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DETERMINATION OF TEMPERATURES IN OSCILLATING BUBBLES: EXPERIMENTAL RESULTS

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Abstract: *The surface temperatures of the plasma core at the final stages of the first contraction phase of spark generated bubbles oscillating under ordinary laboratory conditions in a large expanse of water are determined experimentally. The measurement method is based on the analysis of optical radiation from the bubbles and on an assumption that the plasma core is radiating as a black-body. It is found that the maximum surface temperatures of the plasma core range from 4300 K to 8700 K and these temperatures decrease with a bubble size.*

Keywords: Bubble oscillations, Spark generated bubbles, Temperature in bubbles.

1. Introduction

Bubble oscillations remain an important topic in fluid dynamics. In experimental studies of free bubble oscillations spark generated bubbles represent very useful tools (Huang et al., 2014). The value of temperature in a bubble interior during the final stages of the first contraction has been attracting interest for years, see, e.g., Golubnichii et al. (1980), Baghdassarian et al. (2001), Brujan et al. (2005), Brujan & Williams (2005). In the present paper it is intended to deal with this interesting topic in a greater detail. The analysis is devoted to free bubble oscillation under ordinary laboratory conditions in a large expanse of liquid.

2. Experimental setup

Freely oscillating bubbles were generated by discharging a capacitor bank via a sparker submerged in a laboratory water tank. Both the spark discharge and subsequent bubble oscillations were accompanied by intensive optical and acoustic radiations. The optical radiation was monitored by a detector, which consisted of a fiber optic cable, photodiode (Hammamatsu photodiode type S2386-18L), amplifier, and A/D converter (National Instruments PCI 6115, 12 bit A/D converter with a sampling frequency of 10 MHz). The acoustic radiation was monitored with a Reson broadband hydrophone type TC 4034. The output of the hydrophone was connected via a divider 10:1 to the second channel of the A/D converter. In the experiments a larger number of almost spherical bubbles freely oscillating in a large expanse of liquid were successively generated. The size of these bubbles, as described by the first maximum radius R_{M1}, ranged from 18.5 mm to 56.5 mm, and the bubble oscillation intensity, as described by the non-dimensional peak pressure in the first acoustic pulse $p_{zp1} = (rp_{p1})/(p_\infty R_{M1})$, ranged from 24 to 153. Here p_{p1} is the peak pressure in the first acoustic pulse $p_1(t)$, p_∞ is the ambient (hydrostatic) pressure at the place of the sparker, and r is the hydrophone distance from the sparker centre. Both R_{M1} and p_{zp1} were determined in each experiment from the respective pressure record.

3. Results

An optical record (represented by a voltage $u(t)$ at the output of the optical detector) consists of a pulse $u_0(t)$ that is radiated during the electric discharge and the following explosive bubble growth, and of the pulse $u_1(t)$ that is radiated during the first bubble contraction and the following bubble expansion. The dynamic range of the optical detector was not sufficiently high to record both $u_0(t)$ and $u_1(t)$ in one experiment with a good fidelity. Therefore two sets of experiments were done. The first set of

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experiments was aimed at recording the pulse $u_0(t)$ undisturbed, and the second set of experiments was aimed at recording the pulse $u_1(t)$ with an acceptable noise. A link between the two sets of experiments was achieved by using statistical averages from the first set of records to compute the respective values for the second set of records.

An example of the optical pulse $u_1(t)$ from the second set of experiments is given in Fig. 1.

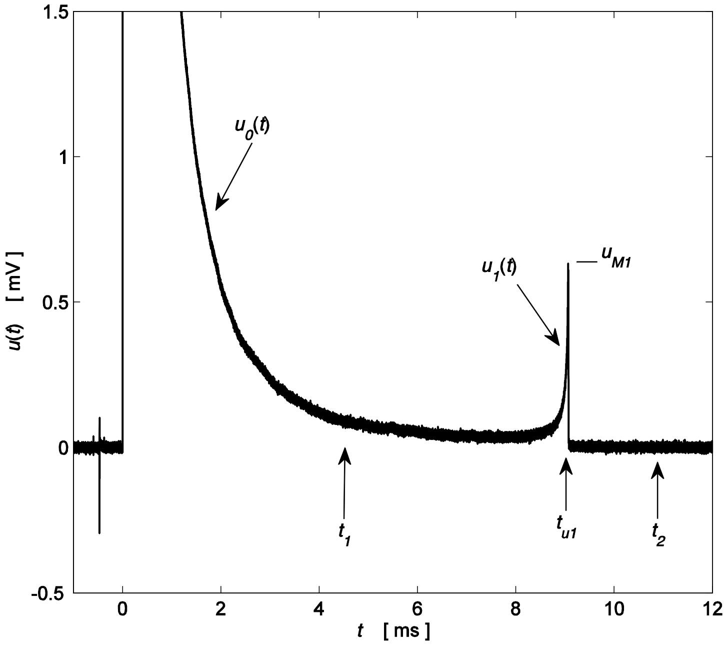

Fig.1: A voltage u(t) at the output of the optical detector. The spark generated bubble has a size R_{M1} = 55.2 mm, and oscillates with an intensity p_{zp1} = 153.2. The time, at which the bubble attains the first maximum radius R_{M1}, is denoted as t_1, and the time, the bubble attains the second maximum radius R_{M2}, as t_2. The pulse $u_0(t)$ is defined to be within the interval $(0,t_1)$, the pulse $u_1(t)$ within the interval (t_1,t_2).

In Fig. 1 the pulse $u_0(t)$ is clipped due to the limited dynamic range of the optical detector. The maximum value of the pulse $u_1(t)$ has been denoted as u_{M1} and the time of its occurrence as t_{u1}. As can be seen in Fig. 1, the optical radiation from the bubble decreases rapidly to zero after t_{u1}. Another interesting fact which can be seen in Fig. 1 is the occurrence of the optical radiation from the bubble during the whole first oscillation. The source of this persisting optical radiation is a plasma core. The bubble interior is filled with two substances. First, it is a transparent matter, which is, most probably, hot water vapour. And second, there is opaque plasma at the bubble centre. The existence of this hot plasma core during the whole first bubble oscillation, that is, even long after the electric discharge has terminated is an astonishing phenomenon observed already by Golubnichii et al. (1980).

Under an assumption that a hot plasma core in a bubble centre radiates as a black-body, an equation enabling the determination of the plasma surface temperature $\Theta(t)$ has been derived in Vokurka & Plocek (2013). The derivation is based on the Stefan-Boltzman Law, the equation of energy partition during the electric discharge, the time variation of the bubble radius $R(t)$, and the voltage $u(t)$ at the output of the optical detector. Particularly, for the voltage record $u_1(t)$ from the second set of experiments the corresponding temperature $\Theta(t)$ is given by the following equation

$$\Theta^4(t) = \frac{\langle \Theta_{M0} \rangle^4 \langle R_{M0} \rangle^2}{\langle u_{M0} \rangle} \frac{u_1(t)}{R_p^2(t)} \quad . \tag{1}$$

Here u_{M0} is the maximum voltage in the pulse $u_0(t)$ and this voltage corresponds to the bubble radius R_{M0}. The surface temperature of the plasma, when the bubble during its growth attains the radius R_{M0}, is Θ_{M0}. The angle brackets < > denote the average values on the first set of experiments. For a given bubble size

R_{M1} these average values can be computed using the regression lines and the polynomial derived in Vokurka & Plocek (2013): $<\Theta_{M0}> = -0.11R_{M1}+17.4$ [kK, mm], $<R_{M0}> = 0.1836R_{M1}$, and $<u_{M0}> = 1.25 \times 10^{-4}R_{M1}^2$ [V, mm].

In Eq. (1), R_p is a radius of a light emitting hot plasma core. An estimate of the radius R_p can be obtained from the knowledge of the bubble wall radius R and of the volume the plasma core occupies in the bubble interior. Denoting a reduction factor as q ($q < 1$), then $R_p = qR$. The variation of the bubble wall radius R with time can be computed using a theoretical bubble model. The exact value of the reduction factor q is not known at present. In this work an estimate of the reduction factor $q = 0.8$ will be used for the vicinity of the first minimum radius R_{m1}, irrespective of the bubble oscillation intensity p_{zp1}.

An example of the variation of the plasma core surface temperature Θ with time t during the first bubble contraction and the following expansion, as computed with eq. (1), is given in Fig. 2.

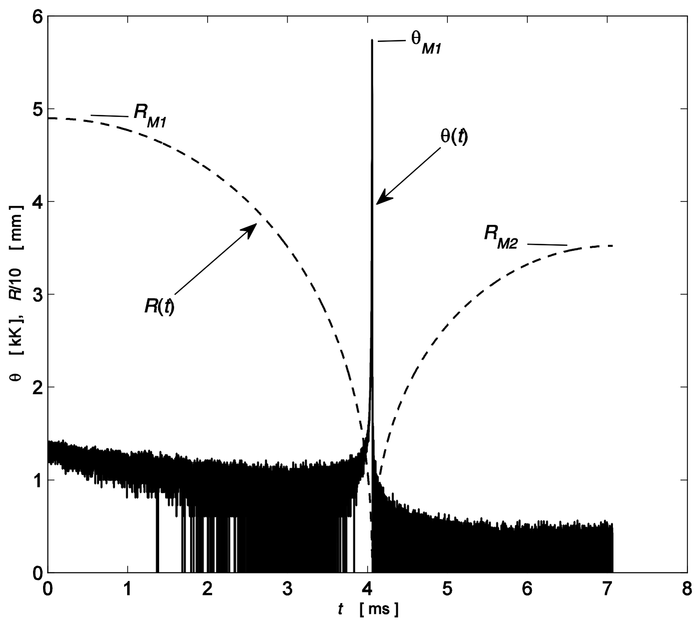

Fig. 2: A time variation of the plasma core surface temperature Θ and of the bubble wall radius R. The size of the experimental bubble is R_{M1} = 49.0 mm, the bubble oscillation intensity is p_{zp1} = 142.1.

A few comments concerning Eq. (1) and Fig. 2 should be presented now. Eq. (1) has been derived under an assumption that the plasma core is a black-body radiator. This assumption seems to be correct in those instants, when the pressure and temperature in the bubble interior are high. And this is fulfilled only in the vicinity of R_{m1}. Hence the computed temperature $\Theta(t)$ shown in Fig. 2 is correct only in the vicinity of the maximum value Θ_{M1}. In other instants the computed temperatures represent just a very rough estimate.

In Eq. (1), only the voltages $u_1(t)$ and u_{M0} are measured directly. The radii $R(t)$ and R_{M0} are computed using Herring's simplified model (Buogo & Vokurka, 2010). The parameters R_{M1} and p_{zp1} have been determined for each record $u_1(t)$ from the associated pressure record. Using these parameters the first bubble minimum radius $R_{m1} = f(R_{M1},p_{zp1})$ can be computed. An estimate of the corresponding plasma core radius is then $R_{pm1} = 0.8R_{m1}$. Thus, using the measured values of u_{M1}, R_{M1}, and p_{zp1} from the second set of experiments and the average values of $<\Theta_{M0}>$, $<R_{M0}>$, and $<u_{M0}>$ determined for a given bubble size R_{M1} from the regression lines and the polynomial given above, the temperature Θ_{M1} can be computed. The values of Θ_{M1} determined in this way for different bubble sizes R_{M1} are displayed in Fig. 3.

The temperatures Θ_{M1} given in Fig. 3 can be compared with experimental results of other researchers. For example, Golubnichii et al. (1980) found that the maximum in the spectrum of the optical radiation lies approximately at 500 nm. Then, using the Wien's Law, the temperature Θ_{M1} = 5800 K is obtained (in this case R_{M1} was 30 mm). Baghdassarian et al. (2001) determined that Θ_{M1} = 7800 K (now R_{M1} ranged from 0.6 mm to 0.8 mm). Finally Brujan et al. (2005) , and Brujan and Williams (2005) determined that Θ_{M1} = 8150 K (in this case R_{M1} ranged from 0.65 mm to 0.75 mm).

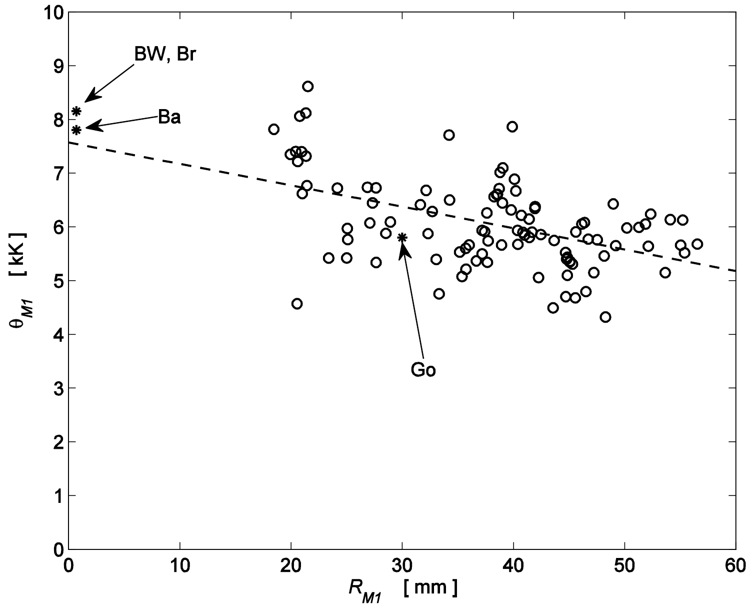

Fig. 3: Variation of experimentally determined maximum surface temperatures of the plasma core during the first bubble contraction Θ_{M1} with the bubble size R_{M1}: 'o' - the values of Θ_{M1} determined in this work, '' - the values of Θ_{M1} determined in works of other researchers.*

4. Conclusions

The surface temperatures of the plasma core inside the spark generated bubbles at the final stages of the first contraction phases have been determined experimentally. It has been found that these temperatures range from 4300 K to 8700 K. Even if the method used here gives only approximate results, these values are in a relatively good agreement with the temperatures published by other researchers.

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