

Cavitation Bubble Collapse Shape

Like any other accelerating liquid/gas interface, the surface of a bubble is susceptible to Rayleigh-Taylor instability, and is potentially unstable when the direction of the acceleration is from the less dense gas toward the denser liquid. Of course, the spherical geometry causes some minor quantitative departures from the behavior of a plane interface; these differences were explored by Birkhoff (1954) and Plesset and Mitchell (1956) who first analysed the Rayleigh-Taylor instability of bubbles. As expected a bubble is most unstable to non-spherical perturbations when it experiences the largest, positive values of d^2R/dt^2 . During the growth and collapse cycle of a cavitation bubble, there is a brief and weakly unstable period during the initial phase of growth that can cause some minor roughening of the bubble surface (Reynolds and Berthoud 1981). But, much more important, is the rebound phase at the end of the collapse when compression of the bubble contents causes d^2R/dt^2 to switch from the small negative values of early collapse to very large positive values when the bubble is close to its minimum size.

This strong instability during the rebound phase appears to have several different consequences. When the bubble surroundings are strongly asymmetrical, for example the bubble is close to a solid wall or a free surface, the dominant perturbation that develops is a re-entrant jet. Of particular interest for cavitation damage is the fact that a nearby solid boundary can cause a re-entrant microjet directed toward that boundary. The surface of the bubble furthest from the wall accelerates inward more rapidly than the side close to the wall and this results in a high-speed re-entrant microjet that penetrates the bubble and can achieve very high speeds. Such microjets were first observed experimentally by Naude and Ellis (1961) and Benjamin and Ellis (1966). The series of photographs shown in figure 1 represent a good example of the experimental observations of a developing re-entrant jet. Figure 2 presents a comparison between the re-entrant jet development in a bubble collapsing near a solid wall as observed by Lauterborn and Bolle (1975) and as computed by Plesset and Chapman (1971). Note also that depth charges rely for their destructive power on a re-entrant jet directed toward the submarine upon the collapse of the explosively generated bubble.

Other strong asymmetries can also cause the formation of a re-entrant jet. A bubble collapsing near a

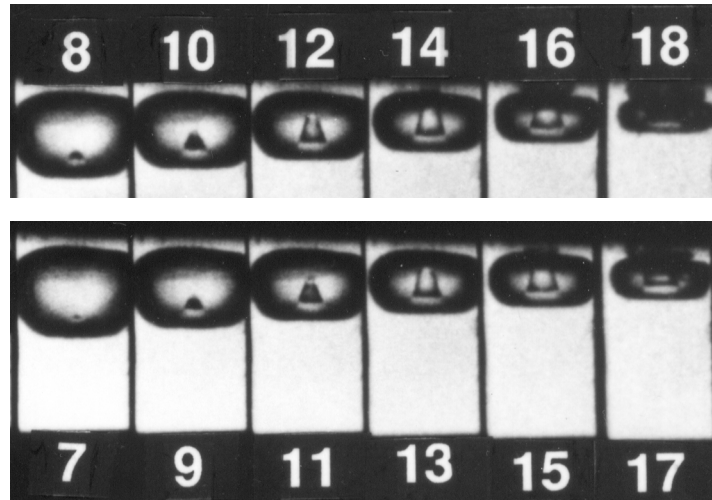


Figure 1: Series of photographs showing the development of the microjet in a bubble collapsing very close to a solid wall (at top of frame). The interval between the numbered frames is $2\mu s$ and the frame width is $1.4mm$. From Tomita and Shima (1990), reproduced with permission of the authors.

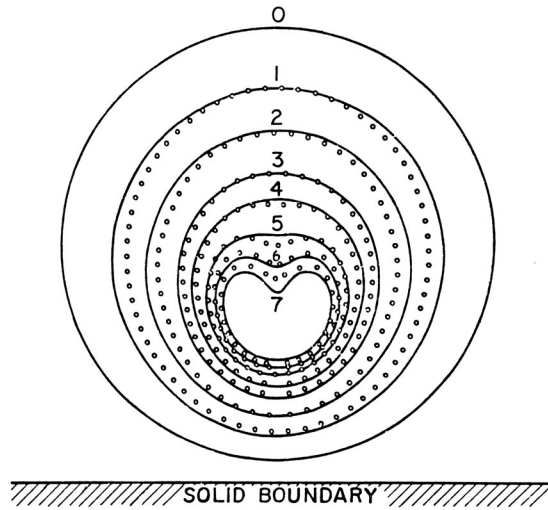


Figure 2: The collapse of a cavitation bubble close to a solid boundary in a quiescent liquid. The theoretical shapes of Plesset and Chapman (1971) (solid lines) are compared with the experimental observations of Lauterborn and Bolle (1975) (points). Figure adapted from Plesset and Prosperetti (1977).

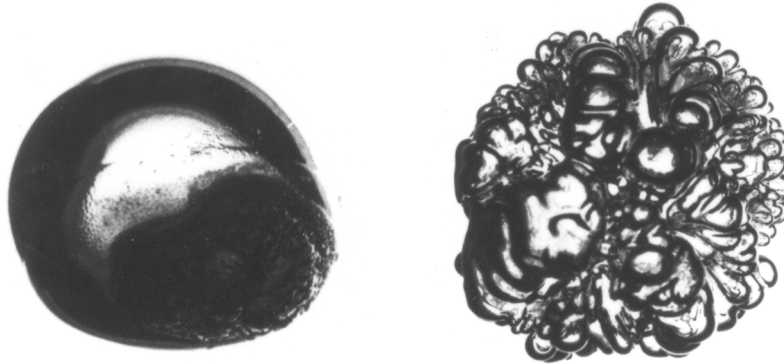


Figure 3: Photographs of an ether bubble in glycerine before (left) and after (right) a collapse and rebound, both bubbles being about 5 – 6mm across. Reproduced from Frost and Sturtevant (1986) with the permission of the authors.

free surface produces a re-entrant jet directed *away* from the free surface (Chahine 1977). Indeed, there exists a critical flexibility for a nearby surface that separates the circumstances in which the re-entrant jet is directed away from rather than toward the surface. Gibson and Blake (1982) demonstrated this experimentally and analytically and suggested flexible coatings or liners as a means of avoiding cavitation damage. Another possible asymmetry is the proximity of other, neighboring bubbles in a finite cloud of bubbles. Chahine and Duraiswami (1992) showed that the bubbles on the outer edge of such a cloud will tend to develop jets directed toward the center of the cloud.

When there is no strong asymmetry, the analysis of the Rayleigh-Taylor instability shows that the most unstable mode of shape distortion can be a much higher-order mode. These higher order modes can dominate when a vapor bubble collapses far from boundaries. Thus observations of collapsing cavitation bubbles, while they may show a single vapor/gas volume prior to collapse, just after minimum size the *bubble* appears as a cloud of much smaller bubbles. An example of this is shown in figure 3. Brennen (1995) shows how the most unstable mode depends on two parameters representing the effects of surface tension and non-condensable gas in the bubble. That most unstable mode number was later used in one of several analyses seeking to predict the number of fission fragments produced during collapse of a cavitating bubble (Brennen 2002).