Cavitating Bubbles

We end our brief survey of the dynamics of cavitating bubbles with some experimental observations of single bubbles (single cavitation *events* in real flows for these reveal the complexity of the micro-fluid-mechanics of individual bubbles. The focus here is on individual events springing from a single nucleus. The interactions between bubbles at higher nuclei concentrations will be discussed later.

Pioneering observations of individual cavitation events were made by Knapp and his associates at the California Institute of Technology in the 1940s (see, for example, Knapp and Hollander 1948) using high-speed movie cameras capable of 20,000 frames per second. Shortly thereafter Plesset (1949), Parkin (1952), and others began to model these observations of the growth and collapse of traveling cavitation bubbles using modifications of Rayleigh's original equation of motion for a spherical bubble. However, observations of real flows demonstrate that even single cavitation bubbles are often highly distorted by the pressure gradients in the flow. Before describing some of the observations, it is valuable to consider the relative sizes of the cavitation bubbles and the viscous boundary layer. In the flow of a uniform stream of velocity, U, around an object such as a hydrofoil with typical dimension, ℓ, the thickness of the laminar boundary layer near the minimum pressure point will be given qualitatively by $\delta = (\nu_L \ell/U)^{\frac{1}{2}}$. Comparing this with the typical maximum bubble radius, R_m, given by equation (Nhb4), it follows that the ratio, δ/R_m, is roughly given by

$$\frac{\delta}{R_m} = \frac{1}{2(-\sigma - C_{pmin})} \left\{ \frac{\nu_L}{\ell U} \right\}^{\frac{1}{2}} \tag{Nhf1}$$

Therefore, provided $(-\sigma - C_{pmin})$ is of the order of 0.1 or greater, it follows that for the high Reynolds numbers, $U\ell/\nu_L$, that are typical of most of the flows in which cavitation is a problem, the boundary layer is usually much thinner than the typical dimension of the bubble.

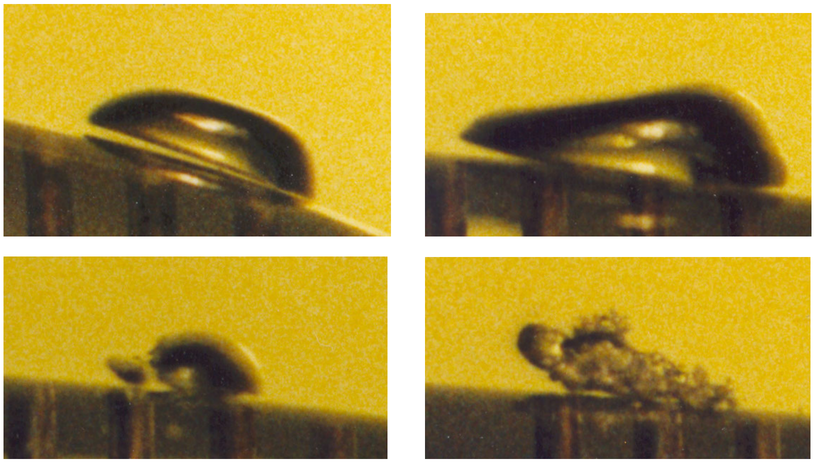

Figure 1: A series of photographs illustrating, in profile, the growth and collapse of a traveling cavitation bubble in a flow around a $5.08cm$ diameter headform at $\sigma = 0.45$ and a speed of $9\ m/s$. the sequence is top left, top right, bottom left, bottom right, the flow is from right to left. The lifesize width of each photograph is $0.73cm$. From Ceccio and Brennen (1991).

Recently, Ceccio and Brennen (1991) and Kuhn de Chizelle *et al.* (1992a,b) have made an extended series of observations of cavitation bubbles in the flow around axisymmetric bodies, including studies of the scaling of the phenomena. The observations at lower Reynolds numbers are exemplified by the photographs of bubble profiles in figure 1. In all cases the shape during the initial growth phase is that of a spherical

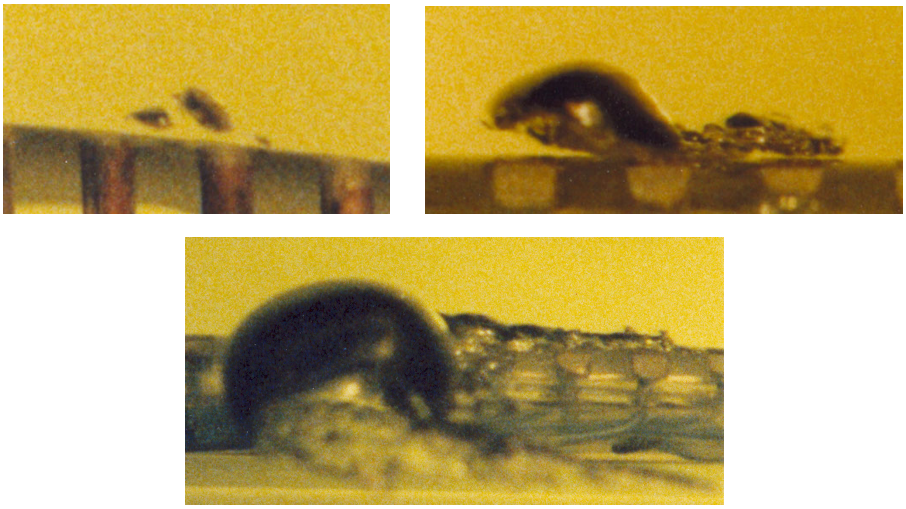

Figure 2: Examples of bubble fission (upper left), the instability of the liquid layer under a traveling cavitation bubble (upper right) and the attached tails (lower). From Ceccio and Brennen (1991) experiments with a $5.08cm$ diameter ITTC headform at $\sigma = 0.45$ and a speed of $8.7m/s$. The flow is from right to left. The lifesize widths of the photographs are $0.63cm$, $0.80cm$ and $1.64cm$ respectively.

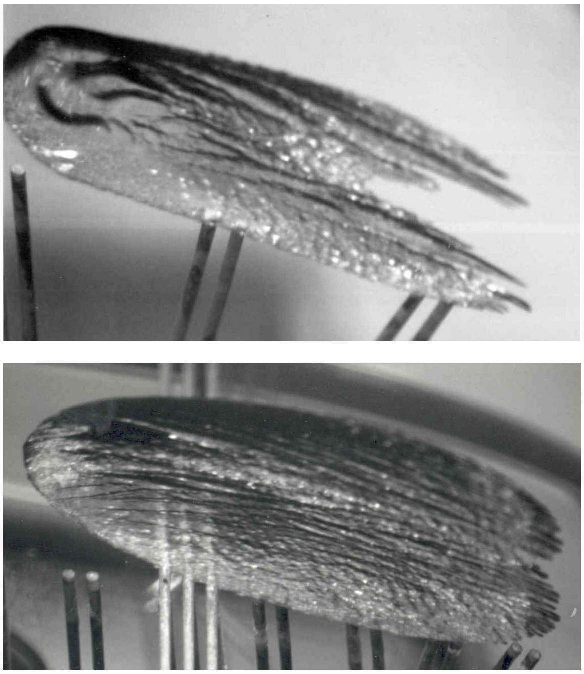

Figure 3: Typical cavitation events from the scaling experiments of Kuhn de Chizelle *et al.* (1992b) showing transient bubble-induced patches, the upper one occurring on a 50.8 cm diameter Schiebe headform at $\sigma = 0.605$ and a speed of 15 m/s, the lower one on a 25.4 cm headform at $\sigma = 0.53$ and a speed of 15 m/s. The flow is from right to left. The lifesize widths of the photographs are $6.3cm$ (top) and $7.6cm$ (bottom).

cap, the bubble being separated from the wall by a thin layer of liquid of the same order of magnitude as the boundary layer thickness. Later developments depend on the geometry of the headform and the Reynolds number. In some cases as the bubble enters the region of adverse pressure gradient, the exterior frontal surface is pushed inward, causing the profile of the bubble to appear wedge-like. Thus the collapse is initiated on the exterior frontal surface of the bubble, and this often leads to the bubble fissioning into forward and aft bubbles as seen in figure 1. At the same time, the bubble acquires significant spanwise vorticity through its interactions with the boundary layer during the growth phase. Consequently, as the collapse proceeds, this vorticity is concentrated and the bubble evolves into one (or two or possibly more) short cavitating vortices with spanwise axes. These vortex bubbles proceed to collapse and seem to rebound as a cloud of much smaller bubbles. Ceccio and Brennen (1991) (see also Kumar and Brennen 1993) conclude that the flow-induced fission prior to collapse can have a substantial effect on the noise produced.

Two additional phenomena were observed. In some cases the layer of liquid underneath the bubble would become disrupted by some instability, creating a bubbly layer of fluid that subsequently gets left behind the main bubble (see figure 2). Second, it sometimes happened that when a bubble passed a point of laminar separation, it triggered the formation of local *attached cavitation* streaks at the lateral or spanwise extremities of the bubble, as seen in figure 2. Then, as the main bubble proceeds downstream, these *streaks* or *tails* of attached cavitation are stretched out behind the main bubble, the trailing ends of the tails being attached to the solid surface. Tests at much higher Reynolds numbers (Kuhn de Chizelle *et al.* 1992a,b) revealed that these *events with tails* occured more frequently and would initiate attached cavities over the entire wake of the bubble as seen in figure 3. Moreover, the attached cavitation would tend to remain for a longer period after the main bubble had disappeared. Eventually, at the highest Reynolds numbers tested, it appeared that the passage of a single bubble was sufficient to trigger a *patch* of attached cavitation (figure 3, bottom), that would persist for an extended period after the bubble had long disappeared.

In summary, cavitation bubbles are substantially deformed and their dynamics and acoustics altered by the flow fields in which they occur. This necessarily changes the noise and damage produced by those cavitation events.