Light from oscillating bubbles – persisting mystery

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Abstract Spark discharges in water have been used to generate oscillating bubbles. During a spark discharge intensive optic and acoustic pulses are emitted. The discharge channel expands violently and converts into a radially oscillating almost spherical bubble. The plasma in the bubble interior cools down during the growth phase which follows the discharge. However, during the next compression phase the plasma in the bubble interior is compressed and heated and optic and acoustic pulses are emitted again. Using a photodiode and a hydrophone the optic and acoustic emission from the spark discharge and subsequent bubble oscillation phases could be recorded simultaneously. By analyzing the acoustic wave the bubble size and its oscillation intensity can be determined. However, now these data are accompanied by a light emission record which significantly enhances understanding of the spark bubble behavior.

1 INTRODUCTION

Light emission from bubbles oscillating in liquids has been studied extensively in experiments where bubbles are generated using a wide variety of techniques. These techniques include acoustic cavitation [1], laser generated bubbles [2, 3], spark generated bubbles [4], and conical bubbles [5]. Despite all of this effort, however, the mechanism of light emission is still not well understood.

In this presentation the first results obtained in our experiments with large spark generated bubbles oscillating in water are given. An obvious advantage of the large bubbles is that they can be more easily studied and one can observe details not seen in previous works. The technique of low voltage spark discharges makes it also possible to generate bubbles of different sizes and oscillating with different intensities [6], which further enhance the data analysis. And finally, by recording both optical and acoustic radiation from the bubble simultaneously, a deeper insight into the phenomena of light emission is possible. Results presented here are an extension of the work published in reference [7].

2 EXPERIMENTAL SETUP

Freely oscillating bubbles have been generated by discharging a capacitor bank via a sparker submerged in water. Both the spark discharge and subsequent bubble oscillations are accompanied by intensive optical and acoustic radiation. The optical radiation has been received with a photodiode (Hamamatsu type S2386-18L, usable spectral range 320 nm to 1 100 nm), the acoustic radiation has been monitored with a broad band hydrophone (Reson type TC 4034, usable frequency range 1 Hz to 470 kHz). The output voltages from the photodiode and hydrophone have been recorded using a data acquisition board (National Instruments PCI 6115, 12 bit A/D converter) having a sampling frequency of 10 MHz. A schematic diagram of the experimental setup is shown in Figure 1. A more detailed description of the experimental setup is given in [6].

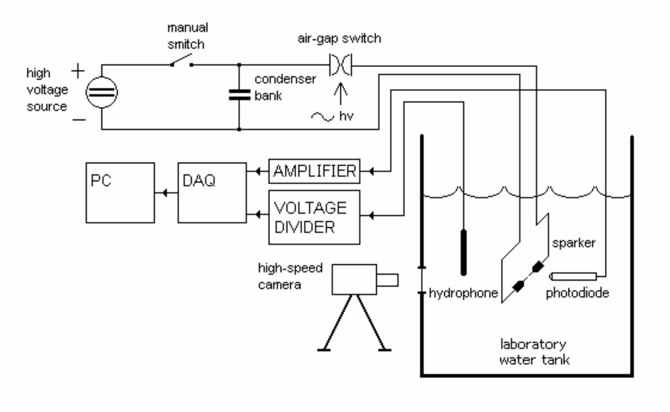

Figure 1. *Schematic diagram of the experimental setup*

3 RESULTS

An example of a pressure record obtained with the hydrophone is given in Figure 2a, and an example of a photodiode output voltage is given in Figure 2b. As can be seen, both records consist of initial pulses $p_0(t)$ and $u_0(t)$, radiated during the spark discharge, and of first pulses $p_1(t)$ and $u_1(t)$, radiated during the first bubble compression.

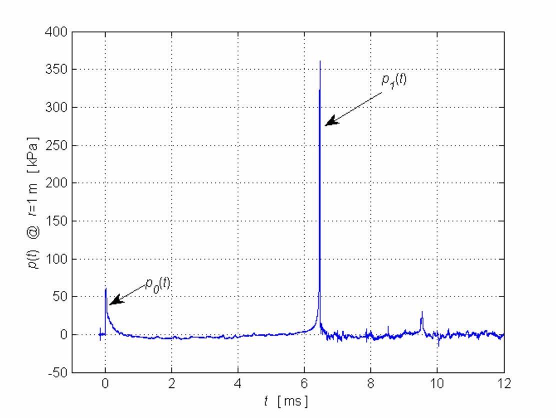

Figure 2a. *An example of pressure record*

From the pressure records it is possible to determine for each bubble its size, represented by the first maximum bubble radius R_{M1}

$$R_{M1} = \frac{T_{o1}}{2T_{zc1}\sqrt{\dfrac{\rho_\infty}{p_\infty}}} \quad .$$

Here T_{o1} is the time of the first oscillation (determined as the interval between $p_0(t)$ and $p_1(t)$), T_{zc1} is a non-dimensional time of the first oscillation, ρ_∞ is the liquid density and p_∞ is the ambient pressure at the place of the bubble. Further from the pressure records it is possible to determine for each bubble also intensity of bubble oscillations, represented by a non-dimensional peak pressure in the first bubble pulse p_{zp1}

$$p_{zp1} = \frac{p_{p1}}{p_\infty}\frac{r}{R_{M1}} \quad .$$

Here p_{p1} is the peak pressure in the first bubble pulse, and r is the distance from the bubble center to the hydrophone.

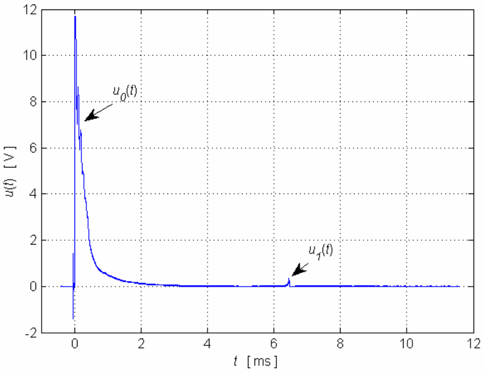

Figure 2b. *An example of photodiode voltage record*

From the peak values of optical pulses $u_0(t)$ and $u_1(t)$, using the Steffan-Boltzmann law, a rough estimate of the surface temperature of the compressed bubble can be obtained. Assuming that the maximum surface temperature of the discharge channel is about 20 000 K (see, e.g. ref. [8]), then one obtains for the surface temperature of the compressed bubble a value 8 000 K.

From the records of photodiode output voltage a number of further quantities can be determined. These include, for example, the peak voltage u_{p1} in the first pulse, and the width Δ of the first pulse.

A detailed view at the first pressure pulse $p_1(t)$ and optical pulse (voltage output from the photodiode) $u_1(t)$ is shown in Figure 3. These two pulses have been recorded simultaneously and in the records displayed the times corresponding to the beginning of the spark discharge have been aligned for the purpose of pulses comparison. It can be seen that the optical pulse is much wider than the pressure pulse and grows relatively slowly to a peak value u_{p1}. An interesting fact is that it attains this peak value a few microseconds before the pressure pulse attains its peak value p_{p1} (and hence before the bubble is compressed to its minimum volume). Similar phenomenon has also been observed by other researchers [3, 4]. After reaching the peak value the optical radiation is decreasing rapidly to almost zero value.

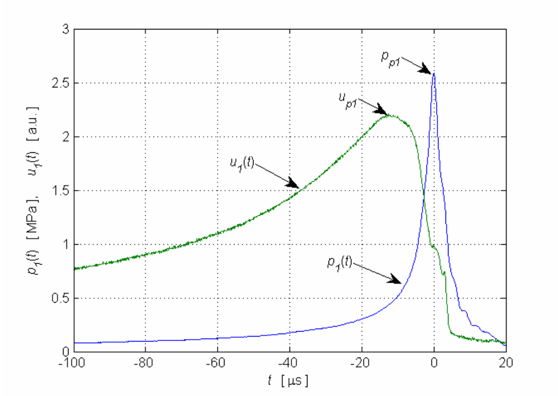

Figure 3. *Comparison between the first optical pulse* $u_1(t)$ *and the first pressure pulse* $p_1(t)$*. In this concrete example the bubble size was* $R_{M1}=38$ *mm and the non-dimensional peak pressure in the first pulse is* $p_{zp1}=107$

The experiments have been repeated many times and thus it was possible to record the first voltage pulses $u_1(t)$ for different bubble sizes, R_{M1}, and different intensities of oscillations, p_{zp1}. The variation of peak voltage in the first optical pulse, u_{p1}, with bubble size, R_{M1}, is shown in Figure 4. It can be seen that the peak voltage, u_{p1}, grows with bubble size, R_{M1}, faster than it would follow from the assumption of adiabatic bubble compression. It is remarked here that the peak voltages u_{p1} are correlated with bubble oscillation intensities p_{zp1} only weakly. And the large scatter in the values of u_{p1} is due to a relatively large random behavior associated with bubble generation and its oscillations [6].

From the individual records of the first optical pulse $u_1(t)$ a full width at one-half of the maximum value of the pulse, Δ, could also be determined. The variation of the pulse width, Δ, with bubble size, R_{M1}, is shown in Figure 5. Again, it can be seen that the pulse width, Δ, grows with bubble size, R_{M1}, faster than it would follow from the assumption of adiabatic bubble compression. And again, the correlation of widths, Δ, with bubble oscillation intensities, p_{zp1}, is very weak. A relatively large scatter in the values of Δ documents a large random behavior associated with bubble generation and its oscillations, as already mentioned above.

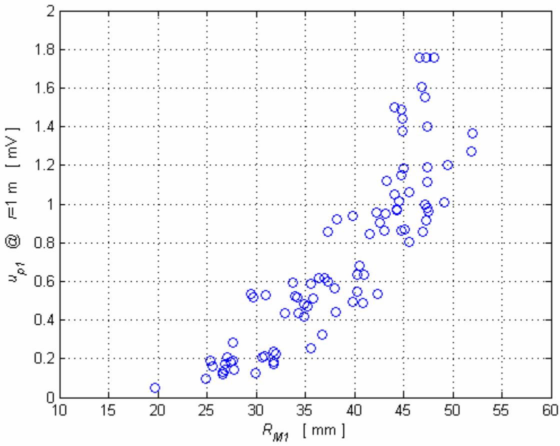

Figure 4. *Variation of the first optical peak voltage* u_{p1} *with bubble size* R_{M1}

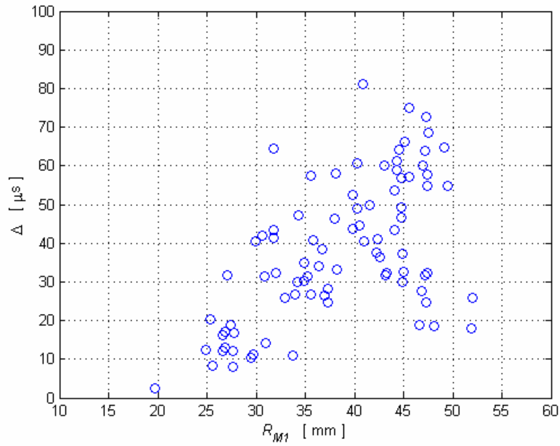

Figure 5. *Variation of the first optical pulse width* Δ *with bubble size* R_{M1}

In Figure 6 a comparison of optical pulse widths Δ determined in different experiments is given. Data displayed in this figure must be compared mutually with certain care, as they represent very different experimental conditions. For example, the spark generated bubbles are one thousand-time larger than the bubbles generated in single bubble oscillations experiments. Hence, their thermal behavior will be quite different. Also the initial temperature in laser and spark generated bubbles is extremely high. On the other hand the initial temperature in single bubble experiments is, most probably, close to the ambient temperature. Despite these large differences it is interesting to see that the data points are ordered in the graph rather reasonably.

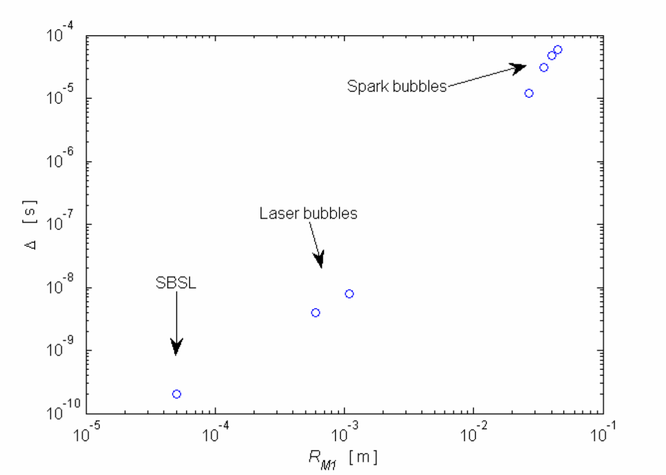

Figure 6. *Comparison of pulse widths determined in different experiments (SBSL – single bubble oscillation [1], laser generated bubbles – data from ref. [2, 3], spark bubbles – experiments reported in this work)*

4 CONCLUSIONS

The large experimental bubbles studied here made it possible to observe the form of the optical pulse radiated during the bubble oscillation in greater detail than reported in previous works [1–4]. The first optical pulse, $u_1(t)$, is much broader than the first pressure pulse, $p_1(t)$, and reaches its peak value already before the bubble is compressed to its minimum volume. After reaching the peak value the optical radiation is decreasing very rapidly to almost zero value. The observed features of the optical pulse together with the determined variations of peak values and widths of the optical pulses suggest a more complex behavior of bubble interior than it is assumed in most present theoretical models.

ACKNOWLEDGMENTS

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