EXPERIMENTAL STUDY OF DETONATING GAS BUBBLE OSCILLATIONS USING A SHOCK TUBE

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Oscillations of bubbles containing a mixture of a detonating gas with argon in their interior are studied. The bubbles are excited for oscillations by a pressure step generated in a shock tube. A bubble wall motion is observed by a rotating mirror camera and a radiated pressure wave by a needle hydrophone. For weak pressure steps the bubble behaves as an ordinary gas bubble. However, above a certain pressure step threshold ignition of the detonating gas occurs. Due to released heat the bubble oscillation intensity is amplified. The data obtained are used to estimate pressures and temperatures in the compressed bubble.

1. Introduction

Physical processes accompanying oscillations of bubbles in liquids have been a subject of intensive experimental and theoretical research for many years. As in other branches of science, experimental data also serve here both to motivate further theoretical work and to verify the theory. Up to now most of the experimental data in the research on bubble oscillations have been obtained by recording the bubble motion using high-speed photography [1–3]. This technique provides, first of all, information on bubble shape and bubble radius time history. Another method for recording the bubble wall motion is based on light beam scattering by the bubble [4].

The oscillatory motion of the bubble wall is accompanied by a variation of the pressure and temperature in the bubble interior and in the surrounding liquid. The pressure changes inside the bubble were measured by Jensen [5], and outside the bubble, e.g., by Ward and Emmony [6,7]. In contrast to recording the bubble wall motion and accompanying pressure changes, measurement of the interior temperature represents an intriguing task that has not yet been solved, to this author's best knowledge. A partial solution to this problem could be provided by using bubbles filled with detonating gas, because after reaching the ignition temperature of the gas, a microexplosion ensues, which can be easily detected. From the knowledge of the bubble volume, the respective temperature can then be computed and compared with published data. This should allow one to draw conclusions about the actual temperature in the bubble.

The detonating gas has been used in research on bubbles for a long time. Kogarko et al. [8], and Popov and Kogarko [9], for example, exploited the detonating gas as an inexpensive source of intensive underwater sound. However, during the underwater detonating gas explosion, an oscillating vapour bubble was generated.

Popov and Kogarko [9] published comprehensive data on such a bubble and these experimental data were evaluated by this author in Ref. [10]. Detonating gas bubbles were also used in the studies of shock-wave propagations in liquid-gas media [11–13]. To gain a better understanding of the physical phenomena involved in these complex processes, experiments with single detonating gas bubbles were performed by Gülhan [12], and Fujiwara and Hasegawa [14].

In this paper a further study of the detonating gas bubble oscillations is presented. As in Refs. [12,14] the bubbles are excited to oscillations by pressure steps generated in a shock tube. Besides observing the bubble wall motion by the rotating mirror camera, the pressure wave emitted by the bubble is also monitored using a needle hydrophone. Experiments are performed for different pressure step strengths both under and above the ignition point of the detonating gas, which makes it possible to estimate the ignition temperature and compare it with data found in the literature [15]. In comparison with previous work [9,12,14], a much more detailed description of the studied phenomena is obtained.

2. Experimental setup

The experimental setup used here to study the oscillations of the bubbles containing a detonating gas in their interior is the same as that described in Refs. [16,17]. Therefore only a brief summary is given here. The vertical shock tube used in the experiments consisted of three sections. The high-pressure section was filled with nitrogen at a pressure p_4. The low-pressure section contained air at atmospheric pressure $p_1 = 0.1$ MPa. The lowest section of the tube was filled with 85 % diluted glycerine. The high- and low-pressure sections were separated by a membrane. The heating wires were used to tear up the pre-stressed membrane at a precisely defined moment.

The experimental bubbles of an initial radius R_i were generated at the orifice of a small L-shaped tube submerged in glycerine. The mixture of the detonating gas and argon ($30\,\%(2H_2 + O_2) + 70\,\%Ar$, expressed in volume ratios), which was prepared in a pressurized bottle, was supplied to the L tube via a needle valve. The bubbles rose with a velocity of about $0.06\,\mathrm{m\,s^{-1}}$. A light gate was used to synchronize bubble occurrence in an observation section with the discharge of a condenser battery across the heating wires, and the following initiation of a shock wave in the air. The shock wave was transmitted into glycerine as a pressure step having a rise time of about $\Delta t = 20\,\mu s$. The pressure step had the approximate form given by the following equation

$$p_\infty = \begin{cases} p_{\infty i}, & t < 0, \\ p_{\infty i} + \Delta p\, t/\Delta t, & 0 \le t \le \Delta t. \\ p_{\infty i} + \Delta p = p'_\infty, & \Delta t < t. \end{cases} \tag{1}$$

Here $p_{\infty i}$ is the initial ambient pressure in the liquid and p'_∞ is the pressure behind the step. The pressure step strength Δp varied according to p_4 and ranged from 0 to 1.1 MPa. The constant part behind the leading edge of the pressure step lasted for approximately $\Delta T = 750\,\mu s$.

The pressure field, p, in the liquid was monitored by a needle hydrophone, the sensitive area of which was usually set at a distance $r = 3\,\mathrm{mm}$ from the bubble centre. The bubble wall motion was observed by a rotating mirror camera with framing rates up to $250000\,\mathrm{s}^{-1}$. Further details regarding the experimental arrangement used can be found in Refs. [16,17].

3. Results and discussion

Using the experimental setup described in the previous section the oscillations of the detonating gas bubbles in glycerine were studied in great detail for different pressure steps Δp. In the case of weak pressure steps ($\Delta p < \Delta p_{\mathrm{thr}}$, where Δp_{thr} is a threshold value for gas ignition) the bubbles behaved as ordinary gas bubbles. However, for stronger pressure steps ($\Delta p \geq \Delta p_{\mathrm{thr}}$) the detonating gas in the bubble interior was usually ignited during bubble compression and the bubble oscillations became more intensive.

Examples of the oscillating bubble photographs obtained for the two different regimes are shown in Fig. 1. The interval between subsequent frames on the film was $4.5\,\mu\mathrm{s}$, but only selected frames are shown in Fig. 1. It can be seen that during the compression phase the bubbles retained their spherical shape. However, after reverting the wall motion direction in the minimum radius R_{m1}, the bubbles entered the expansion phase, during which their shapes became partially deformed. The deformation was symmetrical to the direction of the pressure step propagation. In the vicinity of the maximum radius R_{M2} the bubbles recovered almost spherical shapes again. For later times the shape deformations became even more pronounced. This study is therefore limited to the first compression and expansion phases only, for which the spherical shape was approximately preserved.

Examples of the bubble radius vs. time histories are shown in Fig. 2. These graphs correspond to the photographs shown in Fig. 1. Each displayed point was computed as an average from two mutually perpendicular bubbles' dimensions. Evidently the points corresponding to the expansion phase represent only a rough estimate of an equivalent radius. For a better evaluation of the significant radii R_{i}, R_{m1}, and R_{M2} the experimental points are fitted by a curve $R(t)$. The initial radii R_{i}, as determined from different records, were rather well reproducible, and it was found that $R_{\mathrm{i}} = 1.65 \pm 0.10$ mm.

Examples of recorded acoustic waves radiated by oscillating bubbles without and with ignition are shown in Fig. 3. Comparison of Figs. 1 to 3 shows a distinct difference between the two kinds of oscillating bubbles. Whereas in the first case ($\Delta p < \Delta p_{\mathrm{thr}}$) the bubble performed ordinary damped oscillations, in the second case, during almost adiabatic gas compression, the temperature in the gas reached the ignition point and a microexplosion occurred. Due to the thermal energy released, the gas pressure and temperature increased and this resulted in an amplification of the bubble oscillation intensity. A following interesting feature could be seen in some photographs: whereas during oscillations of an ordinary gas bubble only a single ring representing one outward-travelling spherical wave could usually

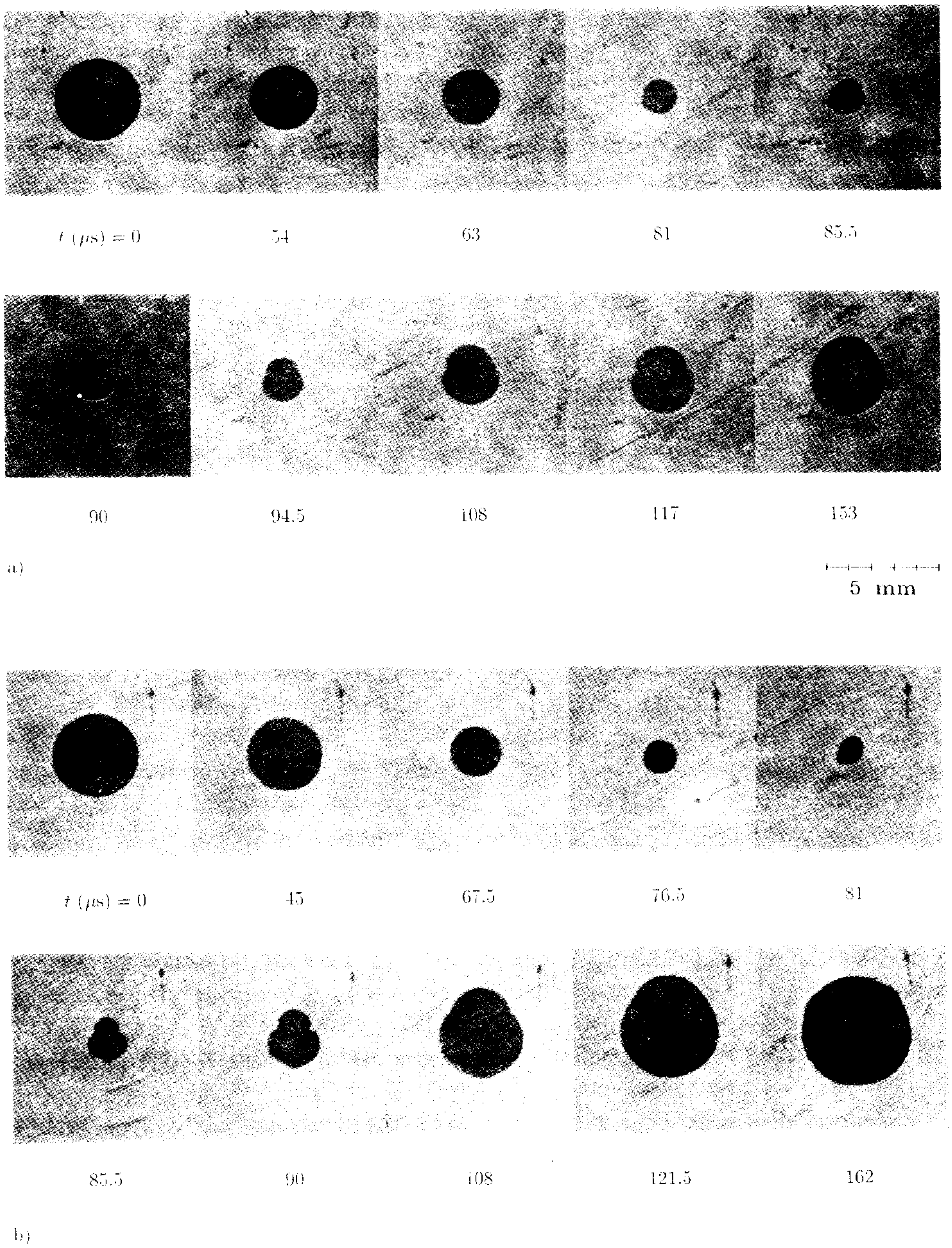

Fig. 1. Detonating gas bubble oscillations in glycerine. In the photographs the pressure step propagates downwards and the bubble translates upwards. The frames were taken at times t. a) Non-ignited bubble, the pressure step $\Delta p = 0.65$ MPa, initial bubble radius R_i=1.82 mm. b) Ignited bubble, the pressure step $\Delta p = 0.8$ MPa, initial bubble radius $R_i = 1.77$ mm.

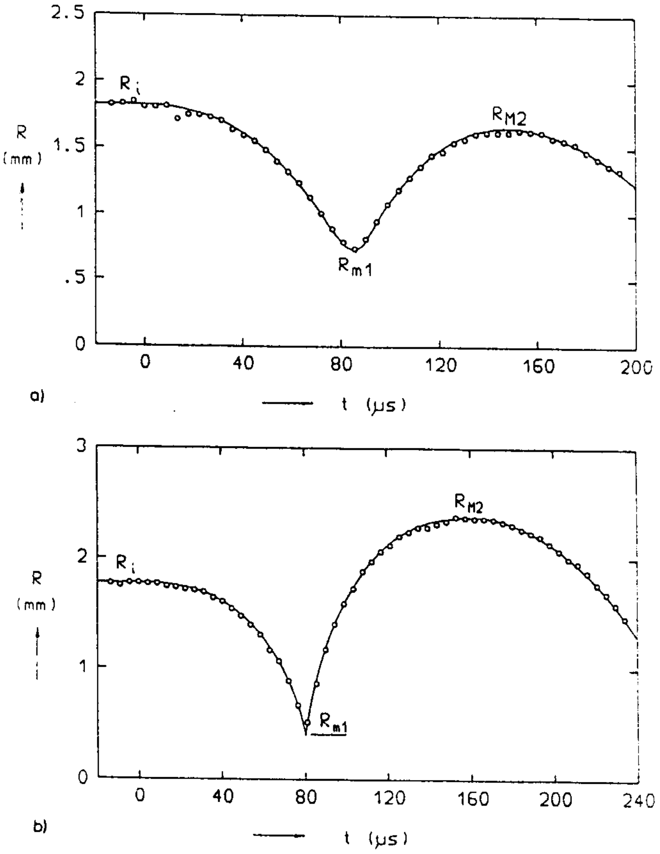

Fig. 2. Experimentally determined variations of the bubble radii R with time t for detonating gas bubbles oscillating in glycerine. a) Non-ignited bubble, $\Delta p = 0.65$ MPa, $R_i = 1.82$ mm, $R_{m1} = 0.74$ mm, $R_{M2} = 1.63$ mm. b) Ignited bubble, $\Delta p = 0.8$ MPa, $R_i = 1.77$ mm, $R_{m1} = 0.46$ mm, $R_{M2} = 2.42$ mm.

be seen at the frame taken shortly after the bubble reaches the minimum volume, then, in the case of the microexplosion, several rings could be seen. An explanation for the multiple rings is that ignition apparently starts in the bubble center, where, due to gas cooling through the wall, the temperature is the highest. The detonation wave is then reflected at the bubble wall and at the center several times and each time it is reflected at the wall a pressure ripple is transmitted into the liquid. These ripples must have only small amplitudes because no additional peaks can be seen in the pressure wave record shown in Fig. 3b, but they must be sufficiently steep to be recorded in the photographs.

Let us now estimate the ignition pressure and temperature and the maximum pressure in the gas in the bubble interior. As can be seen in Fig. 2b the bubble of an initial radius $R_i = 1.77$ mm is under the action of a pressure step $\Delta p = 0.8$ MPa compressed to a minimum radius $R_{m1} = 0.46$ mm and then fired. The

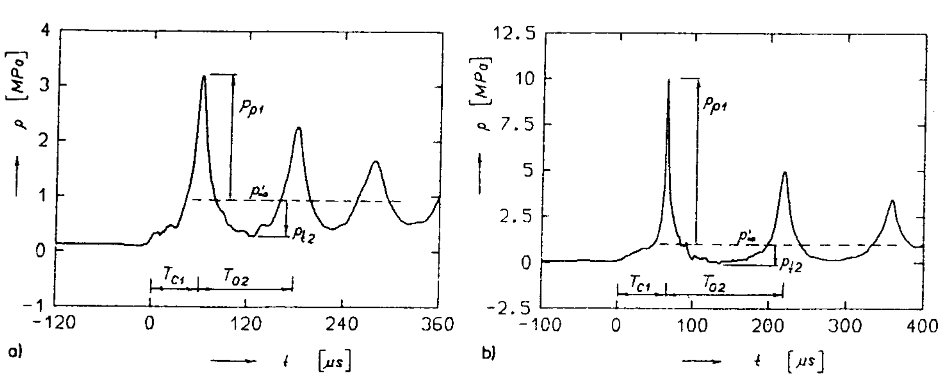

Fig. 3. Pressure waves radiated by detonating gas bubbles oscillating in glycerine. The waves were measured at a distance $r = 3$ mm from the bubble's center, $R_i = 1.65$ mm (estimated). a) Non-ignited bubble, $\Delta p = 0.84$ MPa, $p_{p1} = 2.22$ MPa, $p_{t2} = -0.67$ MPa, $T_{c1} = 68.4\,\mu$s, $T_{o2} = 118.2\,\mu$s. b) Ignited bubble, $\Delta p = 0.92$ MPa, $p_{p1} = 8.94$ MPa, $p_{t2} = -1.03$ MPa, $T_{c1} = 64.8\,\mu$s, $T_{o2} = 153.6\,\mu$s.

corresponding ignition pressure P_{IG} can be approximately found from the equation of adiabatic compression as

$$P_{IG} = p_{\infty i} \left(\frac{R_{m1}}{R_i} \right)^{-3\gamma} = 54.8 \text{ MPa}, \tag{2}$$

and similarly the ignition temperature Θ_{IG} as

$$\Theta_{IG} = \Theta_i \left(\frac{R_{m1}}{R_i} \right)^{-3(\gamma - 1)} = 2800 \text{ K}. \tag{3}$$

Here $p_{\infty i} = 100$ kPa is the initial ambient pressure, $\Theta_i = 291$ K is the initial ambient temperature, and $\gamma = 1.56$ is the ratio of the specific heats for the gas mixture 30 % $(2H_2 + O_2)$+70 % Ar.

The computed ignition temperature may be compared with the experimental values given in the literature. For example, Kumagai [15] summarizes results from different sources. According to Kumagai [15], the measured values range from 670 to 1170 K, where the large variance in the measured values is due to the method of measurement. It can be seen that the measured ignition temperatures are much lower than that computed here. There are two possible effects which seem to be responsible for this difference. First, when determining the ignition temperature experimentally, an important role is played by the period of induction (the time interval between the instant of reaching the ignition temperature and the instant the ignition really starts). It is evident that the shorter the available period of induction, the higher must be the ignition temperature. The values reported by Kumagai [15] were usually measured with the period of induction equal or larger than 0.5 s. On the other hand, from Fig. 2b it can be estimated that here the period of induction should be less than 5 μs. Hence the respective ignition temperature must be much higher than 1170 K in the case of oscillating bubble.

The second explanation for the discrepancy lies in the validity of Eq. (3). This equation was derived under an assumption of adiabatic compression. However, in a real bubble there will always be a heat flux from the gas into the liquid, and hence the temperature attained will be lower than 2800 K. A combination of the effects of the induction period and of the heat flux can then help to explain the difference found.

After the ignition, the pressure and temperature in the bubble interior increase violently. The maximum pressure P_{M1} attained can be estimated as follows: the peak pressure in the radiated wave measured at a distance $r = 3$ mm equals $p_{\mathrm{p1}} = 8.94$ MPa (see Fig. 3b). Assuming as above $R_{\mathrm{m1}} = 0.46$ mm and a spherical wave propagation (the $1/r$ law) the peak pressure at the bubble wall is

$$P_{\mathrm{p1}} = \frac{p_{\mathrm{p1}} r}{R_{\mathrm{m1}}} = 58.3 \text{ MPa}. \tag{4}$$

Hence the maximum pressure at the bubble wall is (assuming that the pressure behind the step is $p'_\infty = 1$ MPa, cf. Fig. 3b)

$$P_{\mathrm{M1}} = P_{\mathrm{p1}} + p'_\infty = 59.3 \text{ MPa}. \tag{5}$$

Thus, the pressure increase due to the detonating gas ignition is approximately 4.5 MPa.

From the bubble radius vs. time histories it is possible to determine the significant radii R_{i}, R_{m1}, and R_{M2} for different oscillation intensities (see, e.g. Fig. 2). From the pressure vs. time records (such as Fig. 3) a number of further quantities can be determined. These are the time of bubble compression T_{c1}, the time of oscillation T_{o2}, the peak and trough pressures p_{p1} and p_{t2}, respectively, and the acoustic energy in the first bubble pulse, ΔE_{a1}. The acoustic energy was determined using the formula

$$\Delta E_{\mathrm{a}} = 4\pi r^2 \frac{1}{\rho_\infty c_\infty} \int_{t_1}^{t_2} p_{\mathrm{a}}^2 \mathrm{d}t, \tag{6}$$

where $\rho_\infty = 1220$ kg m^{-3} is the liquid density, $c_\infty = 1920$ m s^{-1} is the speed of sound in the liquid, $t_1 = 0$, $t_2 = T_{\mathrm{c1}} + T_{\mathrm{o2}}/2$, $p_{\mathrm{a}} = p - p_\infty$, and p is the total pressure measured at a distance r from the bubble center.

The quantities R_{i}, R_{m1}, R_{M2}, T_{c1}, T_{o2}, p_{p1}, p_{t2}, and ΔE_{a1} were also computed using a theoretical model for a non-ignited spherical bubble as given in Ref. [17]. In these computations the initial radius was assumed $R_{\mathrm{i}} = 1.65$ mm, the distance $r = 3$ mm, the rise time $\Delta t = 20\,\mu$s, and Δp ranged from 0 to 1.2 MPa. The values of the physical constants $(\gamma, p_{\infty\mathrm{i}}, \rho_\infty, \ldots)$ have been already mentioned above.

Both the experimental and theoretical data were normalized using the relations

$$Z = \frac{R}{R_{\mathrm{i}}}, \qquad T_{\mathrm{z}} = \frac{T}{R_{\mathrm{i}}\sqrt{\dfrac{\rho_\infty}{p_{\infty\mathrm{i}}}}}, \qquad p_{\mathrm{z}} = \frac{p}{p_{\infty\mathrm{i}}}\frac{r}{R_{\mathrm{i}}}.$$

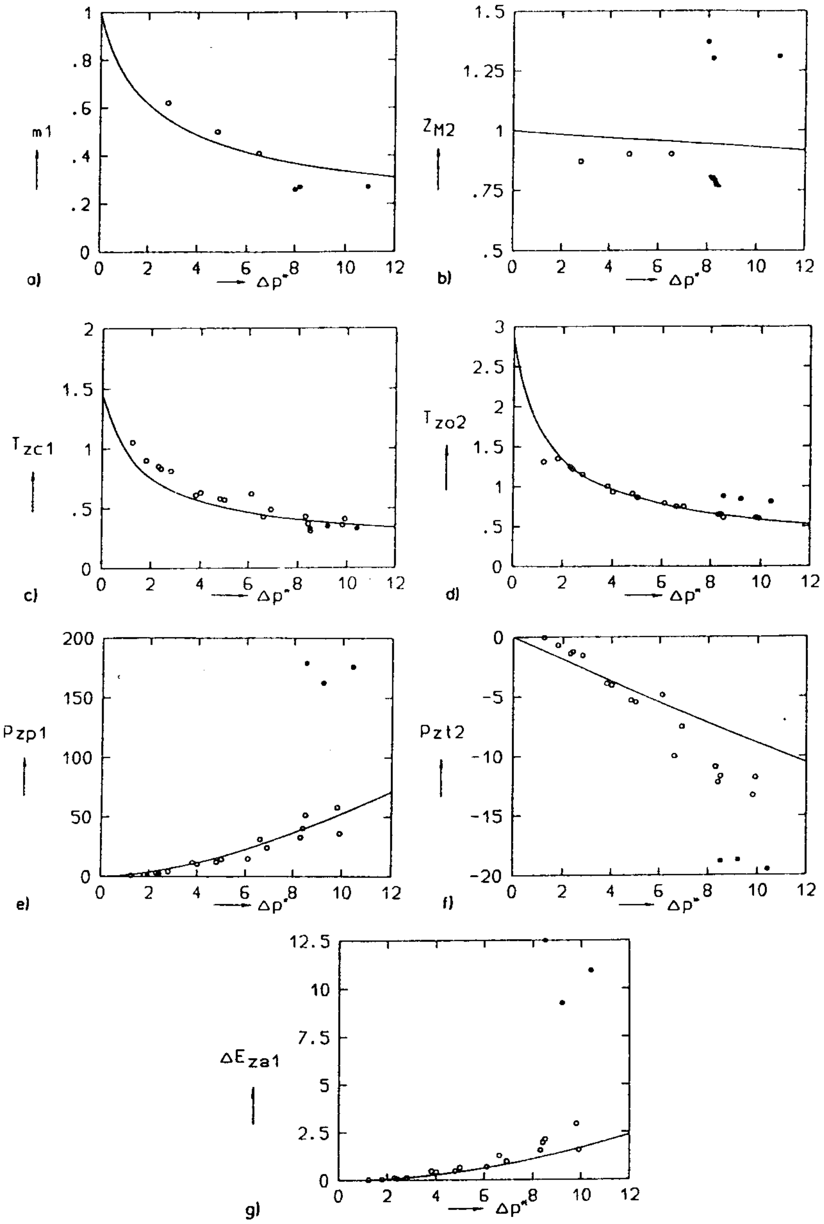

Fig. 4. Variation of the normalized data with the pressure step Δp^* (o — experimental non-ignited bubbles, • — experimental ignited bubbles, solid line — theory for non-ignited bubbles). a) First minimum radius Z_{m1}. b) Second maximum radius Z_{M2}. c) First compression time T_{zc1}. d) Second oscillation time T_{zo2}. e) First peak pressure in the radiated wave p_{zp1}. f) Second trough pressure in the radiated wave p_{zt2}. g) Acoustic energy in the first bubble pulse ΔE_{za1}.

$$\Delta p^* = \frac{\Delta p}{p_{\infty i}}, \qquad \Delta E_{za} = \frac{\Delta E_a}{\frac{4}{3}\pi p_{\infty i} R_i^3}.$$

Variations of the normalized data with the pressure step Δp^* are displayed in Fig. 4.

From Fig. 4 it can be seen that for non-ignited bubbles the differences between the theoretical and experimental values are usually larger for weaker steps Δp^* (see, e.g. data of Z_{m1}, Z_{M2}, T_{zc1}, and T_{zo2}). The deviations are such that for weaker pressure steps Δp^*, a stronger bubble oscillations damping can be observed. On the other hand, it seems that the bubbles are oscillating more intensively than predicted by the theory for stronger pressure steps Δp^*. This can be seen best from values of p_{zt2}, where for stronger Δp^* the experimental data are even more negative (which means a larger bubble expansion) than predicted by the theory. Another interesting fact regarding the experimental non-ignited bubbles is that more acoustic energy is carried away by the bubble pulse than predicted by the theory.

From Fig. 4 one can also see that the value of the threshold pressure step is approximately $\Delta p^*_{thr} \approx 8$. However, it can be seen that even for stronger pressure steps the gas does not necessarily ignite. After the detonating gas ignites the bubble behaviour seems to be stabilized, i.e., independent of the real value of Δp^*. Thus, the minimum radii of the exploded bubbles are typically $Z_{m1} \approx 0.27$, the maximum radii $Z_{M2} \approx 1.31$ etc. It is also notable that the value $Z_{m1} \approx 0.27$ lies rather deep under the theoretical curve, though one would expect that after the detonating gas was fired the increased gas pressure would tend to stop the bubble wall motion immediately, hence reverting the motion at larger Z_{m1}.

4. Conclusion

Oscillations of bubbles containing a detonating gas in their interiors have been studied. The bubbles were excited for free oscillations by a pressure-step-wave. For weaker steps ($\Delta p < \Delta p_{thr} \approx 0.8$ MPa) the experimental bubbles behaved as ordinary gas bubbles. In this case, comparison with theoretical results have revealed a more intensive bubble wall damping during the compression phase (partly due to increased acoustic radiation), followed by an excessive expansion. These deviations depend on the pressure step strength: damping predominates for weaker steps and excessive expansion for stronger ones.

When the pressure step exceeds the value Δp_{thr}, the ignition of the detonating gas changes the whole picture. The pressure and temperature in the compressed gas are further increased, which results in bubble oscillation intensity amplification. Due to the nonuniform temperature field in the compressed bubble, the ignition starts at the bubble center. A detonating wave is then reflected at the bubble wall several times, each reflection being accompanied by a transmission of a pressure ripple into the liquid. These ripples can be seen in the photographs as concentric rings.

The experimental data obtained also allow for a quantitative evaluation of the processes involved. For example, it was possible to estimate the ignition pressure $P_{\mathrm{IG}} = 54.8$ MPa and temperature $\Theta_{\mathrm{IG}} = 2800$ K and the increased maximum pressure in the bubble interior $P_{\mathrm{M1}} = 59.3$ MPa. The computed ignition temperature was compared with the experimental values given in the literature [15], and it was found that the experimental values are much lower. The reason for the difference can be both the extremely short time interval ($< 5\,\mu$s), during which the temperature in the bubble is sufficiently increased, and the heat flux from the bubble. The values of P_{M1} and Θ_{IG} can also be compared with theoretical computations performed by Gülhan [12], who has found the maximum pressure $P_{\mathrm{g,\,max}} = 34.4$ MPa and maximum temperature $T_{\mathrm{g,\,max}} = 3475\,\mathrm{K}$.

In comparison with previous work [9,12,14], the oscillations of detonating gas bubbles were studied in great detail here. In Refs. [9,12,14] the measurements were usually carried out only for one or two intensities of bubble oscillation (and the intensity was even not closely specified), and the research concentrated on high-speed photography records. Even if the pressure waves were also recorded, with the exception of those given in Ref. [9], they were highly distorted and thus unsuitable for further processing. The data measured here, on the contrary, consisted of a large array of values, including the three significant bubble radii and pressure wave parameters, and all these values were recorded for different intensities of bubble oscillations.

It is hoped that the extensive experimental data presented in this paper could be used by theoretical researchers for validation of their models. In this connection, as a typical example, a recent excellent theoretical paper on thermal behaviour of bubbles by Prosperetti [18] can be mentioned. The theoretical model presented in Ref. [18] is unfortunately not compared with any empirical data, simply because they were evidently not available at that time.

In closing, a few recommendations for further work can also be formulated. First, to be able to estimate the temperature in the bubble interior using the detonating gas method, the experimental ignition temperatures obtained for very short periods of induction are needed. Also, experiments similar to those described here, but exploiting different bubble sizes, liquids, and gases, are necessary. It is believed that such experiments will help to clarify the complicated physical processes accompanying the oscillations of bubbles in liquids.

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