Stability in Single Bubble Sonoluminescence

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Abstract: Single bubble sonoluminescence in an air-water system has been shown to occur along a unique surface in the acoustic pressure-ambient radius-dissolved gas concentration parameter space where the bubble is stable both in shape and in (average) size. In this paper, we show how the bubble deviates from the expected path traced by the shape-instability threshold as a function of pressure in order to reach the observed stability.

INTRODUCTION

Single bubble sonoluminescence (SBSL) is a phenomenon in which an acoustically levitated bubble is made to oscillate so violently that pulses of light are emitted at the time of collapse (1). In contrast to the previously known phenomenon now called multi-bubble sonoluminescence (MBSL), SBSL consists of a single bubble which becomes stabilized against shape instabilities (S-I) and (bubble size) growth (2). The typical mechanisms responsible for S-I are the Faraday and the Rayleigh-Taylor instabilities (3), and for growth is rectified diffusion (RD)(4). Thus, for SBSL to be possible, several conditions must be met. i) the bubble must be below the S-I threshold. ii) the bubble must be at the RD threshold for zero net growth. iii) the RD threshold must be such that a small decrease (increase) in the bubble size places the bubble in a growth (dissolution) region. In this paper we show how the bubble deviates from the expected path in the acoustic pressure-ambient radius \( (P_a, R_0) \) parameter space in order to achieve the observed stability. The cause of the deviation is apparently internal chemical reactions occurring during the bubble collapse, as theorized by Lohse et al. (5), which result in a much lower growth rate by RD.

GROWTH AND MECHANICAL STABILITY

In fig. 1, the \( P_a \) threshold for S-I is shown. The symbols (except for the open circles) indicate the shape mode observed right after the bubble becomes unstable. These measurements were made in an air/water mixture driven at 20.6 kHz. The maximum bubble radius that can be levitated is approx. 150 \( \mu \text{m} \) which corresponds to the resonance size at 20 kHz. Note that SBSL occurs only in the upper left-hand corner (open circles). This figure serves to illustrate how small the SBSL parameter space is. The solid line corresponds to the RD threshold for 70\% dissolved gas (air) concentration \( (C_i/C_{0L}) \) where \( C_i \) is the concentration in the liquid far from the bubble and \( C_{0L} \) is the saturation value at ambient pressure. In general, lower concentrations will shift the RD curve upwards (larger \( P_a \)) and vice versa.

In the laboratory only \( P_a \) is usually controlled whereas the bubble size is determined by the other experimental parameters. For example bubbles below the RD threshold will dissolve and those above will grow until they reach the S-I threshold. When they reach the S-I curve, bubbles will break up and coalesce in a continuous cycle unless they grow beyond the maximum size for levitation and escape the field. In the case where the S-I curve lies below the RD curve, the bubble will dissolve before reaching instability. For this reason, only regions of the \( P_a, R_0 \) space where S-I is above RD will be available for steady state experiments. Such region has been shaded in Fig. 1.

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the higher values of $P_a$ ($\geq 1$ bar), the breakup and coalescence will occur so quickly that the bubble will practically be on the S-I curve most of the time. When this is the case, the bubble will start emitting light at around 1.3 bars but in a rather erratic fashion ($\approx 1$ flash per 10 acoustic cycles) due to its instability. This phenomenon has been termed transient SL.

When the value of $C_i/C_{i0L}$ is less than 50% and $P_a \approx 1.15$ bars, however, the bubble begins to deviate from the S-I curve toward a smaller $R_0$ (see also Ref. 6) and becomes stable (Fig. 2 square symbols). The smaller the gas concentration is, the smaller $R_0$ becomes for a given $P_a$ (see Ref 2, figs. 1a-c). As $P_a$ is increased, $R_0$ first decreases (lower branch) and then increases (upper branch) until it reaches the extinction threshold where SBSL is no longer observed. In the lower branch, the value of $C_i/C_0$ calculated from the bubble radial motion begins to decrease as $P_a$ is increased. At the upper branch, $C_i/C_0$ reaches a value $\approx 1\%$ of $C_i/C_{i0L}$ (the actual gas concentration far from the bubble) and it stays constant. At any other point in the observable $P_a-R_0$ space ($P_a \leq 1.15$ bars in shaded region) the value of $C_i/C_{i0L}$ appears to equal $C_i/C_0$.

These observations are consistent with Lohse et al.'s hypothesis in which the non-noble gases in air ($O_2$, $N_2$) begin to react chemically and as a consequence become inactive in the diffusive process. A larger portion of these gases will become inactive as the internal temperatures and pressures increase (due to the larger $P_a$) until only Argon is present inside the bubble. Thus, the effective $C_i/C_0$ will decrease at first (lower branch) until it reaches a minimum value (upper branch) of 1% of $C_i/C_{i0L}$ which is the same as the proportion of Ar in air. We propose, however, that even though other processes are affecting the gas diffusion, the 'regular' RD (4) can still be used to explain the growth stability of the bubble. This is based on the fact that all along the upper and the lower branches, conditions ii and iii above are still met if the measured value of $C_i/C_0$ is used instead of $C_i/C_{i0L}$ for the gas concentration. This can be seen in Fig. 2, where the symbols represent the measured data for $C_i/C_{i0L} = 14\%$ and the solid lines correspond to the theoretical RD curves for various values of $C_i/C_0$ as indicated. The intersections of the symbols and solid lines indicate the effective gas concentration 'seen' by the bubble. Note that, as required by condition iii above, the slope of the RD curves is almost always positive (within the experimental uncertainty) at the intersections. A positive slope causes the bubble to cross from a growth to a dissolution region as $R_0$ increases. Note also that, coincidentally, light begins to be emitted as the upper branch is reached. This might be an indication that Ar is a more efficient gas for light emission due to its large heat-capacity ratio. On the other hand, it could be the result of the higher $P_a$ value generating a more violent collapse.

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REFERENCES