Is thermal behavior of spark generated bubbles adiabatic?

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Introduction

The thermal behavior of bubbles intensively oscillating in liquids is still not well understood. The reason is a relative large complexity of this phenomenon and difficulties associated with obtaining suitable experimental data. In theoretical analysis dealing with low intensity gas bubble oscillations it is usually assumed that the bubbles behave adiabatically or isothermally [1]. However, not much is known about high intensity oscillations of vapor bubbles. Based on analysis of experimental data it will be shown in this work that the adiabatic assumption cannot be used when dealing with spark generated bubbles.

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 1100 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 more detailed description of the experimental setup is given in [2].

Results

An example of a photodiode output voltage is given in Figure 1, and an example of a pressure record obtained with the hydrophone is given in Figure 2. As can be seen, both records consist of initial pulses, radiated during the spark discharge, and of first pulses, radiated during the first bubble compression.

It can be seen in Figure 1 that the explosive growth of the spark generated bubble is accompanied by intensive thermal radiation. Because of this radiation the bubble does not behave adiabatically in the growth phase. However, as will be shown later, the bubble does not behave adiabatically even during the compression phase, when thermal radiation is insignificant.

To show this let us assume that the oscillating bubble contains a non-condensable gas in its interior and that there is no thermal radiation from the bubble and no heat flow between the gas and the surrounding liquid. Further let us assume that the temperature is distributed homogeneously within the bubble interior.

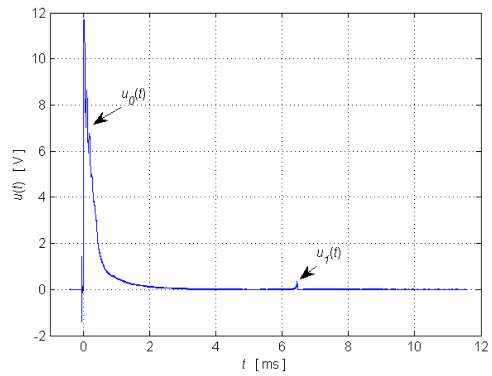

Figure 1: An example of photodiode voltage record.

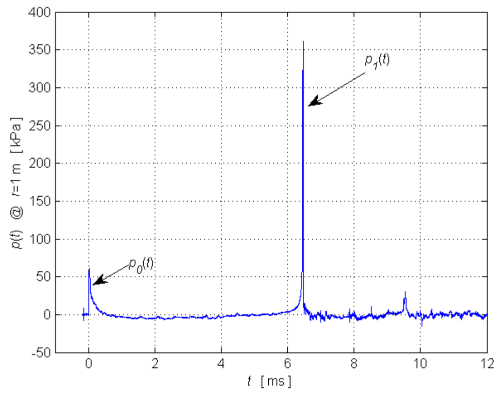

Figure 2: An example of pressure record.

Under these assumptions the temperature Θ_{M0}, which corresponds to the bubble of radius R_{M0}, can be related with a temperature Θ, corresponding to a bubble of radius R, by a simple relation

$$\Theta = \Theta_{M0}\left(\frac{R_{M0}}{R}\right)^{3(\gamma-1)} . \qquad (1)$$

Here γ is the ratio of the specific heats of the non-condensable gas inside the bubble. Similarly, under the same assumptions as given above, the pressure at the bubble wall P, when the bubble has a radius R, can be related with the pressure in infinity, p_∞, by a relation (R_e is the equilibrium bubble radius defined by a condition that $P=p_\infty$, when $R=R_e$)

$$P = p_\infty \left(\frac{R_e}{R} \right)^{3\gamma} \quad . \qquad (2)$$

Even if the photodiode output voltage displayed in Figure 1 is not equal to the temperature of the gas in the bubble, and even if the acoustic pressure displayed in Figure 2 is not equal to the pressure at the bubble wall, it can be seen immediately that equations (1) and (2) cannot be used at the same time to explain the waveforms shown in Figures 1 and 2. Thus already this simple reasoning shows that the adiabatic assumption is not valid for the spark generated bubbles.

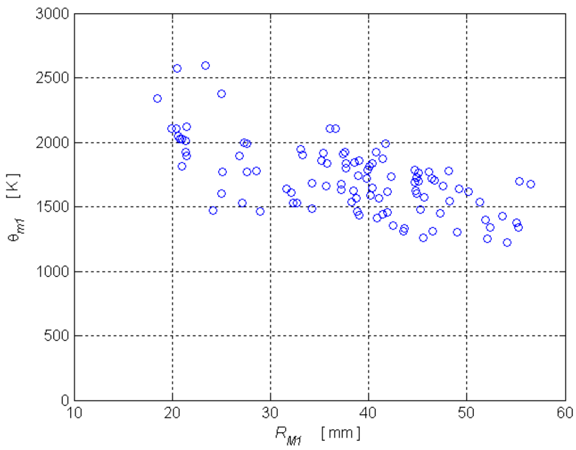

Figure 3: Variation of the temperature Θ_{m1} with bubble size R_{M1}.

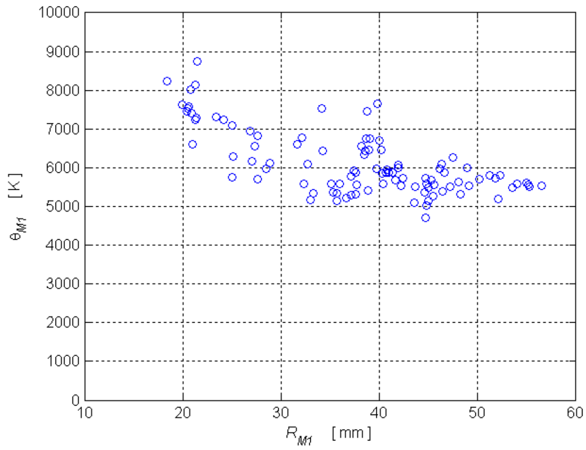

Figure 4: Variation of the temperature Θ_{M1} with bubble size R_{M1}.

Using the Stefan-Boltzmann Law it can be shown that the plasma surface temperature Θ in the bubble of radius R can be determined from the photodiode output voltage u using the following equation

$$\Theta^4 = \frac{\Theta_{M0}^4 R_{M0}^2}{u_{M0}} \frac{u}{R^2} \quad . \qquad (3)$$

Here u_{M0} is the photodiode output voltage corresponding to the bubble of radius R_{M0}. Determination of Θ_{M0} and R_{M0} will be explained elsewhere.

Using Equation (3) two significant temperatures Θ_{m1} and Θ_{M1} can be computed (Θ_{m1} is the surface temperature of the plasma core when the bubble expands to its first maximum radius R_{M1} and Θ_{M1} is the temperature of plasma when the bubble is compressed to its first minimum radius R_{m1}). Variations of Θ_{m1} and Θ_{M1} with maximum bubble radius R_{M1} are shown in Figures 3 and 4. These temperatures can be compared with results of other authors. In [3] the temperature Θ_{m1}=2850 K was determined for spark generated bubbles and in [4] the temperature Θ_{M1}=7800 K was determined for laser generated bubbles. These values are in a relatively good agreement with the temperatures given in Figures 3 and 4.

Conclusions

The thermal behavior of the spark generated bubbles has been studied. The analysis has been based on experimental data obtained with a help of optic and acoustic sensors, and partially also with a high speed camera. It has been shown that the interior of the spark generated bubbles is filled with high temperature plasma during the first oscillation. It has been further shown that the spark generated bubbles do not behave adiabatically. Even more, the temperature is not distributed inside the bubble homogeneously and the plasma is not in thermal equilibrium. The surface plasma temperatures corresponding to the instants of the maximum bubble radius range between 1200 and 2600 K, and the temperatures corresponding to the instants of the minimum bubble radius range between 4700 and 8700 K. These temperatures seem to be in a relatively good agreement with results of other researchers [3, 4].

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