Impulsive Pressure Generation by Bubble/Pressure-Wave Interaction

A. Shima* and Y. Tomita†
Tohoku University, Sendai, Japan
and
T. Sugiu‡
Asahi Glass Company Ltd., Yokohama, Japan

A study concerning the interaction of a bubble with a pressure wave or a shock wave has been made, and some effects on induced impulsive pressure are examined. As a result, it is found that the impulsive pressure is significantly affected by both effects of the characteristics of an applied pressure and the bubble size. Furthermore, it is suggested, from a theoretical consideration, that there is an optimum bubble size where the most intensive bubble collapse can occur for a certain pressure wave. The existence of this optimum bubble size is also confirmed from an experiment based on simultaneous records of bubble collapse and damage pit.

Nomenclature

C_∞ = sound velocity in liquid
$d_{p,M}$ = maximum pit diameter
F_t = impulse $(=\int_0^t p\,dt)$
l_c = distance from bubble center to solid surface
L_t = distance from source of shock wave to pressure transducer
L_u = distance from source of shock wave to bubble center
P_{max} = maximum impulsive pressure
$P_{r=R}$ = pressure at bubble surface
P_s = peak value of applied pressure wave
$P_{\infty,0}$ = pressure in liquid at infinity
$P_\infty(t)$ = time-dependent pressure in liquid around bubble
R = bubble radius
R_e = initial equivalent bubble radius
R_{min} = minimum bubble radius
R_0 = initial bubble radius
t = time
t_c = bubble collapse time
t_p = rise time of pressure wave
t_q = duration of pressure wave
T_∞ = liquid temperature
w = pulse width of pressure wave at half value of P_s
γ = polytropic index

Introduction

CAVITATION damage is caused predominantly by impulsive pressures generated from collapsing bubbles.[1,2] When an initially spherical bubble collapses near a solid boundary, its surface gradually departs from spherical shape due to an induced nonspherical symmetric flow. In suitable conditions, the deformation results in the formation of a liquid jet directed toward the boundary.[3-5] On the other hand, it was demonstrated that a shock wave radiates into the liquid resulting from the rapid rebound of a bubble, yet it collapses nonspherically.[6,7] Both a liquid jet and a shock wave occur and impact on the solid boundary immediately before and after the bubble collapse, and the impact is of very short duration. In this case, various kinds of impulsive pressures will occur successively. They are considered to be important factors contributing to cavitation damage. In general, the induced pressure is so affected by the degree of bubble collapse that it must be significantly dependent on the characteristics of an applied pressure, which acts as a driving force to collapse a bubble. For instance, in the case where a spherical bubble collapses under a stepwise pressure change in liquid – this situation frequently has been taken in the previous theoretical investigations,[1,4,8-10] a smaller bubble results in producing a higher pressure.[8] In actual flow measurements, however, the pressure field around a bubble varies significantly with time history so that the induced impulsive pressure must be influenced by the time dependence of the applied pressure. In fact, it was found that the collapse of a smaller bubble is not as rapid for applied pressures with a finite rise time.[11]

In contrast, even a tiny bubble can collapse rapidly if the applied pressure has a very short rise time attended by a sufficiently large amplitude. This suggests the possibility of high pressure generation by the interaction of a bubble with a shock wave or a pressure wave, some prior investigations concerning this phenomenon are available. Hansson and Mørch,[12] for example, showed the simultaneous collapse of a cluster of cavities based on the energy-transfer model due to bubble/shock-wave interaction. Dear and Field[13] demonstrated the collapse of arrays of cavities. Furthermore, Fujikawa et al.[14] theoretically analyzed the collapse of two bubbles in a compressible liquid and showed that, due to impact of a pressure wave radiated from one bubble, the accelerated collapse as well as the surface deformation of an individual bubble takes place. The authors[11,15-18] have demonstrated the high pressure generation by the bubble/shock-wave interaction. A similar problem also has been studied by Sanada et al.[19] in detail. Recently, an experimental investigation concerning the mechanism of impulsive pressure generation was conducted by Tomita and Shima,[11] who used a very soft material as a solid boundary and succeeded in getting the damage on the material surface due to collapse of a single bubble. As a result of the simultaneous measurements of bubble collapse and damage pit, it was determined that the impulsive pressure contributing directly to material damage is related essentially to the behavior of a liquid microjet.

Received Feb. 11, 1987; revision received Nov. 20, 1987.
*Professor, Institute of High Speed Mechanics.
†Research Associate, Institute of High Speed Mechanics.
‡Engineer.

However, there are still several unknown problems concerning the material failure caused by bubble collapse owing to the complexity of material, especially the dynamic response of material against impulsive pressures with very short duration.

The present paper deals with the problem of bubble/shock-wave interaction. As a result, both effects of characteristics of an applied pressure and of bubble size on the induced impulsive pressure were clarified numerically and compared with experimental results in part.

Theory

In general, a nonspherical bubble collapse is induced after interacting with a pressure wave or a shock wave. To obtain the knowledge about this type of bubble collapse, however, it is helpful to consider that a bubble is assumed to be initially in equilibrium at atmospheric pressure, and that it begins to collapse spherically as well as adiabatically.

Under this assumption, the following equation of the motion of a bubble[18] has been solved numerically:

$$R\ddot{R}\left(1-\frac{2\dot{R}}{C_\infty}\right)+\frac{3}{2}\dot{R}^2\left(1-\frac{4\dot{R}}{3C_\infty}\right)+\frac{1}{\rho_\infty}\Big\{P_\infty(t)-P_{r=R}+\frac{R}{C_\infty}(\dot{P}_\infty-\dot{P}_{r=R})\Big\}=0 \qquad (1)$$

Here $P_{r=R}$ is the pressure at the bubble surface described by the following expression:

$$P_{r=R}=\left(P_{\infty,0}+\frac{2\sigma}{R_0}\right)\left(\frac{R_0}{R}\right)^{3\gamma}-\frac{2\sigma}{R}-\frac{4\mu\dot{R}}{R} \qquad (2)$$

The pressure change around a bubble is introduced into the term $P_\infty(t)$ in Eq. (1). In calculation, two different profiles were supposed, i.e., one is an exponential decay and the other is of triangular form. The expressions for the two are given as follows:

For an exponential decay:

$$P_\infty(t)=P_{\infty,0}, \quad \text{at} \quad t<0$$

$$P_\infty(t)=P_{\infty,0}+P_s\exp(-P_st/F_t), \quad \text{at} \quad 0\le t \qquad (3)$$

For a triangular profile:

$$P_\infty(t)=P_{\infty,0}, \quad \text{at} \quad t\le 0,\ t_q\le t$$

$$P_\infty(t)=P_{\infty,0}+P_st/t_p, \quad \text{at} \quad 0\le t\le t_p$$

$$P_\infty(t)=P_{\infty,0}+P_s(t_q-t)/(t_q-t_p), \quad \text{at} \quad t_p\le t\le t_q \qquad (4)$$

Experiment

An experiment on the bubble/shock-wave interaction was carried out to compare with theory. Figure 1 shows the schematic of the observation section. A small hydrogen bubble was generated by means of the electrolysis of water and was collapsed by a shock wave produced at the instant of underwater spark discharge. The amplitude of the shock wave was measured with a pressure transducer (Swiss Kistler 603B) mounted flush to the solid boundary, which was located on the right-hand side of the source of the shock wave, as indicated in Fig. 1. The distance L_l between the source and the transducer was taken the same as L_u. Figure 2 shows an example of synchroscope trace of shock-wave pressure. In calculation, the first wavy form was replaced by a triangular profile having the same impulse as an original wave. The motion of a bubble was observed by using an Imacon high-speed camera (John Hadland 790), with a Xenon microflash with a light-pulse width of about 50 μs as a light source. The schlieren method was used to document the temporal characteristic of the phenomena. For synchronization with the phenomena, a light radiated at the instant of underwater spark discharge was used. A detailed description concerning the experimental setup including the optical system is given in previous reports.[7,11,20]

In order to measure the damage pit formation caused by the single bubble collapse, a specimen made of indium, which is a very soft material, was used as the solid boundary. The experiment was focused on the case where a small air bubble is initially almost in contact with the surface of the specimen. In this event, the observation section was rotated in the clockwise direction, and, thereafter, a bubble was hit vertically by a shock wave from below. The damaged surface was observed using a microscope.

Results and Discussion

First, numerical calculations using Eq. (1) were performed. The results for an exponential decay and for a triangular profile are shown in Figs. 3 and 4, respectively. In Fig. 4, an isosceles triangular form is assumed, so that $t_q = 2t_p$. In the two figures, P_{max} is the maximum impulsive pressure, attained at the final stage of the bubble collapse. It was found that P_{max} is significantly dependent on the characteristics of an applied pressure, such as the peak pressure P_s, the rise time t_p, and the pulse width w_s at half-value of P_s, as well as the bubble size R_e. For the finite energy case, such as a pulsewise pressure wave with a constant amplitude and duration, there is a corresponding optimum bubble size R_0^* for which the most intensive bubble collapse occurs. The optimum value is located in the region of larger bubbles as any individual parameter among P_s, w, and t_p becomes larger. This includes the obvious fact that sufficiently large energy is required for the intensive collapse of a relatively large bubble. In contrast, it is apparent from the figures that the optimum value of P_{max} shifts to the region of tiny bubbles as the rise time of a pressure wave with constant impulse becomes short. Hence, a smaller bubble may collapse rapidly due to interaction with a shock wave, which usually has a very short rise time. It is observed that the condition of $w\to\infty$ in Fig. 3 corresponds strictly to the stepwise pressure change. On the other hand, in the case of a triangular pressure wave, the $P_{max}-R_0$ curve possesses a shorter pulse width compared with the case for an

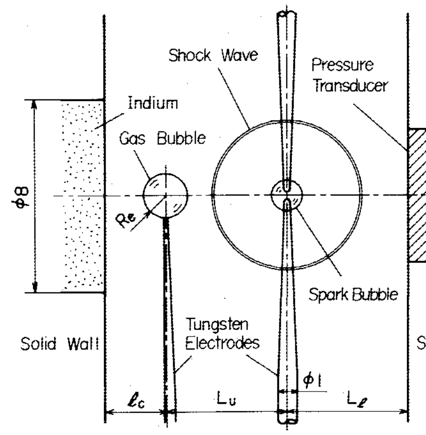

Fig. 1 Schematic view of test section.

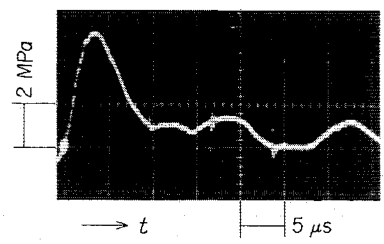

Fig. 2 Synchroscope trace of shock-wave pressure.

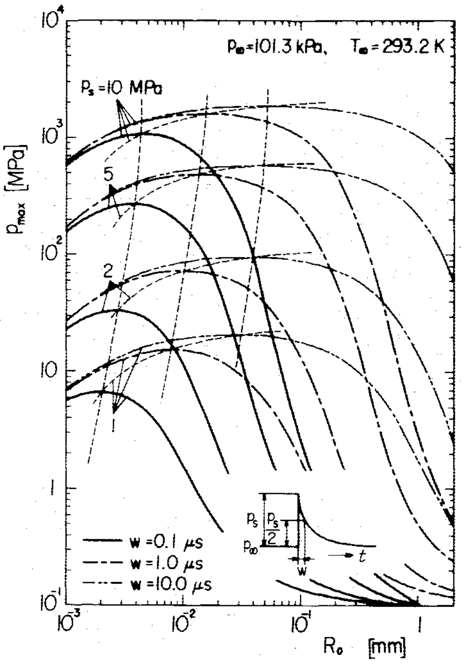

Fig. 3 $P_{max} - R_0$ **curve for a pressure wave of exponential decay.**

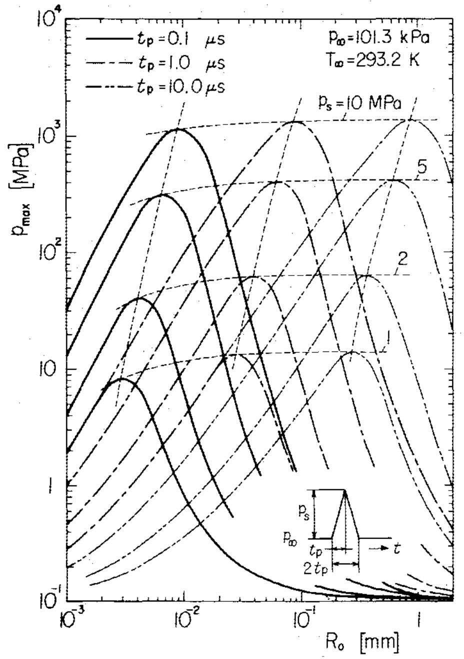

Fig. 4 $P_{max} - R_0$ **curve for a pressure wave of isosceles triangular shape.**

exponential decay due to the difference between the rise times of applied pressure waves.

Next, some theoretical results were compared with the experimentally measured values. Figure 5 shows a typical example of the collapse of a bubble with an initial equivalent radius R_e of 0.38 mm hit by a shock wave with peak pressure P_s of 5 MPa, where the frame interval is 1 μs. A black line appearing in the first frame indicates the primary shock wave, coming from the right, ready to impinge on the bubble. The bubble initially collapses, keeping an almost spherical shape; however, in the last stage of the collapse, its surface, hit by the shock wave, flattens and finally leads to the formation of a liquid microjet. The equivalent bubble radii are determined from the schlieren photographs. The experimental value for the bubble radius is estimated to be larger than the real one, because consideration is not made of the volume loss resulting from the liquid jet formation. Figure 6 shows the comparison

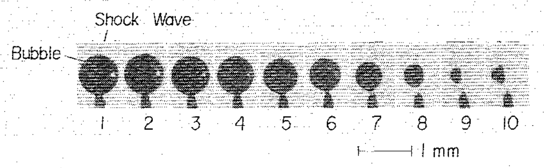

Fig. 5 Collapse of a hydrogen bubble hit by a shock wave (P_s = 5 MPa, R_e = 0.38 mm; frame interval, 1 μs).

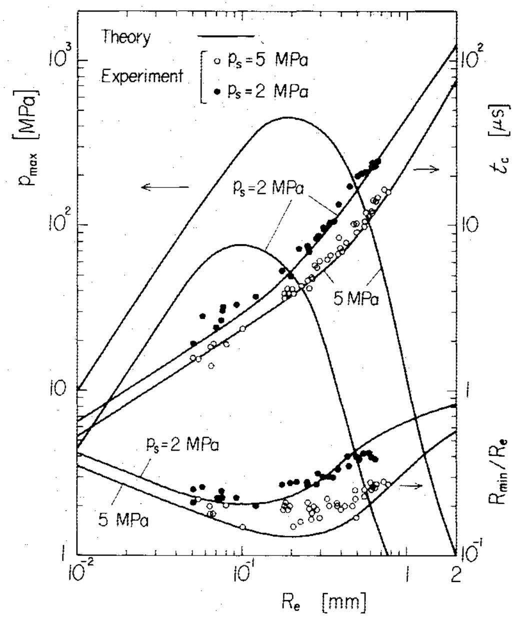

Fig. 6 Variations of P_{max}, t_c, and R_{min}/R_e with R_e (t_p = 2.5 μs when P_s = 5 MPa, and t_p = 1.8 μs when P_s = 2 MPa).

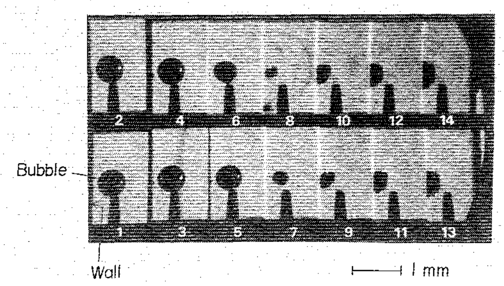

Fig. 7 Collapse of a hydrogen bubble near an indium boundary (P_s = 5 MPa, R_e = 0.27 mm, l_c/R_e = 1.4; frame interval, 1 μs).

between theory and experiment for two different applied pressure waves. As for P_{max}, only theoretical results were described in the figure, owing to the difficulty in measuring the minute impulsive pressures. Good agreement is obtained for the $t_c - R_e$ curve, while slightly different results are found for the $R_{min} - R_e$ curve because of the previously mentioned reason. However, it is observed that the experimental value of the initial equivalent bubble radius R_e, which gives the minimum value of R_{min} (or the maximum value of P_{max}), is almost coincident with the corresponding theoretical value. For instance, R_e is about 0.2 mm when P_s = 5 MPa. A bubble having this optimum radius collapses so rapidly that the generation of a very high impulsive pressure will be possible. In order to clarify this conjecture, an experiment was conducted. For this case, the strength of the shock wave was kept constant for various bubble sizes. Thereafter, subsequent damaged pits were observed. Recently, simultaneous records of the collapse process of a single bubble and the damage pit were demonstrated by Tomita et al.[11,18] Figure 7 shows the motion of a bubble near an indium specimen (l_c/R_e = 1.4). It can be clearly seen that a shock wave is appearing in the eighth frame due to the initial collapse of the bubble. In this case, however, no pitting damage can be detected on the specimen.

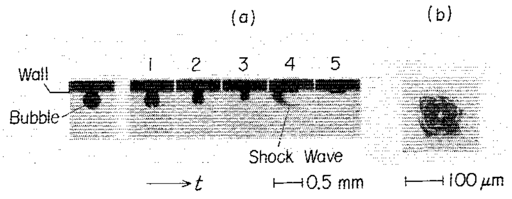

Fig. 8 Simultaneous records of bubble collapse and subsequent damage pit (P_s = 5 MPa, R_e = 0.14 mm; frame interval, 0.5 μs).

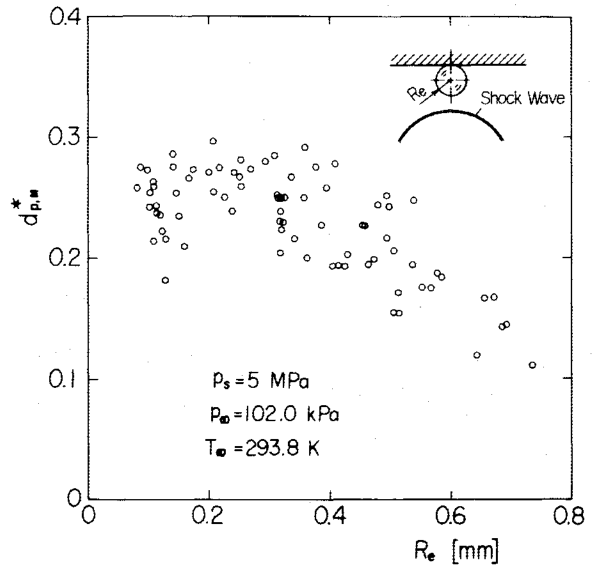

Fig. 9 $d_{p,M}^* - R_e$ curve (P_s = 5 MPa).

On the other hand, Fig. 8 indicates a typical example for the case where a bubble in contact with a solid boundary is hit by a shock wave with P_s = 5 MPa (± 0.5 MPa). A shock wave emitted from a bubble can be seen in the fourth frame. A separate picture at the right-hand corner exhibits the microscopic observation of the subsequent damage pit. Defining $d_{p,M}$ as the maximum outer diameter of the pit and plotting its dimensionless expression $d_{p,M}^*$ ($= d_{p,M}/2R_e$) against various bubble sizes R_e, we obtain Fig. 9. The $d_{p,M}^* - R_e$ curve has a maximum at roughly $R_e \simeq 0.2$ mm. This clearly shows the same tendency as the $P_{max} - R_e$ curve given in Fig. 6, which also has a maximum at the same bubble radius.

Concluding Remarks

A study has been made on the impulsive pressure caused by the interaction of a bubble with a pressure wave or a shock wave. Both the effects of the bubble size and the characteristics of an applied pressure on the impulsive pressure have been clarified. A tiny bubble collapses rapidly due to interaction with a pressure wave having very short rise time, like a shock wave. Larger bubbles, on the other hand, need corresponding larger amounts of energy to collapse intensively. Experimental measurements of the bubble collapse time and the minimum bubble radius are in good agreement with theory. Furthermore, the optimum bubble size found from the calculations is confirmed by the present experiment. An experiment concerning the damage of a soft material exhibits the most intensive damage pit at an optimum bubble size, which agrees qualitatively with the numerical prediction.

Acknowledgments

The present project was financially supported by the Science and Research Grant in Aid from the Ministry of Education of Japan in 1984. The authors wish to express their thanks to Prof. K. Takayama of Tohoku University for his useful suggestions in this work. Assistance received from Mr. N. Miura, Mr. K. Shoji, and Miss N. Inomata is acknowledged with thanks.

References

[1]Rayleigh, Lord, "On the Pressure Developed in a Liquid During the Collapse of a Spherical Cavity," *Philosophical Magazine*, Vol. 34, 1917, pp. 94–98.

[2]Knapp, R. T., "Recent Investigations of the Mechanics of Cavitation and Cavitation Damage," *Transactions of the American Society of Mechanical Engineers*, Vol. 77, Oct. 1955, pp. 1045–1054.

[3]Naudé, C. F. and Ellis, A. T., "On the Mechanism of Cavitation Damage by Nonhemispherical Cavities Collapsing in Contact with a Solid Boundary," *Journal of Basic Engineering, Transactions of the American Society of Mechanical Engineers*, Ser. D, Vol. 83, Dec. 1961, pp. 648–656.

[4]Plesset, M. S. and Chapman, R. B., "Collapse of an Initially Spherical Vapour Cavity in the Neighbourhood of a Solid Boundary," *Journal of Fluid Mechanics*, Vol. 47, May 1971, pp. 283–290.

[5]Lauterborn, W., "Kavitation durch Laserlicht," *Acustica*, Vol. 31, 1974, pp. 51–78.

[6]Fujikawa, S. and Akamatsu, T., "Experimental Investigations of Cavitation Bubble Collapse by a Water Shock Tube," *Bulletin of the Japan Society of Mechanical Engineers*, Vol. 21, Feb. 1978, pp. 223–230.

[7]Shima, A., Takayama, K., Tomita, Y., and Miura, N., "An Experimental Study on Effects of a Solid Wall on the Motion of Bubbles and Shock Waves in Bubble Collapse," *Acustica*, Vol. 48, 1981, pp. 293–301.

[8]Tomita, Y. and Shima, A., "On the Behavior of a Spherical Bubble and the Impulse Pressure in a Viscous Compressible Liquid," *Bulletin of the Japan Society of Mechanical Engineers*, Vol. 20, Nov. 1977, pp. 1453–1460.

[9]Tomita, Y. and Shima, A., "The Effects of Heat Transfer on the Behavior of a Bubble and the Impulse Pressure in a Viscous Compressible Liquid," *Zeitschrift fur Angewandte Mathematik und Mechanik*, Bd. 59, 1979, S. 297–306.

[10]Fujikawa, S. and Akamatsu, T., "Effects of the Non-Equilibrium Condensation of Vapour on the Pressure Wave Produced by the Collapse of a Bubble in a Liquid," *Journal of Fluid Mechanics*, Vol. 97, 1980, pp. 481–512.

[11]Tomita, Y. and Shima, A., "Mechanisms of Impulsive Pressure Generation and Damage Pit Formation by Bubble Collapse," *Journal of Fluid Mechanics*, Vol. 169, Aug. 1986, pp. 535–564.

[12]Hansson, I. and Mørch, K. A., "The Dynamics of Cavity Clusters in Ultrasonic (Vibratory) Cavitation Erosion," *Journal of Applied Physics*, Vol. 51, Sept. 1980, pp. 4651–4658.

[13]Dear, J. and Field, J., "A Study of the Collapse of Cavities Using Two-Dimensional Gelatine Configurations," *Proceedings of International Symposium on Cavitation*, Sendai, Vol. 1, 1986, pp. 89–94.

[14]Fujikawa, S., Hirochi, T., Takahira, H., and Akamatsu, T., "Interactions Between Two Slightly Nonspherical Bubbles in a Compressible Liquid – Part II: Numerical Analysis," *Proceedings of International Symposium on Cavitation*, Sendai, Vol. 1, 1986, pp. 55–60.

[15]Tomita, Y., Shima, A., and Takahashi, K., "The Collapse of a Gas Bubble Attached to a Solid Wall by a Shock Wave and the Induced Impact Pressure," *Journal of Fluids Engineering, Transactions of the American Society of Mechanical Engineers*, Ser. I, Vol. 105, Sept. 1983, pp. 341–349.

[16]Shima, A., Tomita, Y., and Takahashi, K., "The Collapse of a Gas Bubble Near a Solid Wall by a Shock Wave and the Induced Impulsive Pressure," *Proceedings of the Institution of Mechanical Engineers*, Vol. 198C, No. 8, 1984, pp. 81–86.

[17]Tomita, Y., Shima, A., and Ohno, T., "Collapse of Multiple Gas Bubbles by a Shock Wave and Induced Impulsive Pressure," *Journal of Applied Physics*, Vol. 56, July 1984, pp. 125–131.

[18]Tomita, Y., Shima, A., and Sugiu, T., "Mechanisms of Impulsive Pressure Generation and Damage Pit Formation by Bubble-Shock Wave Interaction," *Proceedings of International Symposium on Cavitation*, Sendai, Vol. 1, 1986, pp. 77–82.

[19]Sanada, N., Ikeuchi, J., Takayama, K., and Onodera, O., "Interaction of an Air Bubble with a Shock Wave Generated by a Micro-Explosion in Water," *Proceedings of International Symposium on Cavitation*, Sendai, Vol. 1, 1986, pp. 67–72.

[20]Shima, A., Takayama, K., Tomita, Y., and Ohsawa, N., "Mechanism of Impact Pressure Generation from Spark-Generated Bubble Collapse Near a Wall," *AIAA Journal*, Vol. 21, Jan. 1983, pp. 55–59.