Cavitation Bubble Collapse

We now examine in more detail the mechanics of cavitation bubble collapse. As demonstrated in a preliminary way in section (Ngd), vapor or cavitation bubble collapse in the absence of thermal effects can lead to very large interface velocities and very high localized pressures. This violence has important technological consequences for it can damage nearby solid surfaces in critical ways. In this and the following few sections, we briefly review the fundamental processes associated with the phenomena of cavitation bubble collapse. For further details, the reader is referred to more specialized texts such as Knapp *et al.* (1975), Young (1989) or Brennen (1995).

The analysis of section (Ngd) allowed approximate evaluation of the magnitudes of the velocities, pressures, and temperatures generated by cavitation bubble collapse (equations (Ngd9), (Ngd11), (Ngd12)) under a number of assumptions including that the bubble remains spherical. Though it will be shown in section (Nhd) that collapsing bubbles do not remain spherical, the spherical analysis provides a useful starting point. When a cavitation bubble grows from a small nucleus to many times its original size, the collapse will begin at a maximum radius, R_m, with a partial pressure of gas, p_{Gm}, that is very small indeed. In a typical cavitating flow R_m is of the order of 100 times the original nuclei size, R_o. Consequently, if the original partial pressure of gas in the nucleus was about 1 *bar* the value of p_{Gm} at the start of collapse would be about 10^{-6} *bar*. If the typical pressure depression in the flow yields a value for $(p^*_\infty - p_\infty(0))$ of, say, 0.1 *bar* it would follow from equation (Ngd11) that the maximum pressure generated would be about 10^{10} *bar* and the maximum temperature would be 4×10^4 times the ambient temperature! Many factors, including the diffusion of gas from the liquid into the bubble and the effect of liquid compressibility, mitigate this result. Nevertheless, the calculation illustrates the potential for the generation of high pressures and temperatures during collapse and the potential for the generation of shock waves and noise.

Early work on collapse by Herring (1941), Gilmore (1952) and others focused on the inclusion of liquid compressibility in order to learn more about the production of shock waves in the liquid generated by bubble collapse. Modifications to the Rayleigh-Plesset equation that would allow for liquid compressibility were developed and these are reviewed by Prosperetti and Lezzi (1986). A commonly used variant is that proposed by Keller and Kolodner (1956); neglecting thermal, viscous, and surface tension effects this is:

$$\left(1 - \frac{1}{c_L}\frac{dR}{dt}\right) R\frac{d^2R}{dt^2} + \frac{3}{2}\left(1 - \frac{1}{3c_L}\frac{dR}{dt}\right)\left(\frac{dR}{dt}\right)^2$$

$$= \left(1 + \frac{1}{c_L}\frac{dR}{dt}\right)\frac{1}{\rho_L}\left\{p_B - p_\infty - p_c(t + R/c_L)\right\} + \frac{R}{\rho_L c_L}\frac{dp_B}{dt} \qquad \text{(Nhc1)}$$

where c_L is the speed of sound in the liquid and $p_c(t)$ denotes the variable part of the pressure in the liquid at the location of the bubble center in the absence of the bubble.

However, as long as there is some non-condensable gas present in the bubble to decelerate the collapse, the primary importance of liquid compressibility is not the effect it has on the bubble dynamics (which is slight) but the role it plays in the formation of shock waves during the rebounding phase that follows collapse. Hickling and Plesset (1964) were the first to make use of numerical solutions of the compressible flow equations to explore the formation of pressure waves or shocks during the rebound phase. Figure 1 presents an example of their results for the pressure distributions in the liquid before (left) and after (right) the moment of minimum size. The graph on the right clearly shows the propagation of a pressure pulse or shock away from the bubble following the minimum size. As indicated in that figure, Hickling

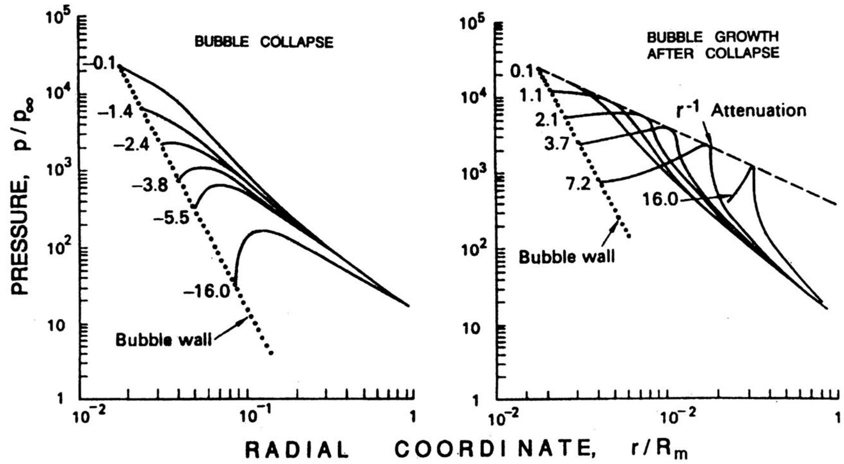

Figure 1: Typical results of Hickling and Plesset (1964) for the pressure distributions in the liquid before collapse (left) and after collapse (right) (without viscosity or surface tension). The parameters are $p_\infty = 1\ bar$, $\gamma = 1.4$, and the initial pressure in the bubble was $10^{-3}\ bar$. The values attached to each curve are proportional to the time before or after the minimum size.

and Plesset concluded that the pressure pulse exhibits approximately geometric attenuation (like r^{-1}) as it propagates away from the bubble. Other numerical calculations have since been carried out by Ivany and Hammitt (1965), Tomita and Shima (1977), and Fujikawa and Akamatsu (1980), among others.

Even if thermal effects are negligible for most of the collapse phase, they play a very important role in the final stage of collapse when the bubble contents are highly compressed by the inertia of the in-rushing liquid. The pressures and temperatures that are predicted to occur in the gas within the bubble during spherical collapse are very high indeed. Since the elapsed times are so small (of the order of microseconds), it would seem a reasonable approximation to assume that the noncondensable gas in the bubble behaves adiabatically. Typical of the adiabatic calculations is the work of Tomita and Shima (1977) who obtained maximum gas temperatures as high as $8800°K$ in the bubble center. But, despite the small elapsed times, Hickling (1963) demonstrated that heat transfer between the liquid and the gas is important because of the extremely high temperature gradients and the short distances involved. In later calculations Fujikawa and Akamatsu (1980) included heat transfer and, for a case similar to that of Tomita and Shima, found lower maximum temperatures and pressures of the order of $6700°K$ and $848\ bar$ respectively at the bubble center. These temperatures and pressures only exist for a fraction of a microsecond.

All of these analyses assume spherical symmetry. We will now focus attention on the stability of shape of a collapsing bubble before continuing discussion of the origins of cavitation damage.