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Real-fluid effects in flow cavitation

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Abstract. The possible role of real fluid effects in two aspects of flow cavitation namely inception and separation is discussed. This is primarily qualitative in the case of inception whereas some quantitative results are presented in the case of separation. Existing evidence clearly indicates that in particular viscous effects can play a significant role in determining the conditions for cavitation inception and in determining the location of cavitation separation from smooth bodies.

Keywords. Flow cavitation; inception; separation; real fluid effects.

1. Introduction

One definition of "cavitation" may be taken to be the formation of a new surface in an otherwise homogeneous body of liquid. This broad definition would include such other phenomena as boiling and evolution. However, at present, we restrict ourselves to cavitation in "cold" liquids. A liquid may be said to be cold if due to vaporization at the new surface the local temperature drop is insignificant compared to the bulk temperature of the liquid. Thus, in a cold liquid, cavities are formed as a result of the liquid being subjected to tensile stresses (or negative absolute pressures). One would expect that if the cavities once formed are subjected to compressive stresses (or positive absolute pressures) they would tend to disappear or collapse. In general, then, cavitation is a physical phenomenon which involves the appearance, development and disappearance of cavities in a body of liquid.

The cavity may contain either permanent gas or vapour, and, depending upon which dominates, we may distinguish between two different types of cavitation, namely (i) gaseous cavitation and (ii) vaporous cavitation. In addition, either type of cavity may be generated in a stagnant or in a flowing liquid. In the former case, normally termed "acoustic cavitation", the liquid is subjected to a time-varying pressure field by external means (for example, using a magnetostrictive device), whereas in the latter case, which may be termed "flow cavitation", the liquid is subjected to a time-varying pressure field due to the dynamic action of the flow. The subject of acoustic cavitation has recently been reviewed comprehensively by Neppiras (1980). In the present paper we consider two aspects of flow cavitation, namely inception and separation. Since review articles on the subject of inception have recently appeared (Acosta & Parkin 1975; Arakeri 1979; Arakeri & Acosta 1979) only its qualitative aspects are covered here. However, on the subject of separation, some earlier results, which are contained in a report (Arakeri 1971) of limited availability, have also been included.

2. Cavitation inception

2.1 *Nuclei and thresholds*

Theoretical predictions (see for example Flynn 1964) indicate that pure homogeneous liquids can withstand considerable tensile stresses, of the order of thousands of atmospheres. However, even carefully treated liquid samples are known to withstand only a moderate tensile stress, of the order of hundreds of atmospheres. This discrepancy has led to the postulation of the presence of weak spots in the liquid samples, commonly known as 'nuclei'. One of the simplest models of a nucleus is the so-called 'free nucleus', which is a spherical bubble containing the vapour of the liquid and some permanent gas. To understand the role of nuclei in cavitation inception it is helpful to consider the static stability of such a free nucleus. With this analysis (see for example Knapp *et al* 1970) it is easily shown that the critical condition for cavitation inception is given by

$$p_v - p_c = 4S/3R, \tag{1}$$

where p_c is the critical pressure, p_v is the vapour pressure of the liquid as its bulk temperature, S the coefficient of surface tension and R the radius of the bubble. From equation (1) it should be apparent that the critical pressure for cavitation inception is always less than p_v but will approach it for sufficiently large values of R. Therefore, from equation (1) it is possible to calculate the threshold pressure required to initiate cavitation from a bubble of radius R. Another interpretation of equation (1) is that there is a critical radius R_c for a given liquid pressure p_L such that nuclei of radius $R_n < R_c$ are stable; whereas, nuclei of radius $R_n > R_c$ are unstable. It follows from (1) that the magnitude of R_c is given by

$$R_c = \frac{4S}{3\,(p_v - p_L)}. \tag{2}$$

It is interesting to extend the above analysis to include pressure fields having a mean component p_{L_0} and a time-varying sinusoidal component of an amplitude p_A. Such pressure fields are the source of acoustically generated cavitation and as will be discussed later, they could be the source of flow cavitation as well. It is of significance here to determine the threshold magnitude of p_A such that a nucleus of initial radius R_n grows to a critical radius R_c. Under the conditions considered, the minimum value of p_L is

$$p_L = p_{L_0} - p_A, \tag{3}$$

and substituting the above in (2) we find that

$$R_c = \frac{4S}{3\,(p_A - p_{L_0} + p_v)}. \tag{4}$$

Now an alternate expression for R_c can be arrived at by considering the condition required for expanding a nucleus of initial radius R_n to the critical size R_c. This is given by

$$p_n (R_n/R_c)^3 + p_v = -p_A + p_{L_0} + (2S/R_c), \tag{5}$$

where p_n is the initial gas pressure in the bubble. If the critical radius R_c is eliminated from (5) using (4) we find a relationship between the threshold pressure p_A denoted by $p_t^{(1)}$ first derived by Blake (see Flynn 1964) given by:

$$p_t^{(1)} = p_{L_0} - p_v + \frac{4S}{3\sqrt{3}\, R_n}\left[1 + (p_{L_0} - p_v)\frac{R_n}{2S}\right]^{-1/2}. \tag{6}$$

Thus equilibrium theory predicts that a nucleus of radius R_n will grow explosively when the acoustic pressure amplitude is increased to the threshold value $p_t^{(1)}$. However, so far we have considered only vaporous growth. There is possibly another mechanism of bubble growth, namely by gaseous diffusion. In particular, as Hsieh & Plesset (1961) have shown, a small bubble which would normally disappear under steady pressure fields can grow by a phenomenon known as rectified diffusion under unsteady pressure fields. Thus, there exists a second threshold pressure amplitude $p_t^{(2)}$ at which a nucleus will start to grow by rectified diffusion. The expression for $p_t^{(2)}$ derived by Hsieh & Plesset is:

$$P_t^{(2)} = \frac{\sqrt{2}}{3}\, p_{L_0}\left[1 + \frac{2S}{R_n P_{L_0}} - \frac{C_\infty}{C_0}\right]^{\frac{1}{2}}. \tag{7}$$

Here C_0 is the saturation concentration of gas at an ambient pressure p_{L_0}, and C_∞ is the actual concentration of the gas in the liquid at a great distance from the nucleus. The above equation is limited to small values of (p_A/p_{L_0}) but computations without this restriction have been provided by Eller & Flynn (1965). A comparison of the two threshold pressures for a fixed value of p_{L_0} and various values of C_∞/C_0 is provided in figure 1. It is to be noted that for nuclei with radii (R_n) between 0·2 μm

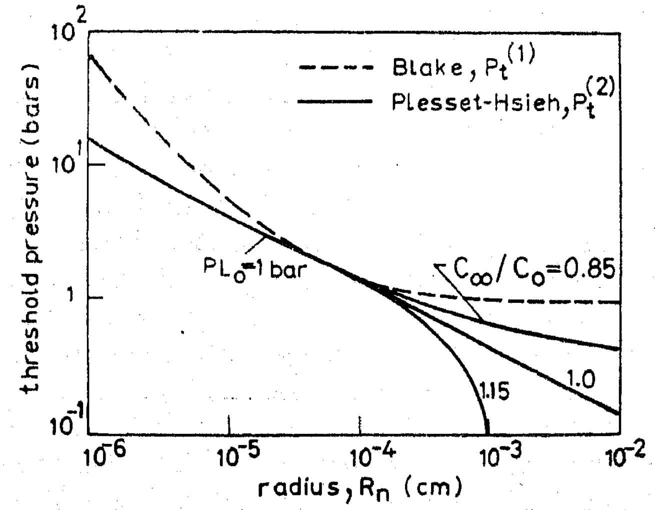

Figure 1. Theoretical thresholds for vaporous and gaseous cavitation.

and 1 μm the two threshold amplitudes are almost equal. However, for nuclei with radii greater than 1 μm, which are found to be plentiful in a flowing liquid (see for example Keller 1972), the threshold amplitude for rectified diffusion can be an order of magnitude smaller than that for vaporous cavitation. Therefore, these observations certainly suggest the possibility that a nucleus initially having a size below the critical size for vaporous cavitation could grow to the critical size by rectified diffusion provided sufficient time is allowed for bubble growth.

2.2 *Bubble trajectory and pressure fields*

As has been indicated previously (Arakeri 1979), bubble growth leading to cavitation is primarily determined by two factors; namely, the magnitude and the duration of low pressures experienced by the nuclei. The bubble growth, of course, is expected only if the magnitude is greater than the threshold value predicted on the basis of static stability considerations indicated in the previous section. The crucial information required then for predicting bubble growth is the knowledge of the magnitude of low pressures as well as the residence time of the bubbles in these low pressure regions. This information can be obtained based on certain assumptions which may not be valid under all conditions of flow cavitation. One example of such calculations where good agreement was found with experiments is due to Plesset (1949). The assumption involved here was that the bubble travels following a streamline at the local liquid velocity ignoring any boundary layer effects. Thus, the bubble follows a trajectory determined by these assumptions. It is conceivable that the bubble may follow a different trajectory if boundary layer effects are included. In order to elaborate further it is worthwhile to note that several different flow regimes can be identified for flow past a solid body. Some of these are listed below:

(i) laminar boundary layer in the region of interest,
(ii) laminar boundary layer followed by turbulent transition in the region of interest,
(iii) laminar boundary layer followed by separation with turbulent transition in the free shear layer leading to reattachment,
(iv) laminar boundary layer followed by separation with turbulent transition in the free shear layer without reattachment, and
(v) turbulent boundary layer in the region of interest.

Observations, for example by Arakeri & Acosta (1973), have indicated the importance of different flow regimes in the mechanism of cavitation inception including bubble growth patterns. Subsequent investigations (see recent review by Arakeri & Acosta 1979) have clearly established that the bubble growth calculations must take into account the modification of the pressure field as well as possible changes in the residence time due to viscous effects. In view of these observations, one can define several classes of trajectories following which bubbles in different trajectories would experience differing pressure fields as well as residence times. The several classes of trajectories possible including the one analyzed by Plesset (1949) are summarized in figure 2. The class I trajectory is essentially the one analyzed by Plesset. It may be noted that if the boundary layer remains laminar, then even if the bubble gets entrained within the boundary layer, the pressure field experienced by the bubbles will be

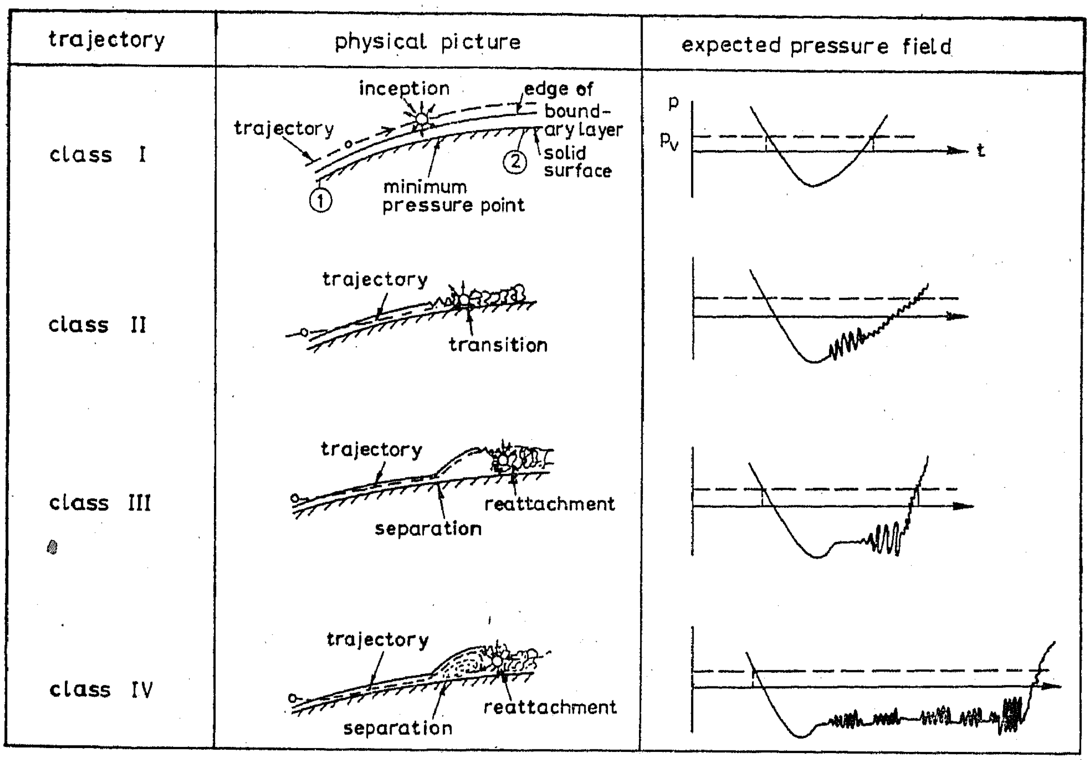

Figure 2. Expected pressure field and physical picture of a nucleus following various trajectories.

similar to the class I trajectory except that the residence time in low pressure regions is likely to be greater. However, if boundary layer transition does occur within the region of interest then the pressure field is modified as shown for the class II trajectory. The primary difference is the addition of unsteady pressures to the existing static pressure distribution. The class III trajectory is the one experienced by a bubble following the free shear layer of a short laminar separation bubble. Again the presence of unsteady pressures is to be noted. Measurements by Arakeri (1974) and Huang & Hannan (1975) have shown that the magnitude of unsteady pressures, particularly in the transition region, can be quite significant. The class IV trajectory is the one in which a bubble spends some time in the recirculating region of a short separation bubble and eventually gets entrained in the free shear layer to be carried into the reattachment region. Thus, the bubble experiences intermittent steady pressures when near separation, and intermittent unsteady pressures when near reattachment. It is expected that the pressure field experienced by a bubble entrained in the free shear layer of long separation *i.e.* without the reattachment bubble would be similar to the one for the class III trajectory. Finally, if the boundary layer is turbulent in the region of interest then the pressure field would be expected to be similar to the class I trajectory apart from the addition of turbulent pressure fluctuations. However, measurements (see for example Huang & Hannan 1975) have shown these to be significantly smaller than those existing in the transition region.

In the foregoing discussion nothing was said about how a bubble comes into the region of low pressures. The initial source of the bubble is likely to be a nucleus existing in the liquid upstream of the body. Thus the complete calculations of bubble growth leading to cavitation inception should include the trajectory analysis starting from a point far upstream of the body. Trajectory analysis upstream of the body was first made by Johnson & Hsieh (1966). In particular, they showed that there exists a " screening effect " where larger, easily cavitable nuclei are pushed away from the boundary layer regions of a body due to pressure gradient effects in the neighbourhood of the stagnation point.

2.3 *Viscous interactions in inception*

As noted earlier, recent observations have clearly indicated that viscous effects do play an important role in cavitation inception. These observations have also lead to useful correlations (Arakeri 1979) to predict the conditions for cavitation inception dominated by viscous effects. The correlations have been found to work; however, the reasons behind the success are not entirely clear. From the discussion in the previous section, we expect the amplitude of unsteady pressures to be at least partially responsible for the viscous interactions in inception. However, here we will try to find out whether these unsteady pressures may also be responsible for modification of the nuclei content of the liquid in the region of separation and/or transition. One observation of Gates & Acosta (1978) is of particular relevance here. They found that bodies which possess laminar separation are relatively insensitive to the nuclei content of the liquid. This strongly suggests that if nuclei content measurements were carried out upstream of a body and within the laminar separated region of the same body near inception conditions, these are likely to be different. Recently, Parkin (1979) has proposed a theoretical explanation for the possible role of laminar separated regions in nucleation. It is suggested that nuclei initially of very small diameter possessing relatively high tensile threshold values grow first by vaporous means in the minimum pressure area and subsequently by gaseous diffusion while entrapped in the separated region. However, the possible role of unsteady pressures in the growth while in the separated region was not considered.

Our considerations of pressure fields encountered by a nucleus trapped in the separated region suggest that growth may be controlled both by the magnitude of the mean or static pressure and the magnitude of unsteady pressures. In particular, we have seen from § 2.1 that the possibility of bubble growth by rectified diffusion in the presence of unsteady pressure fields exists. Further, the threshold amplitude required for bubble growth by rectified diffusion is lower than that predicted for vapour growth in the size range one to ten microns. It is to be noted that measurements by Keller (1972) indicate that nuclei in this range are likely to be available in plenty and at the same time they are not subject to the screening effect described earlier. Therefore, the possibility of bubble growth by rectified diffusion must be considered in the presence of unsteady pressure fields. It is to be granted that growth by this mechanism is relatively slow, but at the same time faster than static diffusion considered by Parkin. Thus, though at first, bubble growth by rectified diffusion was thought to be important only for the class IV trajectory, its importance for other trajectories should not be completely ruled out at this juncture. It must also be pointed out here that rectified diffusion is likely to be an important mechanism for bubble growth only in the transition region of flow, where large amplitude of pressure fluctuations exists within a narrow band of frequencies, as compared to smaller amplitude pressure fluctuations over a wide band of frequencies existing in the turbulent region of flow.

Thus, the above arguments lead to a possible explanation for the observations of Gates & Acosta (1978) that bodies with laminar separation are relatively insensitive to the free-stream nuclei content of the liquid. In addition, the significance of small separated regions in the inception of cavitation is further strengthened. In this regard it is to be pointed out that small laminar separated regions can persist on certain bodies even upto Reynolds numbers exceeding five million. In addition, the measurements of Klebanoff & Tidstrom (1972) indicate that the flow downstream of a small roughness element has similar properties as small laminar separated regions. Therefore, isolated roughness elements buried in a thin laminar boundary layer may be a ready source for cavitation inception. An example of such cavitation commonly termed "spot cavitation" is shown in figure 3 (plate 1) taken from Acosta & Hamaguchi (1967). It is expected that such cavities may be prevalent at higher Reynolds numbers typical of prototype situations. It would then be interesting to investigate whether the appearance of spot-type cavities is also relatively insensitive to the free-stream nuclei content of the liquid.

3. Cavitation separation

3.1 *Background*

We saw in the previous section how viscous effects can play an important role in determining the conditions for the onset of cavitation. If conditions are made favourable beyond onset for additional cavitation growth then subsequently a large vapour cavity will envelope some portion of the body. This condition is normally known as supercavitating flow. In most applications involving supercavitating flows the prediction of the various forces, generated by the device is of utmost importance. It is to be expected that the force coefficients would be dependent not only on such physical parameters like angle of attack, body shape, etc., but also on the starting position of the developed cavity which we may call the position of cavitation separation.

Bodies with sharp corners (such as disks, wedges and sharp-edged hydrofoils at moderately large angles of attack) possess cavitation separation points whose position is known *a priori*; and force coefficients for such bodies can be predicted quite accurately within the potential flow approximations (Wu 1968). But for smooth bodies, the position is not known *a priori* and the condition of smooth separation (Armstrong 1953) is normally invoked to predict the position of cavitation separation. However, this condition does not take into account such real fluid effects as viscosity, surface tension, etc., on the position of cavitation separation. However, as will be seen later, there is now substantial evidence that the position of cavitation separation is in fact influenced by real fluid effects.

3.2 *Cavitation separation from axisymmetric bodies*

Extensive observations of the physical features of supercavitating flows past spheres have been conducted by Brennen (1969a, 1970). Among other things the position of cavitation separation was measured for spheres of various sizes, covering a wide range of Reynolds numbers. The results shown in figure 4 for one value of cavitation number, $\sigma = 0{\cdot}1$, clearly indicate that the position of cavitation separation is a strong

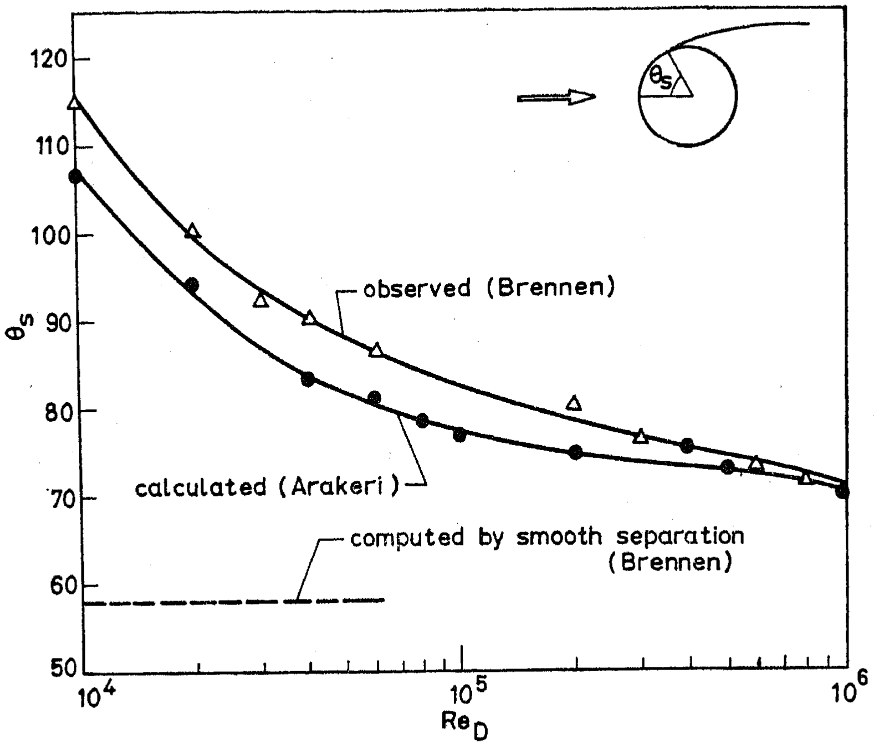

Figure 4. Position of cavitation separation from sphere at $\sigma = 0{\cdot}1$. θ_s is in degrees.

function of the Reynolds number. The observed Reynolds number dependence was first explained by Arakeri (1975) based on flow visualization studies of the real fluid flow in the neighbourhood of cavitation separation. It was noted that cavitation separation is preceded by laminar boundary layer separation and the distance between the two is a strong function of Reynolds number. Based on these findings a correlation was suggested (figure 4) which predicted the observed values by Brennen on spheres quite well.

3.3 *Cavitation separation from slender two-dimensional hydrofoils*

The measured position of cavitation separation from two different sized 8·32% biconvex hydrofoils at zero angle of attack is shown in figure 5. The trend with Reynolds number is found to be similar to that observed in figure 4 for spheres. At zero angle of attack, cavitation separation from the hydrofoils was symmetric on the top and bottom surfaces; the physical appearance of cavitation was in the form of streaks consisting of large cavitation bubbles. Following a suggestion by Brennen (1969b), this type of cavitation separation has been termed 'nucleate cavitation separation'. At small positive angles of attack, the nucleate type of cavitation separation was observed on the top or suction side surface; however, on the bottom or pressure side surface the physical appearance of cavitation was quite different. This latter type had a smooth glassy appearance at separation and has been termed 'viscous laminar cavitation separation' (Arakeri 1975). We might note that this type of cavitation separation was also observed by Brennen on spheres and by Arakeri on two axisymmetric bodies. A few measurements of the position of cavitation separation of the two types noted above with hydrofoil at small positive angles of attack are presented in table 1.

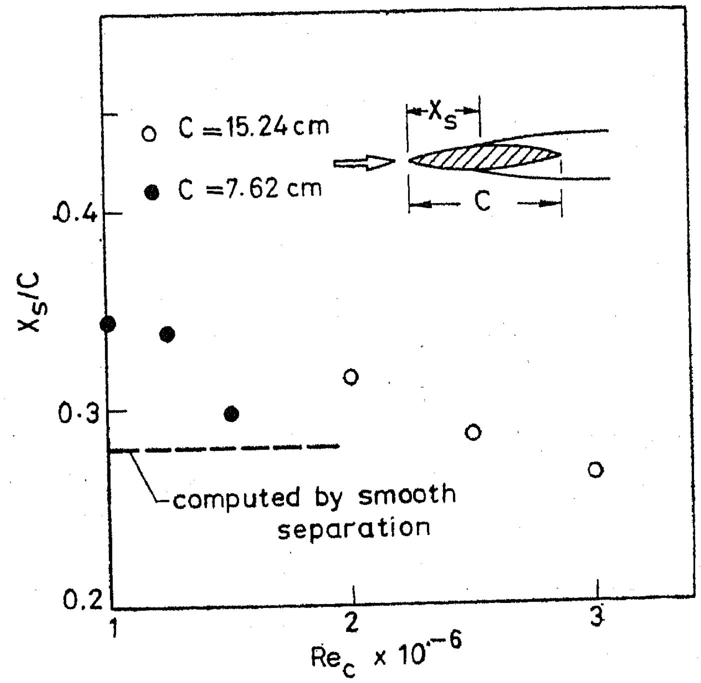

Figure 5. Position of cavitation separation from bi-convex hydrofoil with $\alpha=0$ and $\sigma=0{\cdot}1$ (After Arakeri 1971.)

3.4 *Comparison with theory*

Brennen (1969a) modelled the cavitating flow past a disk and a sphere using one of the nonlinear free streamline theories. His numerical computations included the prediction of the drag coefficient, C_D for both the disk and the sphere as well as of the position of cavitation separation on the sphere using the smooth separation criterion. For the disk, the separation position is fixed and in this case the computed values of the drag coefficient were within about 5% of the measured values. For the sphere in the Re_D range of 3×10^5 to 8×10^5, the agreement was within 10% despite the fact that the position of cavitation separation was predicted (figure 4) quite erroneously based on the smooth separation criterion.

Arakeri (1971) used the linearized theory to predict the position of cavitation separation as well as the force coefficients on a bi-convex hydrofoil at zero and small positive angles of attack. As shown in figure 5, the predicted position of cavitation separation using the smooth separation criterion agrees well with the measurements, in particular at the higher values of Reynolds numbers. Similar agreement on the suction side was found with hydrofoil at small positive angles of attack. However,

Table 1. Cavitation separation position from a hydrofoil at small positive angles of attack and $\sigma = 0{\cdot}1$.

α	Experiment		Theory	
	Suction side	Pressure side	Suction side	Pressure side
1°	0·32	0·75	0·22	0·31
2°	0·25	0·73	0·17	0·35

as indicated in table 1, the difference for the pressure side was quite significant. The observed values were substantially more downstream than those predicted. Even with these differences, good agreement was found between the predicted and observed values of C_D. For the lift coefficient C_L, however, as shown in figure 6 the magnitude was predicted erroneously and even the sign was in disagreement. This may be explained as follows. On the suction side, the cavity separates very near the leading edge and hence the pressure is essentially uniform and equal to vapour pressure. On the pressure side, the cavity is predicted to separate at about 30% of the chord; however, it is observed to separate beyond the minimum pressure point at about 75% of the chord. Thus, the surface between the two is subjected to pressures at least below vapour pressure or even to a small negative pressure. Thus, the net effect is that the average pressure on the suction side is higher than the average pressure on the pressure side resulting in negative C_L at positive angles of attack! This in fact was found to be the case if the observed values of separation were introduced in the theoretical computations. This phenomenon is primarily due to viscous effects which lead to delay in separation; and to the lack of sufficient " nuclei ", which leads to the liquid being able to sustain pressures below vapour pressure or even negative pressures without cavitating.

4. Conclusions

There is overwhelming evidence now that real fluid effects do influence the mechanism of cavitation inception and separation strongly. With regard to inception, it was anticipated that the strong pressure fluctuations which exist within the boundary

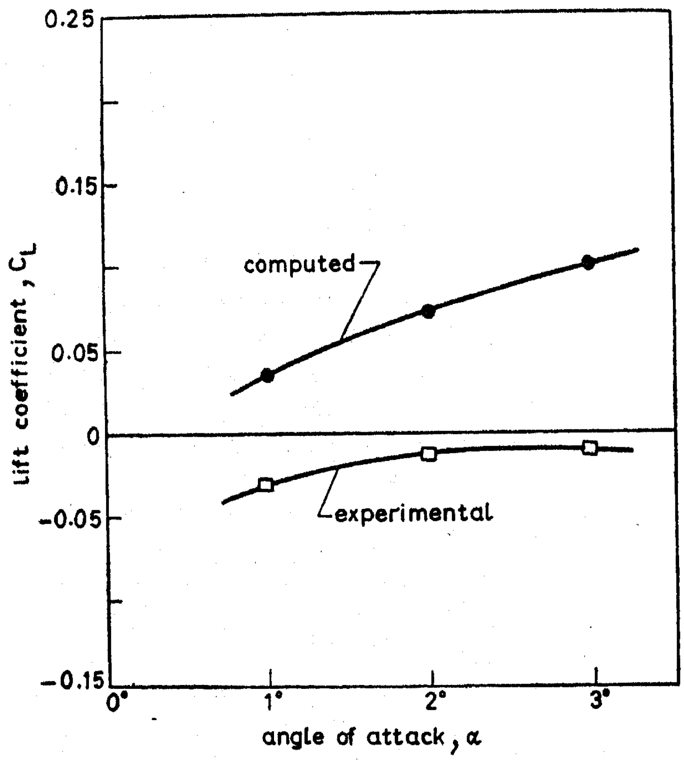

Figure 6. Comparison of experimental and computed lift coefficients on a bi-convex hydrofoil with σ=0·1 (Arakeri 1971).

layer transition region could account for the observed viscous effects. However, it is argued here that these same pressure fluctuations in particular with laminar separation may also be responsible for modification of the nuclei content of the liquid locally. With regard to separation, it is found that cavitation detachment from smooth bodies is strongly dependent on Reynolds number and weakly dependent on Weber number. It is also found that even though the cavitation separation position is predicted quite erroneously using the smooth separation criterion, the drag forces are predicted reasonably well. However, this is not necessarily the case with prediction of lift forces on slender hydrofoils.

List of symbols

A	cross-sectional area, $A = \pi D^2/4$ for sphere and $A = C \times S_p$ for hydrofoil
C	chord of hydrofoil
C_D	drag coefficient, $2D_f/\rho U^2 A$
C_L	lift coefficient, $2L/\rho U^2 A$
C_0	saturation concentration of gas
C_∞	actual concentration of gas
D	diameter
D_f	drag force
L	lift force
p_A	amplitude of the unsteady pressure
p_c	critical pressure given by equation (1)
p_{L_0}	ambient or mean liquid pressure
p_L	liquid pressure
p_n	initial gas pressure
$P_t^{(1)}$	threshold pressure given by equation (6)
$P_t^{(2)}$	threshold pressure given by equation (7)
p_v	vapour pressure of the liquid
p_∞	reference static pressure
R	bubble radius
R_c	critical bubble radius given by equation (2)
R_n	initial bubble radius
Re_C	Reynolds number, UC/ν
Re_D	Reynolds number, UD/ν
S	coefficient of surface tension
S_p	span of hydrofoil
U	reference velocity
X_s	axial location of cavitation separation
α	angle of attack
ρ	liquid density

σ cavitation number, $(p_\infty - p_v)\ \frac{1}{2}\rho U^2$

θ_s angular location of cavitation separation

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Plate 1

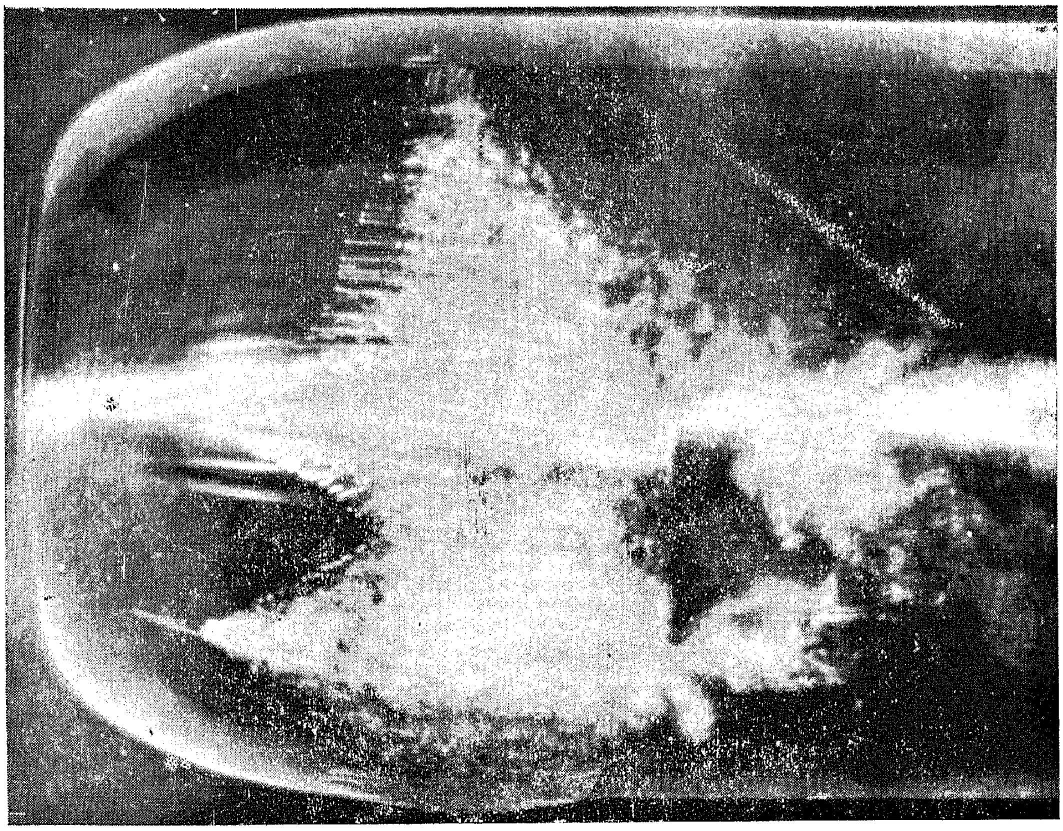

Figure 3. Photograph illustrating spot cavitation. The flow is from left to right. (After Acosta & Hamaguchi 1967.)