REAL FLUID EFFECTS IN SUPER-CAVITATING FLOWS

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1. INTRODUCTION

Super-cavitating flow is characterized by a large vapour or gas cavity enveloping some portion of the body. In most applications involving super-cavitating 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 beginning position of the developed cavity which we may call the position of cavitation separation. Thus, to predict analytically the force coefficients on super-cavitating bodies, knowledge of the position of cavitation separation is essential.

Bodies with sharp corners (such as disks, wedges and sharp-edged hydrofoils at moderately large angles of attack) possess cavitation separation point whose position is known apriori; and force coefficients for such bodies can be predicted quite well within the potential flow approximations /1/. But, for smooth bodies, the position is not known apriori and the condition of smooth separation is usually used to predict the position of cavitation separation. The classical condition for smooth separation requires that the curvature of the free streamlines be finite at separation, in which case it can be shown to be equal to the curvature of the solid body at the detachment point /1/. However, this condition does not take into account such real fluid effects as viscosity, surface tension, etc. on the position of cavitation separation. In the next two sections of present article, evidence is presented which clearly indicates that the position of cavitation separation is in fact influenced by real fluid effects for both axisymmetric and two diamentional slender bodies. In some cases the real fluid effects play a significant role in determining the force coefficients and these aspects are discussed in the remaining sections.

2. CAVITATION SEPARATION FROM AXISYMMETRIC BODIES

Extensive observations on physical features of supercavitating flows past spheres have been conducted by Brennen /2,3/. Among other things the position of cavitation separation was measured for various sized spheres covering a wide range of Reynolds number. The results shown in Figure 1 for the value of cavitation number $\sigma = 0.1$ clearly indicate that the position of cavitation separation is a strong function of Reynolds number. The observed Reynolds number dependence was first explained by Arakeri /4/ based on the 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 to be a strong function of Reynolds number. Based on these findings a correlation was suggested which predicted (Figure 1) the observed values by Brennen on spheres quite well.

3. CAVITATION SEPARATION FROM SLENDER TWO DIMENSIONAL HYDROFOILS

The measured position of cavitation separation from two different sized 8.32 percent bi-convex hydrofoils at zero angle of attack are shown in Figure 2. The trend with Reynolds number is found to be similar to that observed in Figure 1 for spheres. At zero angle of attack cavitation separation from the hydrofoils was symmetric on the top and bottom surfaces, and a photograph illustrating typical physical appearance of cavitation is shown in Figure 3. Following suggestion by Brennen /5/ 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 was quite different. This latter type had smooth glassy appearance at separation and has been termed viscous laminar cavitation separation by Arakeri /4/. We might note that this is the type which was also observed by Brennen on spheres and by Arakeri on two axisymmetric bodies. Few measurements of the position of cavitation separation with hydrofoil at small positive angles of attack are presented in Table I.

4. COMPARISON WITH THEORY

Brennen /2/ modelled the cavitating flow past a disk and sphere using one of the non linear free streamline theories. His numerical computations included the prediction of the drag coefficient, C_D for both disk and sphere as well as prediction 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 five percent of the measured values. For the sphere in the Re_D range of $3X10^5$ to $8X10^5$ the agreement was within ten percent inspite of the fact that the position of cavitation separation was predicted (Figure 1) quite erroneously based on the smooth separation criterion.

Arakeri /6/ 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 2, the predicted position of cavitation separation using the smooth separation criterion agrees well with 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, as indicated in Table 1 the difference for the pressure side was quite significant. The observed values being substantially downstream than those predicted. Even with these differences good agreement was found between the measured and observed values of C_D. On the contrary, as shown in Figure 4 not only the magnitude of lift coefficient, C_L was predicted erroneously but 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 cavity is predicted to separate at about 30% of the chord; however, it is observed to separate at about 75% of the chord. Thus, the surface between the two is subjected to pressures at least below

vapour pressure or even to small amount of negative pressure. Thus, net effect is that 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 leads to delay in separation and due to lack of sufficient "nuclei" which leads to the liquid being able to sustain pressure below vapours pressure or even negative pressures without cavitating.

5. CONDLUDING REMARKS

Basically two types of cavitation separation have been observed namely (i) nucleate and (ii) viscous laminar. It is now known that second type is closely connected with the conventional boundary layer separation. Empirical correlation based on experimental observations suggests that the viscous laminar type is strongly dependent on the Reynolds number and weakly dependent on the Taylor-Saffman parameter which is the ratio of Weber number to Reynolds number. It is expected that dominant type of cavitation separation in liquids with plentiful supply of nuclei would be the nucleate type. The observed values of cavitation separation have always been found to be downstream as compared to the predicted values based on the smooth separation criterion. This error does not seem to induce large discrepancy in the predicted values of drag coefficient under supercavitating conditions. However, the error induces a substantial descrepancy in the predicted values of lift coefficient. Thus, it is strongly recommended that the available correlation be used to predict the cavitation separation position on the pressure side of a hydrofoil or propeller in place of the normally used smooth separation criterion.

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TABLE I
CAVITATION SEPARATION POSITION FROM A HYDROFOIL AT SMALL POSITIVE ANGLES OF ATTACK AND $\sigma = 0.1$

	Experiment		Theory	
α	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

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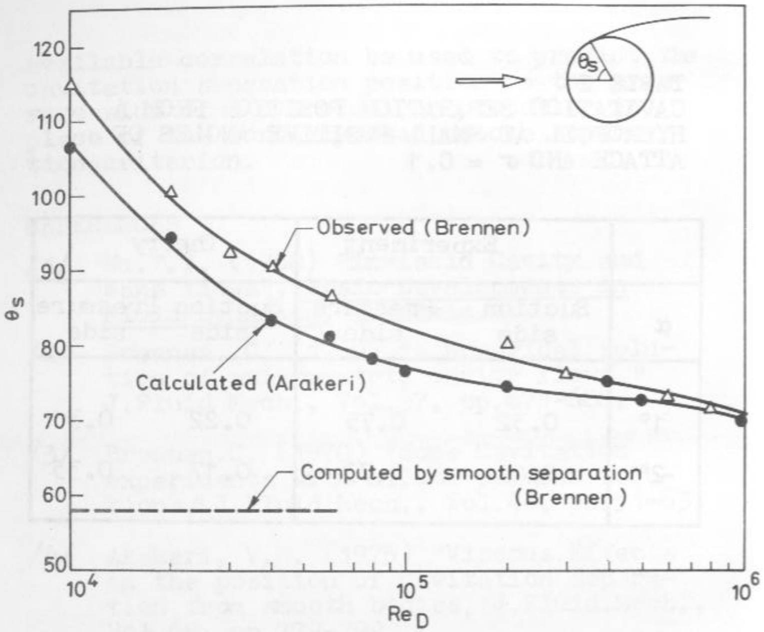

FIG.1. POSITION OF CAVITATION SEPARATION FROM SPHERE AT $\sigma = 0.1$

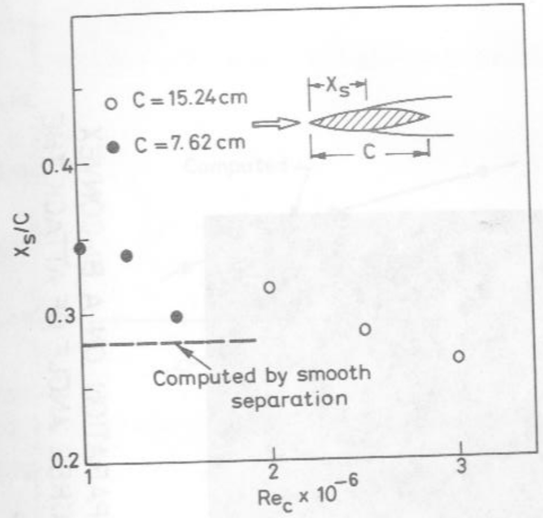

FIG.2. POSITION OF CAVITATION SEPARATION FROM Bi-CONVEX HYDROFOIL WITH $\alpha = 0$ AND $\sigma \cong 0.1$ (Arakeri 1971)

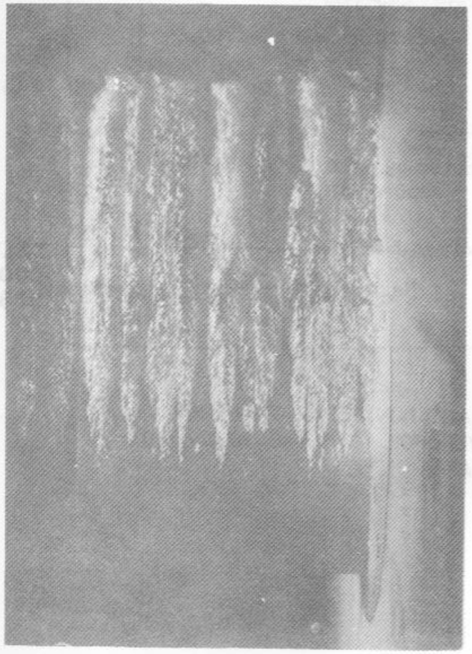

FIG.3. TYPICAL CAVITATION SEPARATION ON A BI-CONVEX HYDROFOIL AT ZERO DEGREE ANGLE OF ATTACK. THE FLOW IS LEFT TO RIGHT.

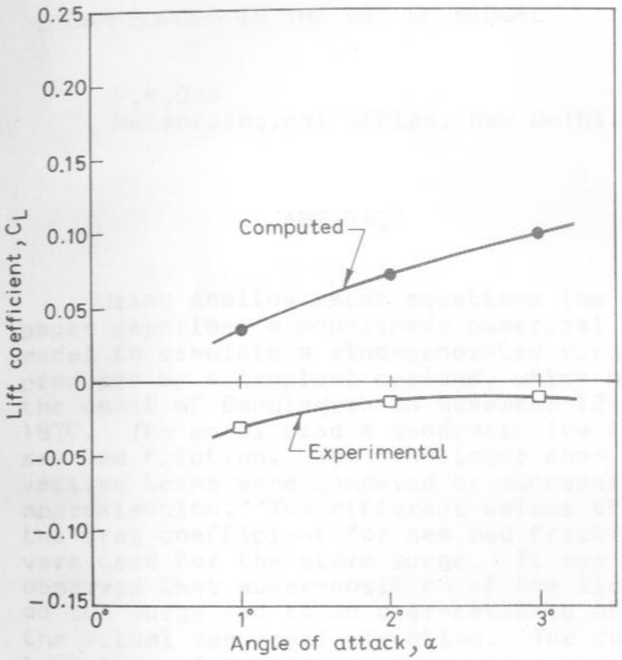

FIG.4. COMPARISON OF EXPERIMENTAL AND COMPUTED LIFT COEFFICIENTS ON A BI-CONVEX HYDROFOIL WITH $\sigma \cong 0.1$ (Arakeri 1971)