Some Viscous and Other Real Fluid Effects in Fully Developed Cavity Flows

Discussion by C. Brennen

California Institute of Technology
Pasadena, California

Some significant differences between fully developed cavity flows and their corresponding potential flow models are described and an attempt is made to interpret the results in terms of the real fluid properties. The phenomenon of cavity separation from a smooth surface and the nature and appearance of the cavity interface are given particular attention.

Introduction

Studies of real fluid effects upon partially or fully developed cavity flow have been receiving more attention of late due to the many interesting comparisons of potential and inviscid flow theory with experiment. The intention of this short paper is to briefly describe some of the effects observed during a series of water tunnel experiments with axisymmetric headforms (some of which have been reported in detail elsewhere) and to surmise qualitatively on some of the general implications and effects. The following section looks at the phenomenon of separation; the Section on "Cavity Surface Appearance and the Nature of the Interfacial Boundary Layer" reviews the appearance of the cavity surface and the closure region. Finally the last Section "Effects of 'Drag-Reducing' Polymer Added to the Water" introduces some of the rather surprising effects observed when small quantities of "drag-reducing" polymer were dissolved in the water of one of the tunnels used.

Cavitation Separation from a Smooth Surface

When separation occurs at a sharp projecting corner on a headform, potential flow theory adequately predicts both the wetted surface pressure distribution and the shape of the cavity for some distance downstream in the majority of flows of practical interest (see for example Ref. [6]). When there is no such corner potential flow solutions necessarily employ the condition of "smooth separation" in order to locate the position of separation. If the headform is a regular "streamlined" shape, then the wetted surface pressure gradient is usually favorable everywhere except at separation where it approaches zero. But in a real flow the wetted surface boundary layer would be expected to separate only in the presence of a finite adverse pressure gradient and at the point of zero wall shear stress. How in practice this inner boundary layer flow is "matched" with the outer potential flow is best illustrated by an example.

The experimentally observed position of separation from a sphere which is fully cavitating lies downstream of that predicted by inviscid theory (see plate 1), the difference increasing as the Reynolds number is reduced [8, 2 and 3]. The results of these references in which spheres of diameters ranging from ¼ in. to 3 in. were used indicate that the position depends primarily upon cavitation number, σ, and Reynolds number, Re (Fig. 1 was compiled using those results). That the dependence upon Weber number is at most secondary, despite the appearance of a significant "separation meniscus" at low Re (see plate 7), is supported by some results with a solution having a much reduced surface tension [2].

On the other hand measurements by Rouse and McNown [10] and Konstantinov [9] indicate that the pressure on the wetted surface, p, does in fact reach its minimum around the theoretical separation position. This suggests that the pressure in the region between the theoretical and observed separation position is roughly constant at the cavity value, p_c (This interpretation is also consistent with the fact that the delayed separation in experiment does not lead to higher values of the total drag on the headform; if anything

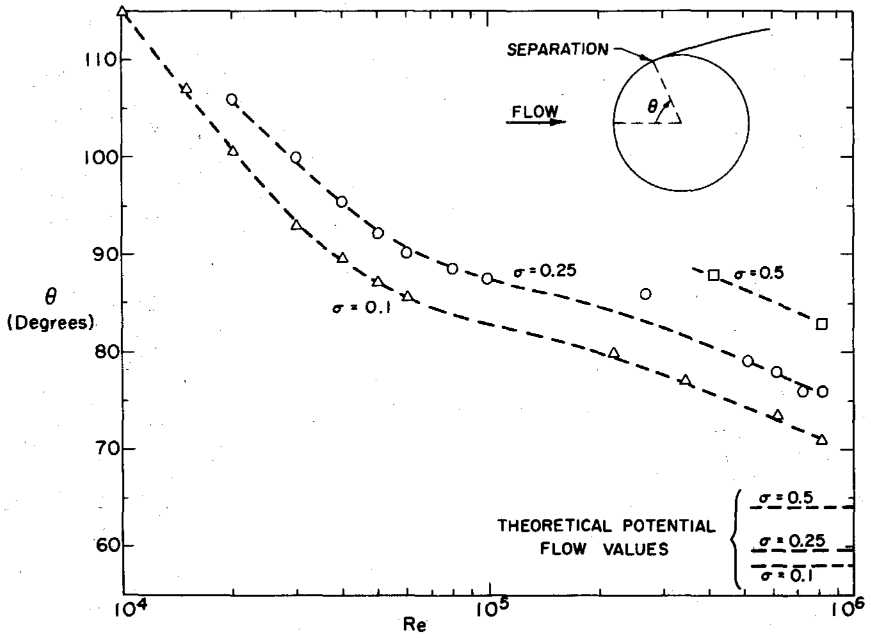

FIG. 1 VARIATION IN THE POSITION OF SEPARATION FROM A SPHERE WITH CAVITATION NUMBER, σ, AND REYNOLDS NUMBER, Re, BASED ON UPSTREAM VELOCITY AND SPHERE DIAMETER.

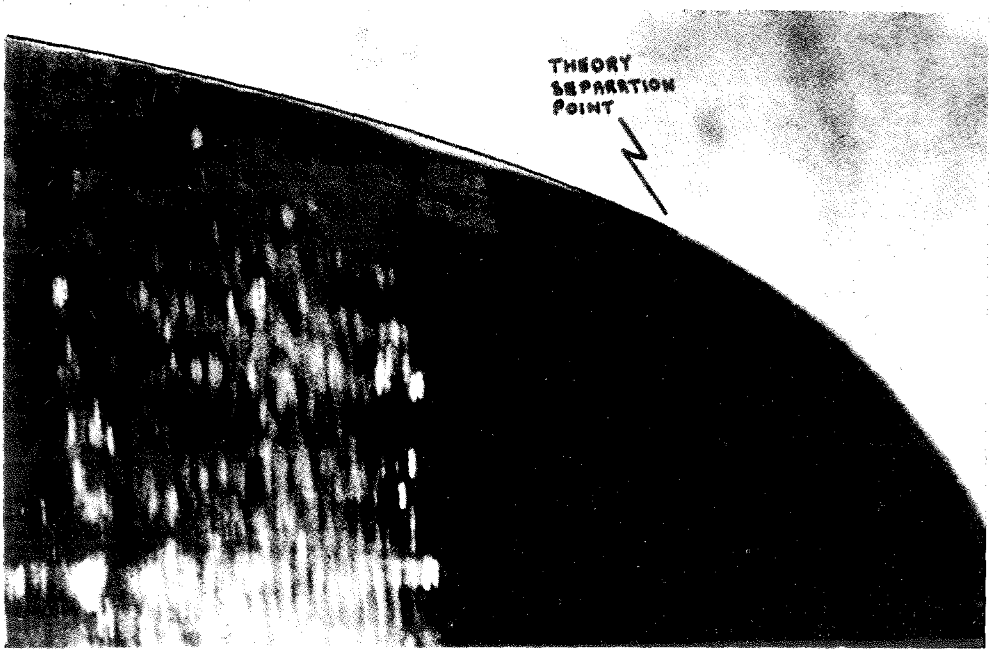

PLATE 1. AN ENLARGEMENT OF A MICROFLASH PHOTOGRAPH OF THE FLOW IN THE NEIGHBOURHOOD OF SEPARATION FROM A 3in. SPHERE WHEN UPSTREAM VELOCITY IS 45 ft/sec AND $\sigma \cong .15$. SUPERIMPOSED UPON THIS IS THE CORRESPONDING CAVITY PROFILE FROM POTENTIAL FLOW THEORY IN WHICH THE "SMOOTH SEPARATION" POSITION IS AS INDICATED.

the reverse appears to be the case). Viscous separation may then be effected by the existence in this region of pressures slightly below that of the cavity. Provided that the residence time of an element of fluid in this region of $p < p_c$ is small cavitation nuclei will not appear.

Conversely there will be other cavity flows in which this residence time is sufficient for significant growth of cavitation nuclei; these may then grow and combine to initiate the large scale cavity. A photograph of a cavitating hydrofoil (plate 2, reproduced, as is plate 3, by permission of Professor A. J. Acosta and V. Arakeri of the California Institute of Technology, under Office of Naval Res. Contract), typifies this type of "nucleate separation" as opposed to the "smooth viscous cavitation separation" from the sphere (plate 1). Transition of the boundary layer prior to "separation" would also effect the issue, delaying possible viscous separation whilst enhancing the chances of nuclei growth. On the other hand a quite small amount of cavity ventilation may raise p_c sufficiently to eliminate the existence of a possible nuclei growth region. Finally plate 3 is included to illustrate an interesting and presumably intermediate form of cavity separation.

Cavity Surface Appearance and the Nature of the Interfacial Boundary Layer

During the water tunnel experiments with spheres and other axisymmetric headforms (Brennen [2 and 4]) a study was also made of the appearance of the cavity surface

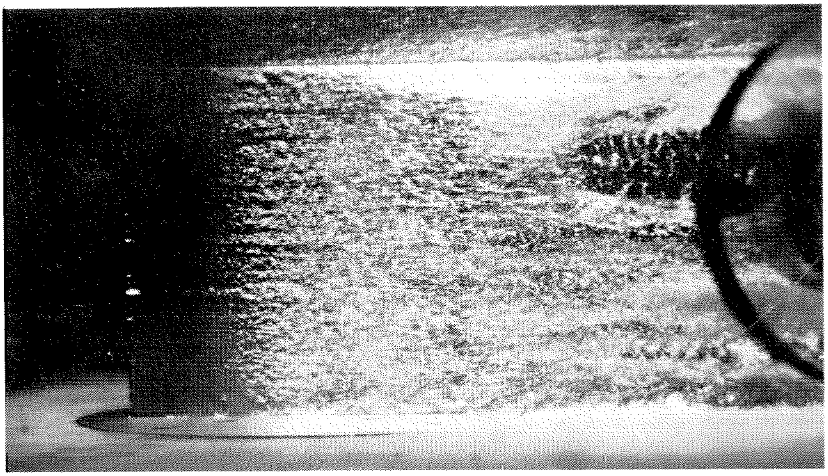

PLATE 2. U ≅ 40 ft/sec, $\sigma \cong 0.19$

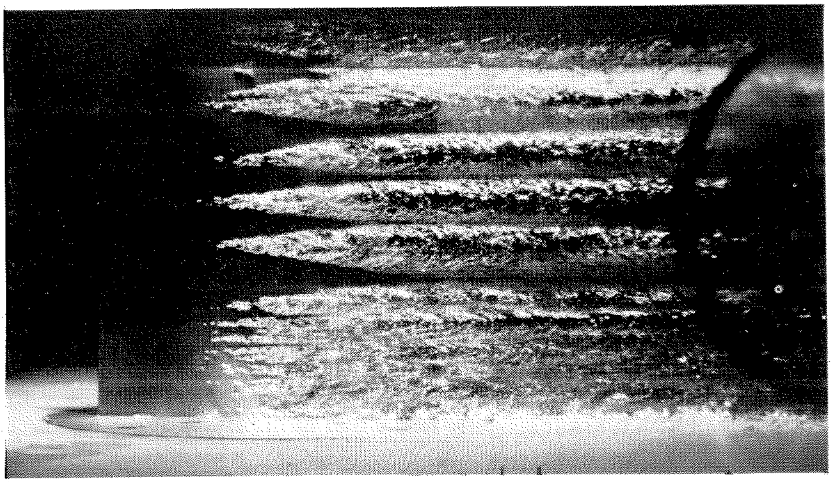

PLATE 3. U ≅ 50 ft/sec, $\sigma \cong 0.13$

CAVITATION OF A THIN BI-CONVEX HYDROFOIL NEAR ZERO ANGLE OF ATTACK. U IS THE UPSTREAM VELOCITY.

following separation. Immediately after that point the surface invariably appeared smooth and glassy, suggesting a laminar boundary layer at separation even at the highest Reynolds numbers (9×10^5 in the case of the 3 in. sphere). With most headforms (eg. plate 4) a system of waves appeared a short distance from separation, and growth in amplitude of these waves during convection downstream normally led to wave break up and a turbulent interfacial boundary layer along the rest of the length of the cavity. As the tunnel speed was reduced both the wavelength and the distance from separation to the point of wave break up increased. By employing ventilation so as to produce fully developed cavities at further reduced tunnel velocities a point was reached at which break up ceased to occur and the waves persisted along the length of the cavity (plate 5). These wave patterns can be fairly satisfactorily ascribed to the growth of an instability in the separated laminar boundary layer, the observed frequency being close to that which has the maximum spatial

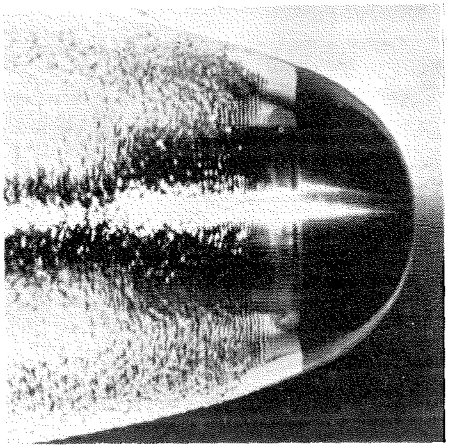

PLATE 4. U ≅ 20 ft/sec

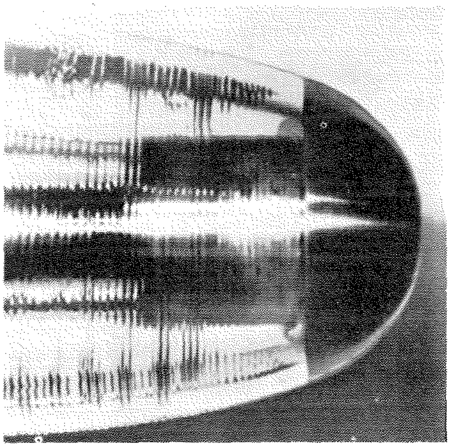

PLATE 5. U ≅ 12 ft/sec

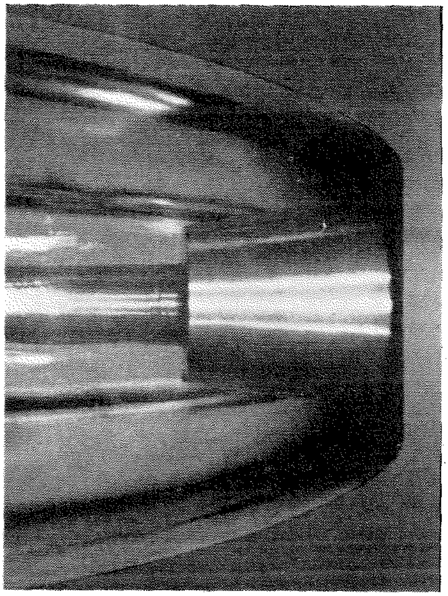

PLATE 6. U ≅ 35 ft/sec

WAVE PATTERNS ON THE SURFACE OF CAVITIES BEHIND A PART-SPHERICAL HEADFORM OF BASE DIAMETER 2.34 in. AND A 3 in. DIAMETER DISC. (U IS THE UPSTREAM VELOCITY).

amplification rate in the layer at or shortly after separation [4]. Among the variously shaped headforms tested only the 3 in. disc produced cavities which were completely clear and glassy at all possible speeds (plate 6).

The nature of the interfacial boundary layer can be seen to have at least one interesting implication. If that layer is turbulent then for most practical flows the rate of diffusion of dissolved air from the water into the cavity will be much greater than that given by diffusion within a purely "potential" flow, See Ref. [1]. (The same will be true of the diffusion of heat required to produce vaporization at the interface). However, in the

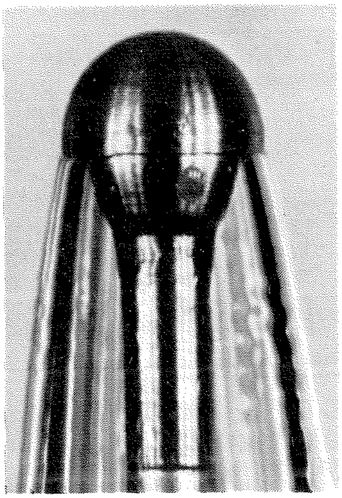

PLATE 7.

PLATE 8.

VENTILATED CAVITIES BEHIND A ¼ in. DIAMETER SPHERE IN WATER AND IN A 50 PPM AQUEOUS SOLUTION OF UNION CARBIDE WSR 301 "POLYOX". UPSTREAM VELOCITY ≅ 12 ft/sec.

steady state, this mass rate of diffusion of air into the cavity must be matched by the rate at which air is entrained away from the cavity in the wake of the highly turbulent closure region. In a recent paper the author compared experimentally measured entrainment rates with theoretically estimated inward rates of diffusion of dissolved air for cavities with a turbulent interface behind a particular headform (Brennen (1968a)). A "semi-theoretical" linear relationship between the partial pressure of air in the cavity, p_{cA} and the air content of the water, P, was thus obtained and this compared favorably with the experimental graph of these quantities. Gadd and Grant [7] found a very much lower value of p_{cA}/P in their experiments with a 5 in. diameter disc, presumably because the "laminar" interface produced by that headform gave rise to much smaller values of the inward diffusion rate.

Effects of "Drag-Reducing" Polymer Added to the Water

Plates 7 and 8 have been included to highlight the principal effect which the additon of 50 PPM. of the long chain molecular polymer, Polyox (Union Carbide WSR 301) has upon fully developed cavity flows. The cavities in these cases had to be produced by ventilation due to the low tunnel velocity (12 ft/sec). In the case of the water flow an increase to around 16 ft/sec in the tunnel velocity was required before the instability waves described in the last section appeared. It seems clear from plate 8 that the effect of the polymer is to produce an instability in the flow around the headform which is then reflected in the surprisingly regular distortion of the separation line. Other similar additives such as Dow Separan AP 30 and guar gum produced similar effects (Brennen [2]).

Concluding Remarks

In conclusion it may be useful to suggest a few particular areas in which further research is indicated:

(i) Since much of the latter part of Section 2 is conjectural further experimental studies of separation would clarify issues. Headform surface roughness and the gas nuclei content of the "free stream" may also be significant in this respect.

(ii) An analysis of the flow in the immediate neighborhood of a viscous cavitation separation point, perhaps along the lines of the treatment given to noncavitating separation by Catherall and Mangler (1966) would be interesting, though the problem may be complicated by the liquid contact angle.

(iii) The real flow in the region of cavity closure and in the cavity wake is normally marked by considerable turbulence and at least small scale unsteadiness. Further studies would increase understanding of the turbulent mixing processes (for example the work of Young and Holl (1966) is a welcome contribution) and entrainment mechanism (see Section 3) in this region.

Acknowledgement

This work has been prepared partly under the support of the Office of Naval Research.

Plates 1, 4, 5, 6, 7 and 8 are reproduced by permission of the Director, Ship Division, National Physical Laboratory.

References

[1] Brennen, C. 1968a. The dynamic balances of dissolved air and heat in natural cavity flows. N.P.L. Ship Div. Rep. No. 115.

[2] Brennen, C. 1968b. Some cavitation experiments with dilute polymer solution. N.P.L. Ship Div. Rep. No. 123.

[3] Brennen, C. 1969a. A numerical solution of axisymmetric cavity flows (to appear shortly in J. Fluid Mech.).

[4] Brennen, C. 1969b. Wave patterns on the surface of hydrodynamic cavities. (Manuscript in preparation.)

[5] Catherall, D. and Mangler, K. W. (1966). The integration of the two dimensional laminar boundary layer equations past the point of vanishing skin friction. J. Fluid Mech., 26, 1.

[6] Fage, A. and Johansen, F. C. 1927. On the flow of air behind an inclined flat plate of infinite space. Proc. Roy. Soc. (London) A*116,* 170-197.

[7] Gadd, G. E. and Grant, S. 1965. Some experiments on cavities behind disks. J. Fluid Mech. 23, 4.

[8] Hsu, E-Y. and Perry, B. 1954. Water tunnel experiments on spheres in cavity flow. Calif. Inst. of Tech. Rep. No. E-24. 9.

[9] Konstantinov, V. A. 1950. Influence of Reynolds number on the separation (cavitation) flow. David Taylor Model Basin Translation, No. 233.

[10] Rouse, H. and McNown, J. M. 1948. Cavitation and pressure distribution: headforms at zero angles of yaw. State Univ. of Iowa, Studies in Engineering, Bull. 32.

[11] Young, J. O. and Holl, J. W. (1966). Effects of cavitation on periodic wakes behind symmetric wedges. ASME Trans. J. Basic Eng. *88* D, 163-176.