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OBSERVATION OF SPHERICAL GROWTH AND COLLAPSE OF A SPARK BUBBLE IN WATER

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An experiment is described where the evolution of a single vapor bubble in water was observed. The bubble was generated by an electric spark between two electrodes designed to provide minimal interference to both liquid motion and the propagation of acoustic waves. The electrostatic energy of the discharge was varied to obtain vapor bubbles with radii ranging from about 2 to 5 centimeters. A high-speed camera was used to visualize bubble evolution, and the films showed that even the largest bubbles maintain spherical shape almost entirely during their lifetime. This confirms that gravity has little influence on the oscillation of bubbles of this size. Acoustic pressure records were found to be in good agreement with a simple model that has been proposed for free oscillation of vapor bubbles. The dependance of peak pressure on bubble radius showed that for this arrangement an optimal value exists for the electrostatic energy that maximizes the acoustic output. This may give indications to increase the efficiency of sound sources based on the implosion of a spark bubble.

1. INTRODUCTION

An electric spark is a convenient way to produce acoustic pulses in water. This method has been widely used for decades in deep-sea prospecting, being more controllable and reproducible compared to the use of explosives. Despite such a wide usage, the understanding of the dynamics of a spark bubble has only been limited so far. In the past literature, spark bubbles with radii of up to about 2 cm only have been studied by optical and acoustical means (a review is in [1]), while investigations on larger bubbles are restricted to those cases where a sparker is operated at sea, pressure records being the only available data [2]. Only recently it has been possible to obtain the first optical study of a bubble several cm in radius, using a 1 kJ spark in a laboratory tank [3]. The results showed that a vapor bubble of this size remains almost spherical and behaves as a constant-pressure cavity for most of its lifetime. A simple Rayleigh-like model is therefore adequate to describe its evolution except for times when the bubble wall velocity exceeds some fixed value. Such a threshold value has been proposed in a model developed by one of the authors [4], which applies to an entire range of middle-sized bubbles (roughly between 1 cm and 10 cm) named “scaling bubbles” [5]. The properties of scaling bubbles can be determined using a dimensionless formulation of the governing equations, for which the effects of gravity, surface tension, viscosity and heat losses can be neglected.

The purpose of the present work is to investigate the region of scaling bubbles to validate the proposed model, and to determine, if possible, a limiting value of bubble size for which scaling laws may apply. For bubbles larger than this value, a lower efficiency is expected for conversion of electrostatic energy into acoustic energy, which implies that an optimal range of bubble sizes and energies exists for sound generation.

2. EXPERIMENT

The general setup of the experiment is shown in Fig. 1. Two electrodes made of 1.3 mm diameter tungsten wire were connected to a capacitor bank with variable capacitance between 40 and 360 μF, that could be charged up to 2.35 kV. The electrodes were placed in a 6 m by 4 m, 5.5 m deep laboratory tank filled with fresh water at 13.2 °C, and reflections from rigid boundaries were kept to a minimum resulting in an echo-free time of approximately 400 μs. The source depth was 2.75 m. Acoustic signatures were recorded using a wideband hydrophone placed at 0.5 m away from the source. The receiving sensitivity of the hydrophone was previously determined in the frequency band 20 kHz to 200 kHz by comparison with a reference standard, giving a mean value of –218 dB re 1 V/μPa with a maximum deviation of ±1 dB up to 160 kHz, and –3 dB at 200 kHz. The hydophone signal was fed into an attenuator and acquired using a 12-bit, 1.25 Msample/s A/D board on a PC, triggering on the closing of the spark switch. The time window was set to include both the pulse due to the first bubble expansion (primary pulse) and the pulse from the first implosion (bubble pulse). From acoustic records, the bubble time, i.e. the time between primary pulse and bubble pulse, the positive peak of the bubble pulse and the negative (expansion) peak between the two could be determined.

Simultaneous optical measurements of the evolution of the vapor bubble were made using a 16 mm film rotating prism camera. Film speed was set at 3000 frames/s, and continuous backlighting was used.

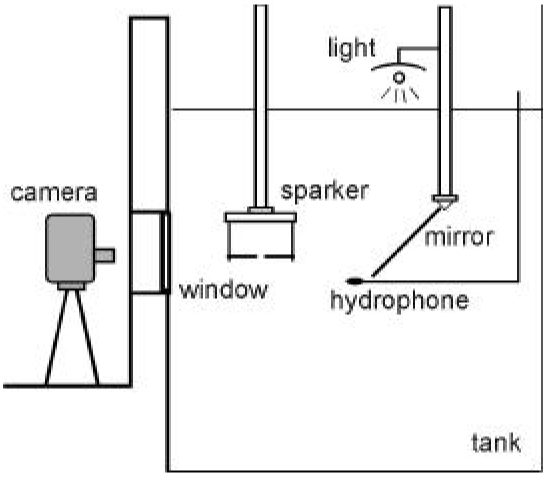

Fig.1: Tank experiment setup.

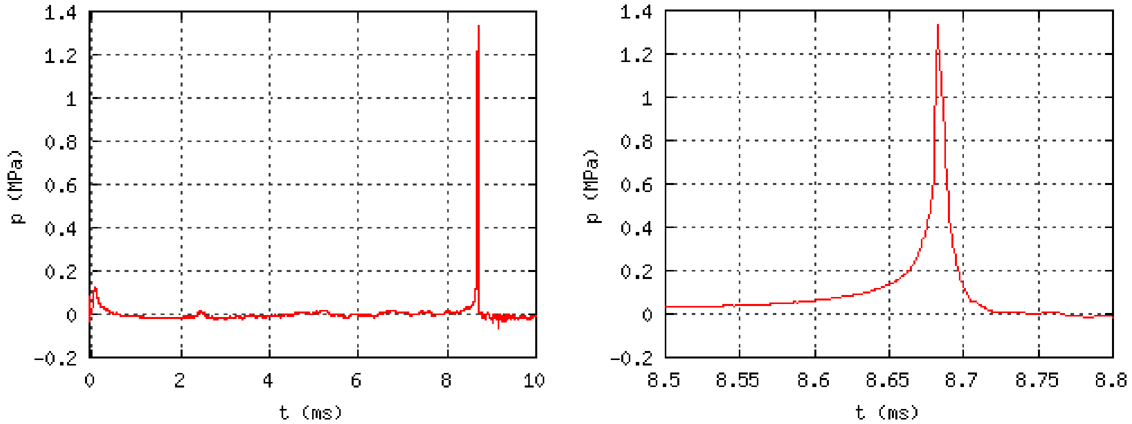

Fig.2: Acoustic signature of a 1 kJ spark bubble: entire bubble evolution (left) and bubble pulse enlarged (right). Hydrophone distance is 0.5 m.

3. RESULTS

A number of shots were taken at different energies, varying the capacitance of the capacitor bank while maintaining a fixed voltage of 2.35 kV. The most critical parameter was found to be the gap distance between the electrodes. For the lowest energies, the electrodes could resist several shots with a gap distance of about 1 mm and a good repeatability was found in the acoustic signatures, regarding the peak pressure values and bubble times. On the other hand, with the highest energies each shot resulted in some erosion of the electrode tips, resulting in a larger gap distance and therefore limiting the number of shots that could be taken before the spark failed, for gap distances greater than approximately 2 mm. The best practice was found to start with an almost closed electrode gap, and to let the gap widen up progressively after each shot. This was found to be rather reproducible, the number of successive shots always being between 2 and 3.

Fig. 2 shows a typical acoustic signature of a 1 kJ spark bubble. The primary pulse, the negative expansion pulse and the first bubble pulse are clearly visible, while successive pulses due to the bubble rebound are hidden by reverberation noise due to reflections by the tank walls and the free surface.

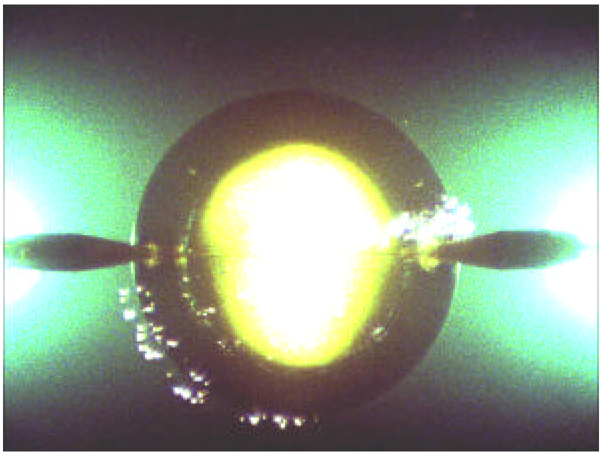

Fig.3: Picture of a spark bubble at its maximum radius of 5 cm.

Fig. 3 shows a picture extracted from a video obtained with the same energy as that of Fig. 2. The picture is taken when the bubble reaches its maximum radius of about 5 cm. The spherical shape is only very slightly distorted due to the presence of the electrode holders.

As the gap progressively widens up during a series of shots at constant energy, the primary pulse slowly shifts to longer times, showing that more time is needed to vaporize the water. Correspondingly, both the bubble time and the bubble pulse peak increase, denoting a progressively larger bubble. In a few shots, the primary pulse appeared further delayed by up to 2 ms: for those cases, the bubble peak was about 20% higher than the average value. When this happened, no following shots could be produced, indicating that the gap distance had nearly reached the maximum value for vaporization and bubble generation.

In Fig. 4 the positive peak pressure of the bubble pulse p_p is plotted against the bubble time t_b for spark bubbles in the range 110 J to 1 kJ. Given t_b, the maximum bubble size R_M can be determined using the approximate expression $R_\mathrm{M} = 0.54\ t_b\ (p_0/r_0)^{1/2}$, derived from Rayleigh's model, where p_0 and r_0 are the hydrostatic pressure and the density of the liquid. The straight line is a linear fit of the data subset in the range 110 J to 440 J. The linear dependence, which applies for scaling bubbles, has the form $p_\mathrm{p} = C\ R_\mathrm{M}$, where the constant C can be interpreted as a dimensionless peak pressure, which is independent of the maximum bubble size R_M [5].

4. DISCUSSION

The plot in Fig. 4 shows that bubbles in the energy range up to 440 J seem to follow scaling laws, while there is a reduction in the peak pressure for higher energies, compared to the value predicted by scaling laws. There is also a wider dispersion in the higher energy data, due to the effect of electrode tip erosion which did not maintain exactly the same conditions among successive shots. However, the dispersion is more on peak pressure rather than on bubble time, suggesting that small electrode gaps might interfere with the propagation of the outgoing pulse which is generated at the very center of the gap, while the growth of the bubble is less sensitive to the gap distance and other geometrical parameters.

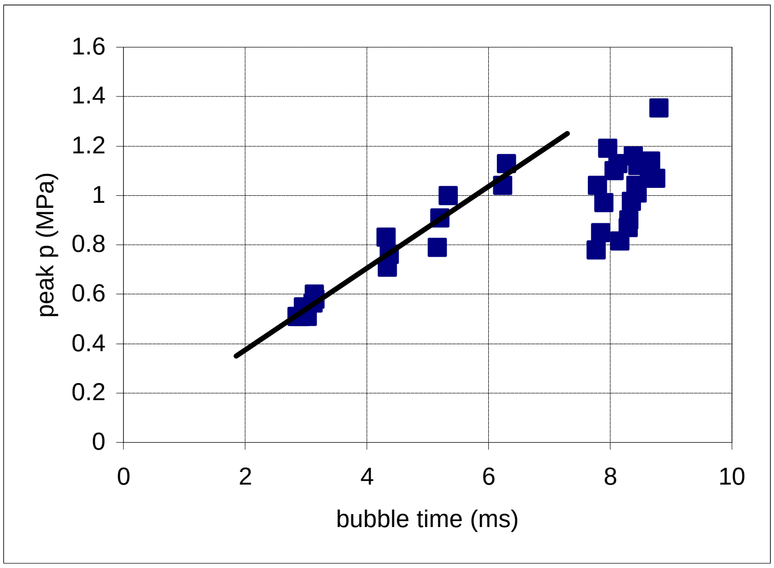

Fig.4: Plot of positive peak pressure of the bubble pulse versus bubble time for spark bubbles in the energy range 110 J to 1 kJ. The straight line is a linear fit between 110 J and 440 J.

The observed reduction in the peak pressure at higher energies could be explained in terms of a lower conversion ratio of electrostatic energy into acoustic energy compared to that of scaling bubbles of smaller sizes, due to the effect of gravity which prevents the bubble to implode maintaining a perfectly spherical shape. An optimal range of electrostatic energies for maximizing the acoustic output of a spark device operating in these conditions should therefore be somewhat lower than the upper limit of 1 kJ. Further work is needed to extend the investigation to higher energies, to confirm that more energy is wasted in losses due to gravity, and to determine a functional dependence of the peak pressure p_p on the bubble size R_M.

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