Cavitation Inception

For illustrative purposes in the last section, we employed the criterion that cavitation occurs when the minimum pressure in the flow just reaches the vapor pressure, $\sigma_i = -C_{pmin}$. If this were the case, the prediction of cavitation would be a straightforward matter. Unfortunately, large departures from this criterion can occur in practice, and, in this section, we shall try to present a brief overview of the reasons for these discrepancies. There is, of course, an extensive body of literature on this subject, and we shall not attempt a comprehensive review. The reader is referred to reviews by Knapp, Daily and Hammit (1970), Acosta and Parkin (1975), Arakeri (1979) and Brennen (1994) for more detail.

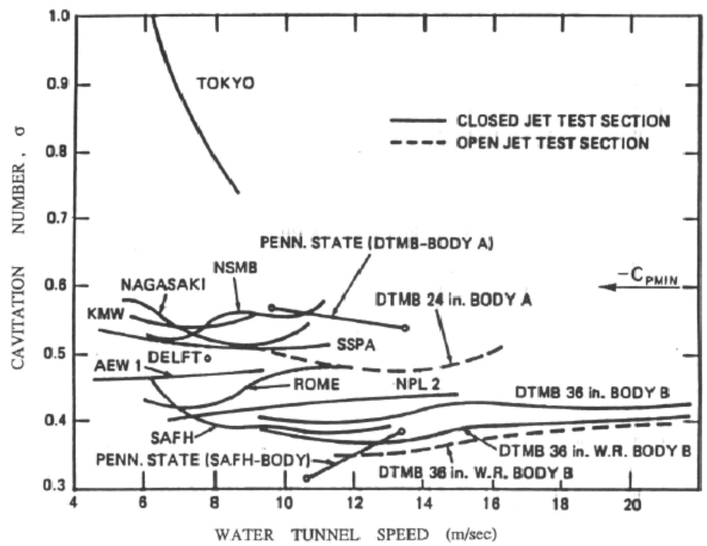

Figure 1: The inception numbers measured for the same axisymmetric headform in a variety of water tunnels around the world. Data collected as part of a comparative study of cavitation inception by the International Towing Tank Conference (Lindgren and Johnsson 1966, Johnsson 1969).

First, it is important to recognize that vapor does not necessarily form when the pressure, p, in a liquid falls below the vapor pressure, p_V. Indeed, a pure liquid can, theoretically, sustain a tension, $\Delta p = p_V - p$, of many atmospheres before nucleation, or the appearance of vapor bubbles, occurs. Such a process is termed homogeneous nucleation, and has been observed in the laboratory with some pure liquids (not water) under very clean conditions. In real engineering flows, these large tensions do not occur because vapor bubbles grow from nucleation sites either on the containing surfaces or suspended in the liquid. As in the case of a solid, the ultimate strength is determined by the weaknesses (stress concentrations) represented by the nucleation sites or "nuclei." Research has shown that suspended nuclei are more important than surface nucleation sites in determining cavitation inception. These suspended nuclei may take the form either of microbubbles or of solid particles within which, perhaps, there are microbubbles. For example, a microbubble of radius, R_N, containing only vapor, is in equilibrium when the liquid pressure

$$p = p_V - 2\mathcal{S}/R_N \qquad \text{(Mbec1)}$$

where $\mathcal{S}$ is the surface tension. It follows that such a microbubble would result in a critical tension of $2\mathcal{S}/R_N$, and the liquid pressure would have to fall below $p_V - 2\mathcal{S}/R_N$ before the microbubble would grow to a visible size. For example, a 10 μm bubble in water at normal temperatures leads to a tension of 0.14 bar.

It is virtually impossible to remove all the particles, microbubbles and dissolved air from any substantial body of liquid (the catch-all term "liquid quality" is used to refer to the degree of contamination). Because of this contamination, substantial differences in the inception cavitation number (and, indeed, the form of cavitation) have been observed in experiments in different water tunnels, and even in a single facility with differently processed water. The ITTC comparative tests (Lindgren and Johnsson 1966, Johnsson 1969) provided a particularly dramatic example of these differences when cavitation on the same axisymmetric headform was examined in many different water tunnels around the world. An example of the variation of σ_i in those experiments, is reproduced as figure 1.

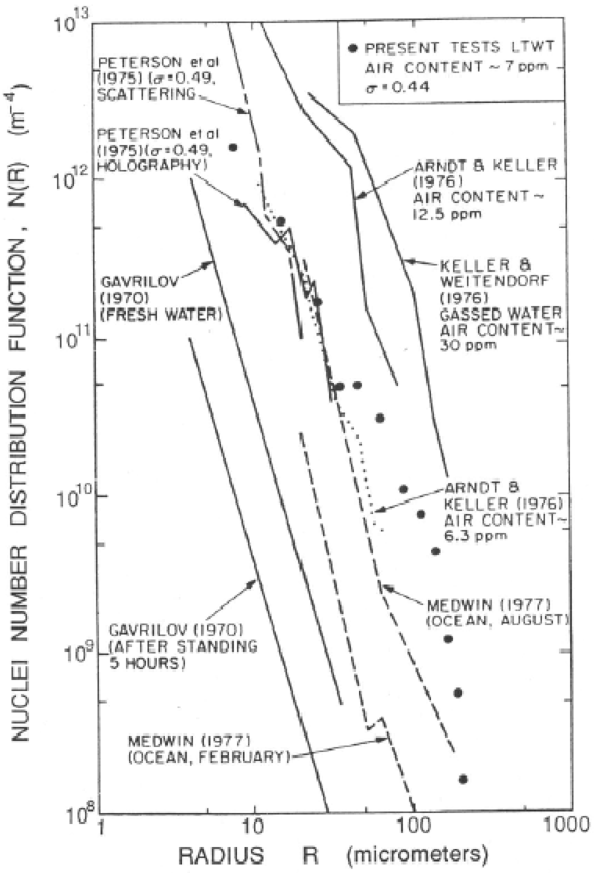

Figure 2: Several nuclei number distribution functions measured in water tunnels and in the ocean by various methods (adapted from Gates and Acosta 1978).

Because the cavitation nuclei are crucial to an understanding of cavitation inception, it is now recognized that the liquid in any cavitation inception study must be monitored by measuring the number of nuclei present in the liquid. This information is normally presented in the form of a nuclei number distribution function, $N(R_N)$, defined such that the number of nuclei per unit total volume with radii between R_N and $R_N + dR_N$ is given by $N(R_N)dR_N$. Typical nuclei number distributions are shown in figure 2 where data from water tunnels and from the ocean are presented.

Most of the methods currently used for making these measurements are still in the development stage. Devices based on acoustic scattering, and on light scattering, have been explored. Other instruments, known as cavitation susceptibility meters, cause samples of the liquid to cavitate, and measure the number and size of the resulting macroscopic bubbles. Perhaps the most reliable method has been the use of holography to create a magnified three-dimensional photographic image of a sample volume of liquid that can then be surveyed for nuclei. Billet (1985) has recently reviewed the current state of cavitation nuclei measurements (see also Katz *et al* 1984).

It may be interesting to note that cavitation itself is a source of nuclei in many facilities. This is because air dissolved in the liquid will tend to come out of solution at low pressures, and contribute a partial pressure of air to the contents of any macroscopic cavitation bubble. When that bubble is convected into a region of higher pressure and the vapor condenses, this leaves a small air bubble that only redissolves very slowly, if at all. This unforeseen phenomenon caused great difficulty for the first water tunnels which were modeled directly on wind tunnels. It was discovered that, after a few minutes of operating with a cavitating body in the working section, the bubbles produced by the cavitation grew rapidly in number, and began to complete the circuit of the facility so that they appeared in the incoming flow. Soon the working section was obscured by a two-phase flow. The solution had two components. First, a water tunnel needs to be fitted with a long and deep return leg so that the water remains at high pressure for sufficient time to redissolve most of the cavitation-produced nuclei. Such a return leg is termed a "resorber". Second, most water tunnel facilities have a "deaerator" for reducing the air content of the water to $20 - 50\%$ of the saturation level at atmospheric pressure. These comments serve to illustrate the fact that $N(R_N)$ in any facility can change according to the operating condition, and can be altered both by deaeration and by filtration.

Most of the data of figure 2 is taken from water tunnel water that has been somewhat filtered and degassed, or from the ocean which is surprisingly clean. Thus, there are few nuclei with a size greater than $100\ \mu m$. On the other hand, it is quite possible in many pump applications to have a much larger number of larger bubbles and, in extreme situations, to have to contend with a two-phase flow. Gas bubbles in the inflow could grow substantially as they pass through the low pressure regions within the pump, even though the pressure is everywhere above the vapor pressure. Such a phenomenon is called pseudo-cavitation. Though a cavitation inception number is not particularly relevant to such circumstances, attempts to measure σ_i under these circumstances would clearly yield values larger than $-C_{pmin}$.

On the other hand, if the liquid is quite clean with only very small nuclei, the tension that this liquid can sustain means that the minimum pressure has to fall well below p_V for inception to occur. Then σ_i is much smaller than $-C_{pmin}$. Thus the quality of the water and its nuclei can cause the cavitation inception number to be either larger or smaller than $-C_{pmin}$.

There are, however, at least two other factors that can affect σ_i, namely the residence time and turbulence. The residence time effect arises because the nuclei must remain at a pressure below the critical value for a sufficient length of time to grow to observable size. This requirement will depend on both the size of the pump and the speed of the flow. It will also depend on the temperature of the liquid for, as we shall see later, the rate of bubble growth may depend on the temperature of the liquid. The residence time effect requires that a finite region of the flow be below the critical pressure, and, therefore, causes σ_i to be lower than might otherwise be expected.

Up to this point we have assumed that the flow and the pressures are laminar and steady. However, most of the flows with which one must deal in turbomachinery are not only turbulent but also unsteady. Vortices occur because they are inherent in turbulence and because of both free and forced shedding of vortices. This has important consequences for cavitation inception, because the pressure in the center of a vortex may be significantly lower than the mean pressure in the flow. The measurement or calculation of $-C_{pmin}$ would elicit the value of the lowest mean pressure, while cavitation might first occur in a transient vortex whose central pressure was lower than the lowest mean pressure. Unlike the residence time factor, this would cause higher values of σ_i than would otherwise be expected. It would also cause σ_i to change with Reynolds number, Re. Note that this would be separate from the effect of Reynolds number on the minimum pressure coefficient, C_{pmin}. Note also that surface roughness can promote cavitation by creating localized low pressure perturbations in the same manner as turbulence.