REMINISCENCES ON BUBBLE DYNAMICS AND CAVITATION

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Abstract: A review of various topics in cavitation and bubble dynamics discussed with Hugh Flynn, many of them still containing unsolved details. Among these are: rectified diffusion of gas into pulsating bubbles and the effect of surface films; parametric shape oscillations of bubbles and the failure to observe resonances; the threshold conditions for cavitation, the cause for the persistence of the required nuclei and the effect of a temporary static pressure increase on the nuclei; the dynamics of an individual cavity growing and collapsing in a compressible liquid and the associated internal pressure and temperature.

INTRODUCTION

In the 1950’s and 60’s, Hugh Flynn and I shared an interest in ultrasonically induced cavitation and non-linear oscillations of gas bubbles in liquids. We were 500 miles apart, so our interactions were limited to the U.S. mail and brief personal contacts during Society meetings and the especially memorable annual "mini- conferences" on cavitation arranged by Prof. Hunt at Harvard in the 60’s.

Flynn’s main contribution to the acoustics of bubbles is his benchmark survey, Physics of Acoustic Cavitation in Liquids (1), reviewing all aspects of the non-linear response of bubbles to acoustic pressures, including what was known in 1964 about the now actively investigated topic of sonoluminescence. Some of his papers on specific bubble phenomena are listed as Ref. (2)-(5). Two patents on apparatus for inducing nuclear and chemical reactions by creating the high pressures and temperatures associated with cavity collapse are Ref. (6) and (7).

This short note attempts to provide brief, elementary descriptions of some of the bubble phenomena, while also mentioning some unsolved details and mysteries. Limited space prevents inclusion of figures to be shown in the oral presentation.

RECTIFIED DIFFUSION OF GAS INTO BUBBLES

If the pressure of air or other gas in a bubble exceeds the saturation pressure of whatever amount of the same gas is already dissolved in the liquid surrounding the bubble, gas diffuses out of the bubble into the liquid in an attempt to reach saturation equilibrium. This ordinarily causes the bubble to shrink and eventually dissolve. However, if an external sound pressure excites the bubble into radial pulsations of sufficient amplitude, gas dissolved in the liquid can diffuse into the bubble by a non-linear process called "rectified diffusion," which competes with the steady outward diffusion. If the radial pulsation is large enough, the rectified diffusion can exceed the outward diffusion and cause the bubble to grow, even if the internal gas pressure is larger than the saturation pressure of the dissolved gas. The acoustic pressure resulting in radial pulsations just large enough to result in inward rectified diffusion equal to the outward diffusion is called the "threshold for rectified diffusion;" the bubble remains fixed in size when excited at this pressure. The threshold pressure depends on the bubble size and concentration of gas dissolved in the liquid. Threshold pressures measured by Eller and Flynn (2), and earlier measurements by Strasberg (8), agree reasonably well with Eller and Flynn’s theoretical estimates, indicating that the phenomenon is well understood. A remaining problem: the effect of films of surfactants and impurities surrounding the bubble surface on the thresholds.

PARAMETRIC SHAPE OSCILLATIONS OF BUBBLES

When an ordinarily quiescent bubble is excited by sound, it can suddenly become visibly unstable at a repeatable sound pressure and dance around violently before breaking up. This instability is attributed to a form of parametric excitation of oscillations in the shape of the ordinarily spherical bubble. Bubble shape oscillations have natural frequencies which vary inversely with the 3/2 power of their radius. Accordingly, periodic oscillations in radius cause the frequency of the shape oscillations to vary periodically, resulting in parametric shape
oscillations when the sound pressure driving the radial oscillations exceeds a critical value. The critical value depends on the excitation frequency, the bubble size, and the surface tension. Eller and Crum's measurements of the critical sound pressure at the onset of instability as a function of bubble size (9) are in fair agreement with earlier measurements reported orally by Strasberg and Benjamin (10), and there is "ballpark" agreement between these two data sets and their theoretical estimates for some bubble radii. However, the theory predicts that resonant instability should occur for bubble sizes having shape oscillation natural frequencies half the excitation frequency, but neither set of experimental data shows reduced critical sound pressures for such bubbles.

CAVITATION: THE GROWTH AND COLLAPSE OF VAPOROUS CAVITIES

The temporary application of a negative pulse of pressure, more negative than the existing ambient static pressure, will cause a small nucleus bubble of gas to grow to many times its original size, the bubble becoming filled mainly with vapor evaporated from the surrounding liquid. When the negative pulse ends, the ambient pressure causes the vapor-filled bubble to collapse. The collapse can become so rapid that the bubble wall velocity exceeds the velocity of sound in the liquid, resulting in a shock wave propagating into the liquid and a very large transient temperature and pressure inside the collapsing bubble. There has been many theoretical and experimental investigations of this phenomenon. A typical calculation described by Flynn (11) starts with a gas bubble in water at atmospheric pressure with an initial radius of $4 \times 10^{-3}$ cm, subjected to a negative half sign-wave pulse of 5 peak atmos. The bubble grows to about 7 times its original size, now filled mostly with water vapor. It then begins to collapse under the external atmospheric pressure. The collapse takes about 26 μsec, the calculated internal pressure and temperature reaching peak values of 14,000 atmospheres and 6,8000K during the last microsecond of collapse. However, these large values have not been verified by any measurements except, perhaps, by indirect estimates based on measurements of sonoluminescence.

PERSISTENCE OF CAVITATION NUCLEI

The ability of ultrasonic pressures of only a few atmospheres to induce cavitation in a liquid requires the presence of nucleus gas bubbles, such as the $4 \times 10^{-3}$ cm bubble assumed above. But it would ordinarily be expected that such bubbles would disappear, the larger ones by rising to the surface and the smaller ones by eventually dissolving (unless the surrounding liquid is very oversaturated with dissolved gas). Several mechanisms have been proposed to account for their persistence, including the formation of a rigid skin of impurities around the nucleus bubble surface, or the stabilization of gas nuclei in cracks on the surface of microscopic solid impurities in the liquid. But predictions of the cavitation inception pressure conflict with the observation that application of a temporary super pressure of only 1/3 atmos. increases the acoustic pressure required for cavitation (12). Accordingly, the mechanism causing the persistence of gas containing nuclei remains a mystery.

REFERENCES*

11. H.G. Flynn, Ref. (1); Fig. 21.
12. M. Strasberg, Ref. (8); last paragraph of Section (d).

*Note: Titles of Ref. (2), (3), (5) & (9) have been abbreviated because of limited space.