally investigated the behaviour of the cavitation bubble cluster formed around a thin platinum wire which is instantaneously heated, showing the following results: When the density of cavitation nuclei is low, each bubble grows independently into a spherical bubble, and then, collapses asymmetrically due to interference. When the density is high, however, the bubbles coalesce into a cylindrical bubble with a rugged surface. This bubble then collapses from both ends,

and separates into several fragments, with interacting each other. It has been suggested that these bubbles are further fragmentized into small nuclei during their collapse. Although many studies on the cavitation nuclei measurements and on the scale effects depending on the nuclei population have been performed, the mechanisms of the cavitation nuclei suspension are poorly understood.

In this paper the following results are presented: The cavitation bubbles make numerous small bubbles (i.e. cavitation nuclei) after their collapse, and the nuclei population varies during the growth and collapse. The number of remaining cavitation nuclei increases with the gas content in the test water and with the roughness of bubble wall. After the bubbles grow and collapse repeatedly several times, the nuclei population density becomes comparable with the one observed in some cavitation tunnels.

Nomenclature

P	: pressure
P_c	: critical pressure
P_i	: initial pressure
P_v	: vapour pressure
R	: radius of nucleus
R_i	: initial radius of nucleus
$R_{i\max}$	: maximum radius of nucleus
$R_{i\min}$	: minimum radius of nucleus
σ	: surface tension

2. Experimental Apparatus
and Procedure

The experimental apparatus, consisting of a hydro shock tube, is shown in Fig. 1. The 50mm diameter shock tube has a high pressure chamber in the lower part, a low pressure chamber in the upper part and a rupturing device. The two

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chambers are separated by a diaphragm. The high pressure chamber, made of glass contains distilled water whose gas content is controlled to 2~12.3 ppm. The liquid surface is about 200 mm below the diaphragm. The test section, located at the bottom of the tube, has a pressure transducer and supports a thin platinum wire, 25 μm in diameter, 10 mm or 16 mm long, 10 mm above the bottom. The platinum wire makes "weak spots" in the water by means of instantaneous electrical heating.

The experiment is performed according to the following procedures:

- (1) The high pressure chamber is thoroughly evacuated in order to remove air from pits and scratches on the inner chamber wall and to remove the gaseous contaminations in the water. Then the water is poured into the chamber. The gas content is controlled in each experiment.
- (2) The pressures in both chambers are adjusted, the high pressure to 300 kPa absolute, and the low pressure to the atmospheric pressure.
- (3) The time sequence of experiments is controlled by a microcomputer. Namely, the platinum wire is electrically heated for 10 ms by connecting it to a charged condenser, and the water temperature around the wire is raised to create "weak spots", then the diaphragm is ruptured. At the same time, the wire temperature and the pressure in the test section are recorded. The dynamic behaviour of cavitation bubbles is photographed in high-speed motion pictures.
- (4) After the above experiments, the test water is sampled from the test section and the dissolved oxygen content is measured by a DO-meter from which the air content is calculated.

3. Experimental Results and Discussion

3.1 Time history of wire temperature and temperature distribution in water

The platinum wire is heated by connecting it to a charged condenser. The calculated time history of the wire temperature and the temperature distribution in water are shown in Fig. 2. The numerical calculations are carried out under the assumption that the temperature is uniform within the wire. When the wire is connected to the condenser, the wire temperature rapidly rises then takes a maximum value and decreases gradually with a decrease in the condenser voltage. When the heating is stopped after 10 ms from the start, the temperature decrease is rapid, but soon it becomes slow due to the development of a thermal boundary layer in water. The thermal boundary layer fairly develops at the time when the first expansion wave arrives at the test section (after 12 ms from the start).

Figure 3 shows the experimental and the numerical results of the wire temperature after 11.3 ms from the start. Both temperatures coincide well with each other up to 10 volts of the charged

Fig. 1 Experimental apparatus consisting of a hydro shock tube.

Fig. 2 Time history of the wire temperature and the distribution of temperatures in the water.

Fig. 3 Wire temperature after 11.3 ms from the start of heating.
 Δ : experimental results
 —: numerical results

condenser voltage, while at above 10 volts the experimental results are lower than the numerical ones. The reason is that a boiling occurs on the wire, when the temperature takes a maximum as shown in Fig. 2. The maximum temperature appears after about 3 ms from the start of heating. If the boiling occurs on the wire under the condition that the charged voltage is 10 volts (the maximum temperature is 166°C), it can be calculated from the Clapeyron-Clausius equation the critical bubble radius in this case being 0.18 μm . A large tensile strength is required to explode such a small bubble under this experimental condition. When the boiling does not happen, in fact, no cavitation bubbles appear under the tensile strength observed in these experiments. Considering these results, the following experiments were made under the condition that there were some small bubbles around the wire resulting from the preceding boiling.

3.2 Growth and collapse of cavitation bubbles

An expansion wave, which is caused by the rupture of the diaphragm, passes through the water to the test section. Then it reflects at the bottom and propagates up to the gas-liquid interface. The expansion wave changes to a compression wave when it reflects at the interface. The compression wave again propagates down to the test section. Thus, the pressure in the test section decreases and increases alternately as shown in Figs. 4, 5 and 6.

Figure 4 shows the dynamic behaviour of bubble growth and collapse with relatively low gas content of 2.7 ppm. The first pressure reduction creates cavitation bubbles at 2.44 ms, and the bubbles grow under the ambient pressure whose value is almost the same as saturated vapour pressure of the bulk temperature. At 4.27 ms, when the compression wave arrives at the test section, the cavitation bubbles begin to collapse. Large fluctuations of the pressure waves are observed due to interferences with reflected pressure waves from the bubbles and the bottom. The wire temperature decreases to a bulk temperature during the first bubble growth, and then it keeps the bulk temperature. The bubbles collapse erratically because of the fluctuations of pressure waves and the nonspherical shape of the bubbles, and they remain in the form of numerous cavitation nuclei, i.e. many small bubbles. When the ambient pressure decreases again at 9.26 ms, many cavitation bubbles grow from the remaining nuclei. With the next intense expansion wave at 10.50 ms, many cavitation bubbles grow once again from the nuclei, and at 11.11 ms, they are united into a single bubble whose shape is erratic.

The collapse of this bubble cluster is well described by the Rayleigh's theory on a single bubble, whose radius is equal to the cluster, at the beginning of its

Fig. 4 Growth and collapse of cavitation bubbles due to decrease and increase in the ambient pressure. The gas content is 2.7 ppm.

collapse. However, the cluster is separated into small bubbles at the middle of the collapse, and they collapse faster. These bubbles remain again in the form of numerous cavitation nuclei.

The following photographs show that the distribution of cavitation bubbles has expanded and moved toward the bottom of the test section by the flow induced by the bubble collapse. Finally, the pressure wave dissipates so that the nuclei do not grow into cavitation bubbles.

Figure 5 shows the behaviour at the same gas content of 2.7 ppm where the number of remaining nuclei is smaller than that shown in Fig. 4 at the first collapse, although the ambient pressure at the bubble formation ($P_{\min} = -106.1$ kPa at 10.17 ms) is lower than the one ($P_{\min} = -12.0$ kPa at 9.26 ms) shown in Fig. 4. The degree of bubble wall roughness is less than that shown in Fig. 4. When the preceding cylindrical bubble is very

Fig. 5 Growth and collapse of cavitation bubbles due to decrease and increase in the ambient pressure. The gas content is 2.7 ppm.

rugged in its shape, the number of remaining nuclei is even greater. The same effect of remaining nuclei is observed even in Fig. 5. The number of bubbles at 10.17 ms is smaller than the one at 12.77 ms, in spite of almost the same ambient pressure. This can be explained as follows: The preceding bubbles in the latter case at 11.88 ms have a much more rugged shape than the ones in the former case at 5.75 ms. However, after the bubble growth and collapse are repeated several times, the number of the remaining nuclei becomes almost comparable with that in Fig. 4.

Figure 6 shows the growth and collapse of cavitation bubbles in the water with relatively high gas content of 10.5 ppm. Many bubbles are formed around the wire by the first expansion wave, then they coalesce and grow into one cylindrical bubble along the platinum wire. The cylindrical bubble has a rugged surface initially, but the surface becomes

Fig. 6 Growth and collapse of cavitation bubbles due to decrease and increase in the ambient pressure. The gas content is 10.5 ppm.

somewhat smooth when the bubble has grown up at 4.20 ms. When the compression wave arrives at the test section at 5.23 ms, the cylindrical bubble collapses from both ends. When the ambient pressure decreases again, the bubbles grow again from the numerous remaining nuclei at 10.38 ms. The number of exploded bubbles is much larger than that shown in Figs. 4 and 5. These bubbles do not grow so large as the bubbles in Figs. 4 and 5. The bubble cluster moves toward the bottom during the repeated growth and collapse.

3.3 Population of cavitation nuclei

A bubble, whose radius is R_i at the initial ambient pressure P_i , explodes at the critical ambient pressure P_c . The pressure P_c is expressed by the following equation under the assumption: the internal gas pressure changes isothermally, the gas diffusion through the bubble wall is negligibly small and the motion of bubble wall is in

Fig. 7 Relationship between the critical pressure and the nucleus radius.

equilibrium dynamically.

$$P_c = P_v - \frac{2\sqrt{3}}{9} \left(\frac{2\sigma}{R_i} \right)^{3/2} / (P_i - P_v + \frac{2\sigma}{R_i})^{1/2} \quad (1)$$

Figure 7 shows the relation between R_i and $P_v - P_c$ and indicates that R_i decreases with an increase in $P_v - P_c$ but R_i does not change so much with P_i . Namely, it shows that a large tensile strength is required to explode a small bubble. The minimum radius of the nucleus, where explosion may start, can be estimated from the observed minimum pressure using Eq. (1). Figure 8 shows the relations between the number of cavitation bubbles counted from the photographs, and the minimum nucleus radius which is estimated from the observed minimum pressure when the bubbles are formed. It is clearly seen that the number of bubbles also increases with the gas content. In Fig. 8 letters I, II, III denote the order of explosion time of the bubble from the remaining nuclei; for example, the letter I denotes the first explosion. After the bubbles grow and collapse repeatedly, the relation shifts toward the direction of increasing number as I-II-III. As the bubbles grow and collapse more repeatedly, the relation can finally be expressed as a straight line.

If all the bubbles, whose radii are larger than the minimum one, explode, it is possible to estimate the number of nuclei from the number of cavitation bubbles which appear on the photograph. Moreover, the population density of the cavitation nuclei can be estimated from the volume occupied by the bubbles. Figure 9 shows the relations between the minimum radius of nuclei R_{min} and the population density of the cavitation nuclei N with radii larger than R_{min} can be expressed by $N \propto R_{min}^{-3}$.

For natural aerosols consisting of many kinds of components whose histories are diversified, Junge [7] shows that the general number density function is expressed by $dN/dR \propto R^{-4}$. This equation

Fig. 8 Number of bubbles counted from the photographs and minimum radius of nuclei estimated from the observed minimum pressure using Eq. (1).

: gas content is 2.7 ppm.
: gas content is 10.5 ppm.

Fig. 9 Population density of cavitation nuclei and minimum radius of nuclei.

: gas content is 2.7 ppm.
: gas content is 10.5 ppm.

can be integrated from R_{min} to R_{max} , and the number of nuclei whose radii are between R_{min} and R_{max} is given by $N \propto (R_{min}^{-3} - R_{max}^{-3})$. Then one can obtain $N \propto R_{min}^{-3}$, because $R_{min}^{-3} \gg R_{max}^{-3}$. This equation

coincides not only with the above mentioned equation expressing the relation for the cavitation nuclei in the shock tube, but also with the approximate equation of the nuclei population density measured in several cavitation tunnels [8].

4. Conclusions

The growth and collapse of cavitation bubbles are observed in distilled water using a hydro shock tube which produces alternately low pressure and high pressure in the test section. From these observation the following results are obtained:

Cavitation bubbles are fragmentized into numerous small bubbles (i.e. cavitation nuclei) after their collapse. The number of remaining nuclei increases rapidly as the gas content increases. However, when the preceding bubble before the collapse is very rugged in its shape, the increase in the number of remaining nuclei is even greater. The nuclei population in the water varies during the growth and collapse of cavitation bubbles, and finally it becomes comparable with the

nuclei population measured in several cavitation tunnels. The bubble cluster, grown from the remaining nuclei, behaves almost like a single bubble in the initial stage of its collapse, but at the middle of collapse it separates into small bubbles again, which then collapse faster.

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