MECHANICS OF VENTILATION INCEPTION

Kenneth L. Wadlin
Langley Aeronautical Laboratory
National Advisory Committee for Aeronautics

* * * * *

The research programs conducted by NACA in connection with ventilation are reviewed to provide examples of ventilation and to indicate some significant parameters influencing its inception. It is shown that low pressure is not a sufficient requirement for ventilation but that separation of the boundary layer is also required. The influence of the free water surface on boundary layer separation is presented as a determining factor involved in ventilation inception. An image system is presented for a surface-piercing strut to indicate the manner in which the free water surface may influence separation of the boundary layer and therefore the inception of ventilation.

* * * * *

INTRODUCTION

Ventilation is an interesting and important subject which has been associated with seaplane hull steps for some time. However, only recently with the renewed interest in hydrofoils and the advent of hydro-skis has much effort been made to understand it. By ventilation is meant the entrance of air from the atmosphere to low pressure areas on lifting surfaces or bodies operating in water. The NACA interest in ventilation has been primarily in connection with seaplane hull steps, hydrofoils and hydro-skis. However, ship hulls, rudders and propellers are also susceptible to this phenomenon. When ventilation occurs, areas which previously were experiencing low pressures are subjected to the relatively high atmospheric pressure or pressures approaching atmospheric pressure. This results in significant changes in the flow patterns and the force characteristics of the elements involved. These force changes may result only in a simple change in static equilibrium. However, in many cases the flow reverts to the unventilated condition before equilibrium is reached and instability occurs. Such instabilities may be manifested as porpoising or skipping of a seaplane and heaving, yawing, or stumbling of a hydro-ski or hydrofoil equipped craft. It therefore becomes important to define those areas where ventilation may be expected in order to avoid them or to make modifications to provide a stable transition from the unventilated to the ventilated condition.

Ventilation is also of interest in connection with supercavitating hydrofoils since the fully ventilated condition is analogous to the zero cavitation number case. As a matter of fact data for the zero cavitation number case are obtained in NACA experimental investigations by inducing ventilation. The lift-drag ratios of hydrofoils designed for supercavitating flow are generally depreciated if operated in the fully wetted condition. Therefore early ventilation may be of interest for efficiency as well as stability reasons when supercavitating hydrofoils are required for high-speed applications. This paper presents a review of some of the work done by NACA in connection with the ventilation of hydrofoils, hydro-skis, and struts. A possible explanation of the cause of ventilation inception is also developed.

EXAMPLES AND EFFECTS OF VENTILATION

On surface-piercing hydrofoils and struts ventilation generally occurs, as might be expected, by air entering along the hydrofoil from the water surface. Experimental studies in connection with this type of ventilation have been carried out by several investigators (see Refs. 1-5). Figure 1 is an example of such a hydrofoil that has ventilated. The photograph is of a surface-piercing dihedral hydrofoil having an NACA 64 A series airfoil section. It can be seen that the ventilated area extends from the water surface to a point near the tip of the hydrofoil. Ventilation in this case started at the water surface and rapidly extended toward the tip of the hydrofoil. The cavity is open to the atmosphere and is very long.

On fully submerged lifting surfaces, however, ventilation occurs through the trailing vortices. Ventilation of this type has been investigated by NACA in connection with experimental studies of hydro-skis operating in the fully submerged condition (6-8). Such ventilation resulted in large and sudden changes in the force characteristics of the hydro-ski and thus stimulated further investigation of the subject. The development of the vortex type of ventilation and the resulting flow changes are shown schematically in Fig. 2. Air enters the low pressure area in the core of the trailing tip vortices at a point some distance aft of the lifting surface and travels up the vortex core to a point which draws closer to the lifting surface as the speed is increased. This continues until the aerated portion of the vortex contacts the surface and the flow separates completely from the leading edge of the surface and complete ventilation occurs. Photographs of two phases of this process are shown in Fig. 3. The surface shown is a flat plate having an aspect ratio of 0.25. The upper photograph shows the flow after the low pressure in the vortex core has vented to the atmosphere. The air appears to enter the vortex at the turbulent area at the base of the roach and extends to a point well forward but not in contact with the plate. The lower

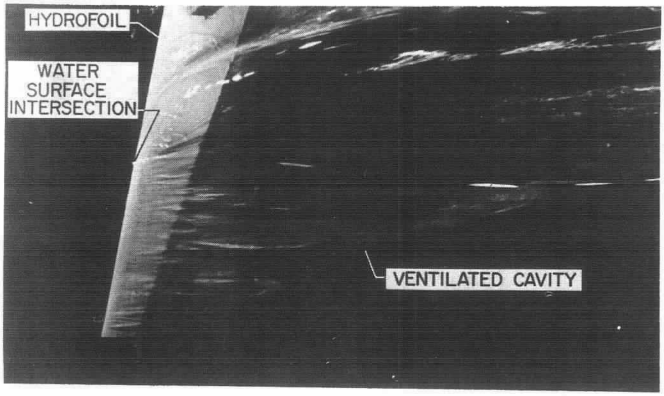

Fig. 1 - Photograph of a surface-piercing hydrofoil ventilated to the atmosphere

Mechanics of Ventilation Inception

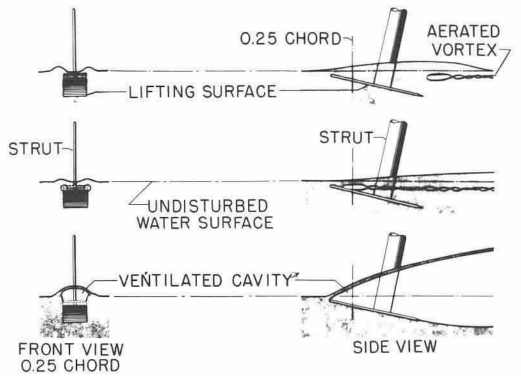

Fig. 2 - Development of vortex ventilation

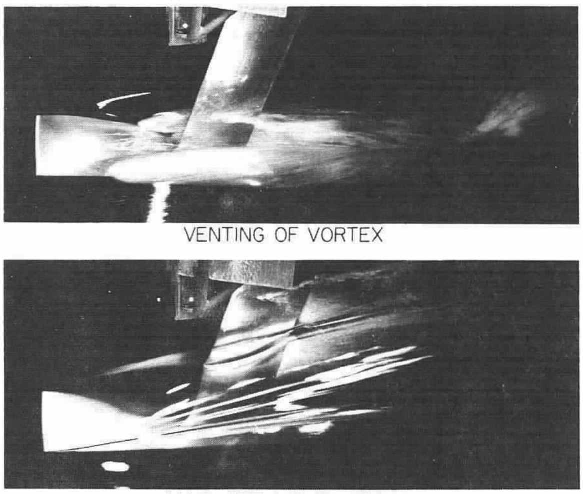

Fig. 3 - Photographs showing the development of vortex ventilation of an aspect-ratio-0.25 flat plate

photograph shows the flow after the aeration of the vortex core had moved progressively forward until it contacted the plate and complete ventilation occurred.

The influence of such ventilation on the lift of the plate is shown in Fig. 4. The lift increased with speed with no noticeable influence of the vortices becoming aerated at speeds below 70 feet per second. However at 70 feet per second when ventilation occurred the lift immediately dropped to a much lower value.

PARAMETERS INFLUENCING VENTILATION INCEPTION

It is apparent from Fig. 4 that the effects of ventilation canbe quite important in any particular application of lifting surfaces. Therefore it is important toknow when

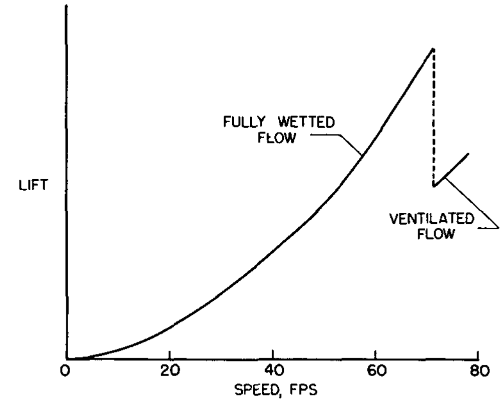

Fig. 4 - Influence of vortex ventilation on the lift of a submerged flat plate having an aspect ratio of 0.25

ventilation may be expected to occur. Figure 5 presents the ventilation inception boundaries for the surface considered in the previous figures. These boundaries define the speed at which ventilation occurred for a given angle of attack for several depths of submersion. The boundaries divide into two definite areas. At the high angles of attack the ventilation inception speed is almost independent of the angle of attack. However, the change in inception speed with depth of submersion is appreciable, increasing rapidly with increasing depth of submersion. At the lower angles of attack this is reversed. Here the incipient ventilation speed is significantly affected by the angle of attack. However, the change with depth of submersion is reduced to a small value. From these tests it appeared that ventilation inception was influenced by, if not the direct result of, boundary layer separation. It appeared that ventilation at high angles might be related to stall or turbulent separation. The ventilation at low angles appeared to be related to laminar separation near the leading edge.

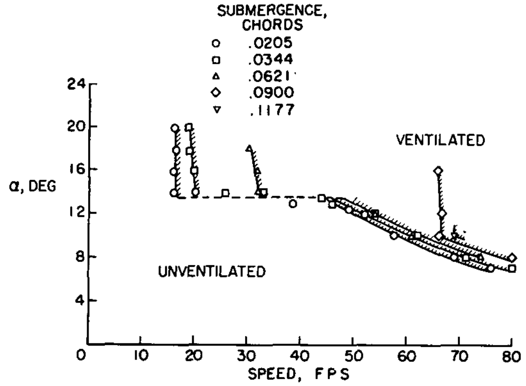

Fig. 5 - Ventilation boundaries for a submerged flat plate having an aspect ratio of 0.25

VENTILATION-SEPARATION RELATIONSHIP

When ventilation inception is assumed to be associated with boundary layer separation, it immediately, as do all boundary layer problems, becomes a complex problem. The simplest case of ventilation is that of the surface-piercing strut. This case will be considered in an effort to gain some understanding of the ventilation-separation relationship.

For blunt-trailing-edge bodies such as cylinders intersecting the water surface there appears to be a definite relationship between the depth of ventilation and the Froude number based on the depth of submergence. This is shown in Fig. 6 where data presented by Wetzel in Ref. 4 have been replotted. The Froude number, based on the depth of submergence, at which cylinders of diameters ranging from 0.031 to 2.00 inches ventilated to the bottom are presented for varying depths of submergence. It can be seen that beyond a depth of submergence of about 2 inches the Froude number based on the depth of submergence at which ventilation occurred was about 1.7. This is a value which has also been found by others (5,9). The relationship between the base pressure coefficient at the lower end of the strut and this Froude number is $C_{p,B} = -2/(Fh)^2$. Figure 6 therefore indicates that at submergence depths greater than 2 inches the pressure coefficient at the tip was constant. However at depths less than 2 inches the pressure coefficient at the tip decreased rapidly. This is as would be expected since as the lower tip of the cylinder approaches the water surface it approaches a constant pressure or free stream velocity boundary and therefore a C_p of zero. Since the pressure coefficient is decreasing, it is necessary for the speed or Froude number to be increased to provide the dynamic pressure head required to overcome the static water head.

Though this relationship between the pressure coefficient and the Froude number based on the depth of submergence applies to the bluff sections such as cylinders, flat plates, or wedges, this is not the case for streamline sections. This is demonstrated in Fig. 7 which was presented in Ref. 10. The strut shown has a chord of 4 inches and an NACA 66_4-021 airfoil section at zero angle of attack. It penetrated the water surface to a depth of 8 inches and was being towed at a speed of 75.8 feet per second. Extensive cavitation can be seen which approached to within about 0.75 inch of the water surface. The presence of cavitation indicates low pressures approximating

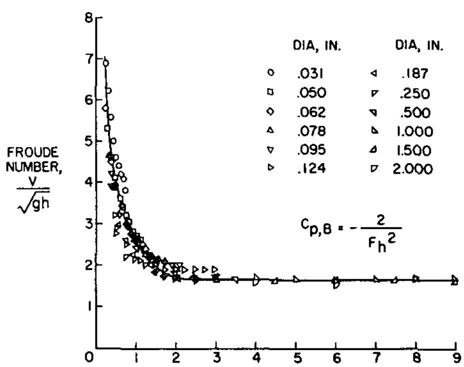

Fig. 6 - Froude number at which ventilation occurs for surface-piercing cylinders at various depths of submergence

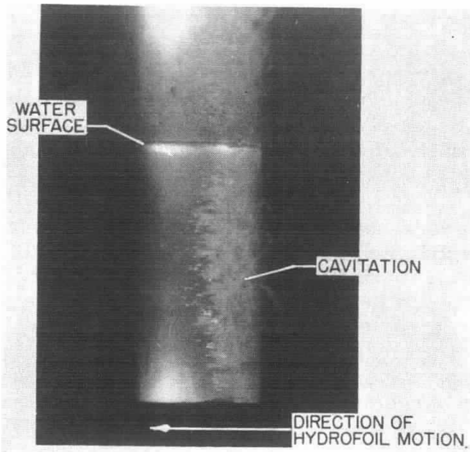

Fig. 7 - Photograph of surface-piercing strut cavitating yet not ventilating

vapor pressure within 0.75 inch of the water surface. Such pressures correspond to water heads of over 30 feet and yet no tendency toward ventilation was apparent. Such observations lead to the conclusion that the turbulent wake behind the cylinder provided low energy paths through which air could enter the low-pressure regions. In the case of the airfoil section the flow about the foil was smooth and of high energy with no turbulent wake in its immediate vicinity and therefore no low energy path through which the air could enter. Of course, such sections do ventilate at higher angles of attack. In such cases the chordwise pressure gradient may have pressure peaks near the leading edge followed by an adverse pressure gradient which could result in boundary layer separation and susceptability to ventilation.

EXPERIMENTAL FLOW STUDIES

In an effort to correlate the presence of separation with the occurrence of ventilation, an oil-flow technique developed at NACA by Donald Loving was used. The technique was developed for use in air but worked as well in water. It consists of putting a thin film of oil on the surface to be investigated and then towing it at a constant speed. The oil tends to wipe off more rapidly in high-energy attached flow and turbulent areas than it does in low-energy separated areas. This results in a greater concentration of oil in the separated areas. The oil pattern is highly visible under ultraviolet light which causes the oil to fluoresce. Figure 8 is a photograph of a typical oil pattern obtained on an unventilated surface piercing hydrofoil having an NACA 64 series section. Above the water surface the oil moved toward the trailing edge. Below the water surface the oil accumulated in the center portion of the chord and was wiped clear in the vicinity of the leading and trailing edges. A laminar separation bubble is indicated by the accumulated oil. As indicated by the sketch the accumulation of oil was due to the forward motion of the boundary layer at the aft end of the bubble moving the oil forward rather than permitting it to be swept downstream by the turbulent flow aft of the bubble.

Figure 9 is a photograph of the same model where air was artificially introduced into the area which the oil pattern indicated to be separated. The air remained in an

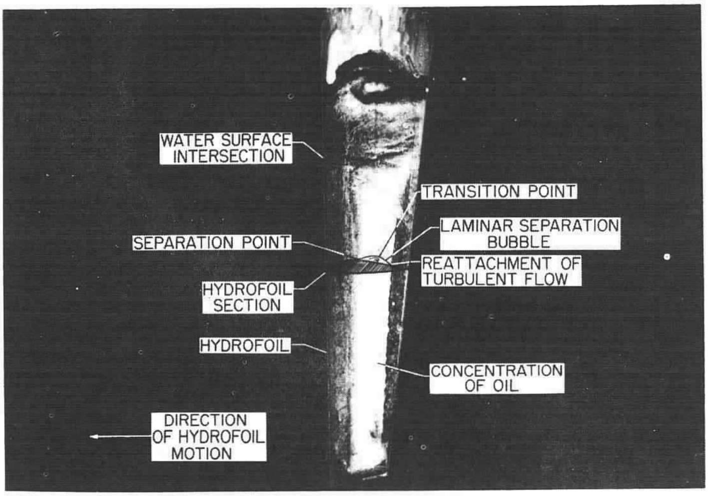

Fig. 8 - Photograph of oil flow pattern showing laminar separation bubble

area whose forward portion closely resembles that of the laminar bubble indicated by the oil-flow pattern shown in Fig. 8. This indicates that ventilation will occur if the foil has a separated flow region and air can get to this region. However, ventilation did not occur naturally in Fig. 9 but was induced by disturbing the water surface in the vicinity of the foil leading edge. When the disturbance was removed the cavity closed at the water surface as can be seen by close inspection of the photograph. The air in the cavity was then entrained by the water and the cavity gradually dissipated until fully wetted flow was again attained. The fact that the foil had separated flow regions of low pressure on it and still did not ventilate naturally or even maintain

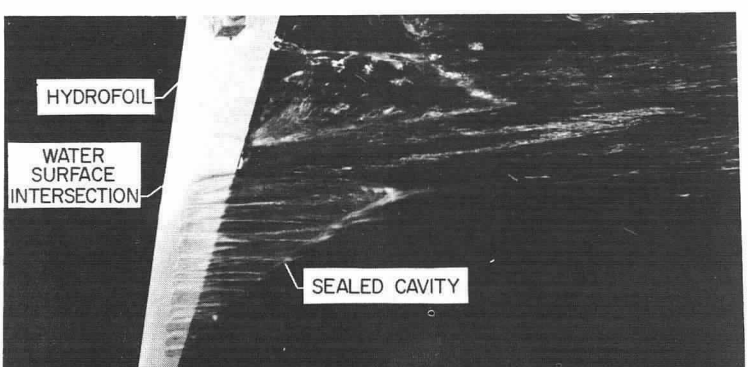

Fig. 9 - Photograph of ventilation of the laminar separation bubble

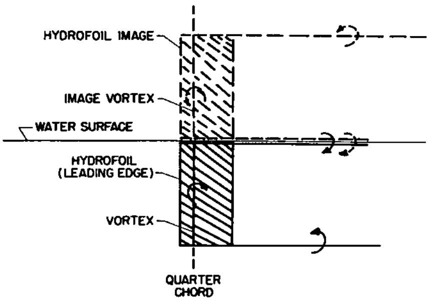

Fig. 10 - Horseshoe vortex system which satisfies the boundary conditions for a surface-piercing strut

ventilation after initial ventilation was induced indicates that the separated region did not extend to the water surface. This could be expected since separation of the boundary layer is strongly influenced by pressure gradients, and the water surface has no such gradient since it is a constant pressure boundary.

MATHEMATICAL MODEL

In an effort to gain some insight as to the extent to which the proximity of the water surface might retard separation the method of images was employed. The image system shown in Fig. 10 was set up to satisfy the condition of constant pressure at the free water surface. A single horseshoe vortex was substituted for the hydrofoil. The bound vortex was located at the quarter-chord and the trailing vortices were located at the tip and at the water surface. The image vortex was located in a similar manner except above the water surface. The vorticity of the image was of opposite rotation as that of the hydrofoil vortex. Such a simplified image system cannot be expected to calculate the flow accurately, especially in areas close to the vortices. However flow directions calculated in the vicinity of the leading edge should provide an indication of the distribution of the load along the span.

Figure 11 presents the spanwise distribution of the parameter $(W/V)/(C_L/2\pi)$ which defines the flow direction at the leading edge of the hydrofoil, where W is the flow velocity normal to the undisturbed stream velocity V and C_L is the lift coefficient of the hydrofoil. It can be seen that the angle of flow rapidly decreases in the vicinity of the water surface, becoming zero at the water surface. Since this flow angle is an indication of the loading, it indicates that the loading also becomes zero at the water surface. As the loading approaches zero, the chordwise pressure gradient must also approach zero and thereby reduce the tendency of the boundary layer to separate. The fact that the chordwise pressure gradient at the water surface is zero would indicate that separation would never occur at the water surface and therefore ventilation would never occur. This is a limitation of the mathematical model. Another limitation of

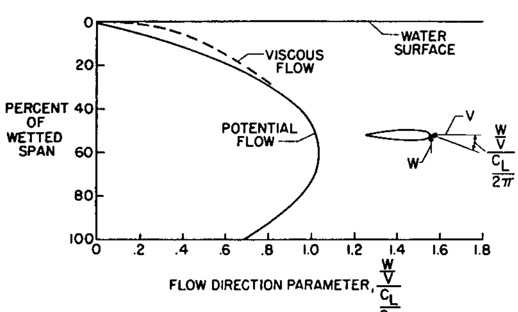

Fig. 11 - Flow direction at the leading edge of a surface-piercing strut obtained by using the method of images

the mathematical model is that it does not account for the effect of speed which is quite apparent in experimental investigations. Both of these deficiencies result from the fact that the mathematical model assumes potential flow.

EFFECT OF VISCOSITY

Efforts to understand the intimate details of the mechanics of ventilation inception have not been extensive. As a result no definite conclusions have developed as to the manner in which the separation at the water surface, which ultimates in ventilation, occurs. It is believed, however, that the usual concept of inviscid irrotational flow outside the boundary layer is not adequate near the water surface, especially in the vicinity of the leading edge of the hydrofoil. In such a case there would be an interaction between the two flows which could result in substantial changes in the pressure gradients and flow. Thus both separation at the water surface and the influence of speed could be explained as a result of such an interaction. Referring back to Fig. 11 it will be noted that since the parameter $(W/V)/(C_L/2\pi)$ is an indicator of the flow angle and loading, it is also an indicator of the perturbation velocity. Viscosity will alter the distribution of this velocity. This is particularly true when the velocity gradients are large. The shear forces due to viscosity tend to average the velocities. That is, the lower velocities in the region close to the water surface will be increased over those predicted by potential flow, while the higher velocities at the greater depths would be reduced. The effect near the surface is of interest in the case being considered. The dashed curve on Fig. 11 is intended to indicate this change in perturbation velocity. It can be seen that though the perturbation velocity approaches zero in the proximity of the water surface, its velocity gradient is greatest there and the effect of viscosity is to increase this gradient. These high velocity-gradients in the vicinity of the water surface are conducive to eddies which would provide low-energy paths to the separated areas farther below the water surface. Since these velocity gradients will increase with stream velocity, the tendency for eddies to form will increase with increasing stream velocity. This is a possible explanation for the influence of velocity on the inception of ventilation which is so apparent in experimental investigations.

CONCLUDING REMARKS

Some understanding of the mechanics of ventilation inception has been gained in that it has been shown that low pressure is not a sufficient requirement for ventilation but that separation of the boundary layer is also required. It has also been found that separation of the boundary layer is greatly retarded by the presence of the free water surface. However further investigation will be necessary before the mechanism of this retardation and how it is influenced by speed is understood and a means of calculating boundaries for the inception of ventilation can be developed.

REFERENCES

1. Breslin, John P. and Skalak, Richard, "An Exploratory Study of Ventilated Flows About Yawed Surface-Piercing Struts," ETT, SIT Rep. 668, 1957

2. Perry, Byrne, "Experiments on Struts Piercing the Water Surface," CIT Rep. E-55.1, 1954

3. Kiceniuk, Taras, "A Preliminary Experimental Study of Vertical Hydrofoils of Low Aspect Ratio Piercing A Water Surface," CIT Rep. E-55.2, 1954

4. Wetzel, J.M., "Experimental Studies of Air Ventilation of Vertical, Semi-Submerged Bodies," St. Anthony Falls Hydraulic Laboratory, U. of Minn., 1957

5. Hay, Donald A., "Flow About Semi-Submerged Cylinders of Finite Length," Princeton University, 1947

6. Wadlin, Kenneth L., Ramsen, John A., and Vaughan, Victor L., Jr., "The Hydrodynamic Characteristics of Modified Rectangular Flat Plates Having Aspect Ratios of 1.00, 0.25, and 0.125 and Operating Near A Free Water Surface," NACA Rep. 1246, 1955

7. Vaughan, Victor L., Jr., and Ramsen, John A., "Hydrodynamic Characteristics Over a Range of Speeds Up to 80 Feet Per Second of a Rectangular Modified Flat Plate Having an Aspect Ratio of 0.25 and Operating at Several Depths of Submersion," NACA TN 3908, 1957

8. Ramsen, John A., "An Experimental Hydrodynamic Investigation of the Inception of Vortex Ventilation," NACA TN 3903, 1957

9. Hoerner, S.F., "Some Characteristics of Spray and Ventilation," Bath Iron Works Corporation, 1953

10. Coffee, Claude W., Jr., and McKann, Robert E., "Hydrodynamic Drag of 12- and 21-Percent-Thick Surface Piercing Struts," NACA TN 3092, 1953

* * * * *

DISCUSSION

H. Saunders (Capt., U.S.N., Ret.)

It seems a pity to me that the use of the single word "ventilation" to signify all aspects of the entrance of air to a region of negative differential pressure in or around or below the water surface has spread so widely within the last few years. This word "ventilation," like everything else, has its proper place in the universe and, if we are to judge by Webster, "ventilation" is something which indicates that air is entering where it is desired or needed. It is most confusing to have the word used also for a situation where the air is definitely detrimental. To cover this second phase we have used the expression "air leakage."

If you don't know whether the air is a good thing or not, then you can speak of "aeration."

J. P. Breslin (Stevens Institute of Technology)

I would like to touch briefly on a few of the highlights which were revealed by an exploratory study* which was conducted at the Stevens Institute Experimental Towing

*J.P. Breslin and R. Skalak, "An Exploratory Study of Ventilated Flows About Yawed Surface-Piercing Struts," ETT Report No. 668, October 1957.

Tank (SETT) under support of the Hydrodynamics Laboratory of the NACA. Some of these results corroborate the findings on ventilation inception as given by Mr. Wadlin and others are offered as additional facts which may be of interest to those who would like to be able to estimate the forces on a ventilating body.

The SETT tests were made with two vertical surface-piercing struts, one being a symmetrical, 2.5-inch circular-arc section and the other a 3-inch cambered section (NACA 4412) which has a nearly flat pressure side. Three modes of inception were found:

1) by ingestion of air through momentarily developed "Rankine" vortices in the unsteady, separated flow attending stall conditions at large angles of yaw (Fig. D1),

2) through aeration of the trailing vortex developed by the lower tip, and

3) through the action of a slight disturbance applied at the suction side near the leading edge at the juncture with the free surface when underway at speeds and angles of yaw well below those for which ventilation occurred spontaneously at stalling conditions.

The first mode was observed in quite some detail through the use of a motion picture camera.

The discovery of the high sensitivity of the flow to slight disturbances (mode 3 above) led to an investigation of the boundary layer by the NACA which was very effectively carried out through the use of the oil-ultra-violet light technique described in the paper. Similar observations at SETT also revealed regions of laminar separation and re-attachment of the boundary layer which are sealed from the free surface by a relatively thin strip of nonseparated flow over the length of the chord at the juncture with the streaming free-surface. This strip is nonseparated because of the near-zero longitudinal pressure gradient imposed by the presence of the free surface. Momentary rupture of this seal permits air to replace the separated fluid and a new flow phase is thereby initiated. The presence of a laminar separation (which, incidentally, does not always give rise to noticeable anomalies in the side-force curve)

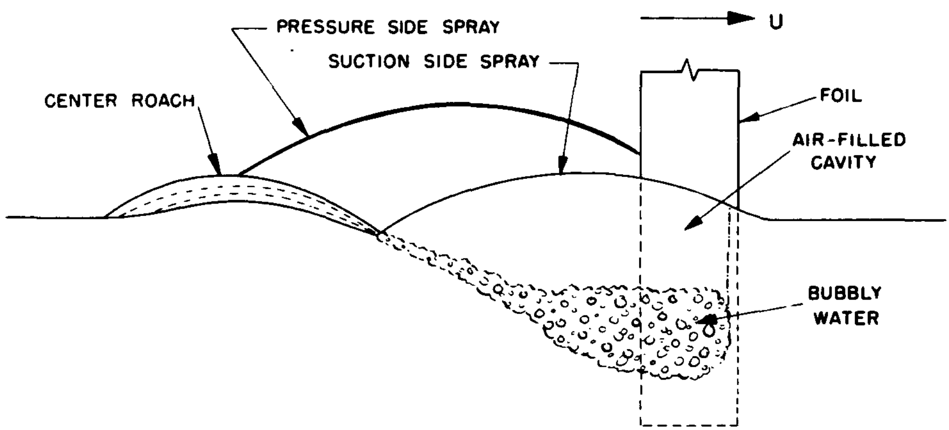

Fig. D1 - Partial cavity formed at low Froude numbers and large angles of attack is a consequence of the low Reynolds numbers at which small models are tested. It is therefore advisable for towing tanks to take measures to insure turbulent boundary layers in any experiment in which ventilation inception conditions are being sought. It is expected that at high Reynolds numbers the susceptibility to ventilation by disturbances around the leading edge at angles of attack well below stall will be small if there are no regions of separation present.

However, attention is invited to the observed fact that once a ventilated flow is developed it is very stable and will persist down to small angles of yaw (or side-force coefficients) as may be seen in a typical set of data from the SETT tests shown in Fig. D2. The ventilated cavity will collapse at conditions beyond that for natural closure only if some means of inhibiting the supply of atmospheric air is applied. Conditions for natural closure of cavities were observed and these are shown in Fig. D3. It appears that a sufficient condition for the existence of full ventilation on the tested models is given by

$$C_s \geq \frac{5}{F_h^2} = \frac{5gh}{U^2}\,, \qquad F_h > 3\,. \tag{D1}$$

However, for operation at C_s-values above this, ventilation will not be easily generated unless boundary layer separation exists. In the absence of such separation it is expected that a rather large disturbance is necessary to develop the other possible flow below stall, viz., full ventilation.

It has been noted, without elaboration by the author, that a fully ventilated flow is analogous to the flow about the same body at zero cavitation index. This is true only at "infinite" Froude number. At finite Froude numbers there appears to be a very plausible connection between the flow in a section of a ventilated flow and that about the corresponding section in a two-dimensional cavitational flow. The conditions which must be imposed in order that these flows be similar can be obtained as follows:

For any point on the wall of a three-dimensional ventilated cavity ($p = p_a$), we have

$$-\frac{2}{F_\zeta^2} = -\frac{2g\zeta}{U^2} = -2\left(\frac{u_3}{U}\right) + \left[\left(\frac{u_3}{U}\right)^2 + \left(\frac{v_3}{U}\right)^2 + \left(\frac{w_3}{U}\right)^2\right]\,, \tag{D2}$$

and

$$\frac{w_3}{U} \approx -\frac{\partial\zeta}{\partial x}\,. \tag{D3}$$

On the wall of a two-dimensional vapor cavity ($p = p_v$), we have

$$\sigma = \frac{p_\infty - p_v}{\frac{1}{2}\rho U^2} = -2\left(\frac{u_2}{U}\right) + \left[\left(\frac{u_2}{U}\right)^2 + \left(\frac{v_2}{U}\right)^2\right]\,. \tag{D4}$$

Here:

- ζ is the vertical distance below the free surface to the point on the ventilated cavity wall (negative downward),
- F_ζ is the "submergence" Froude number,
- g is the acceleration of gravity,

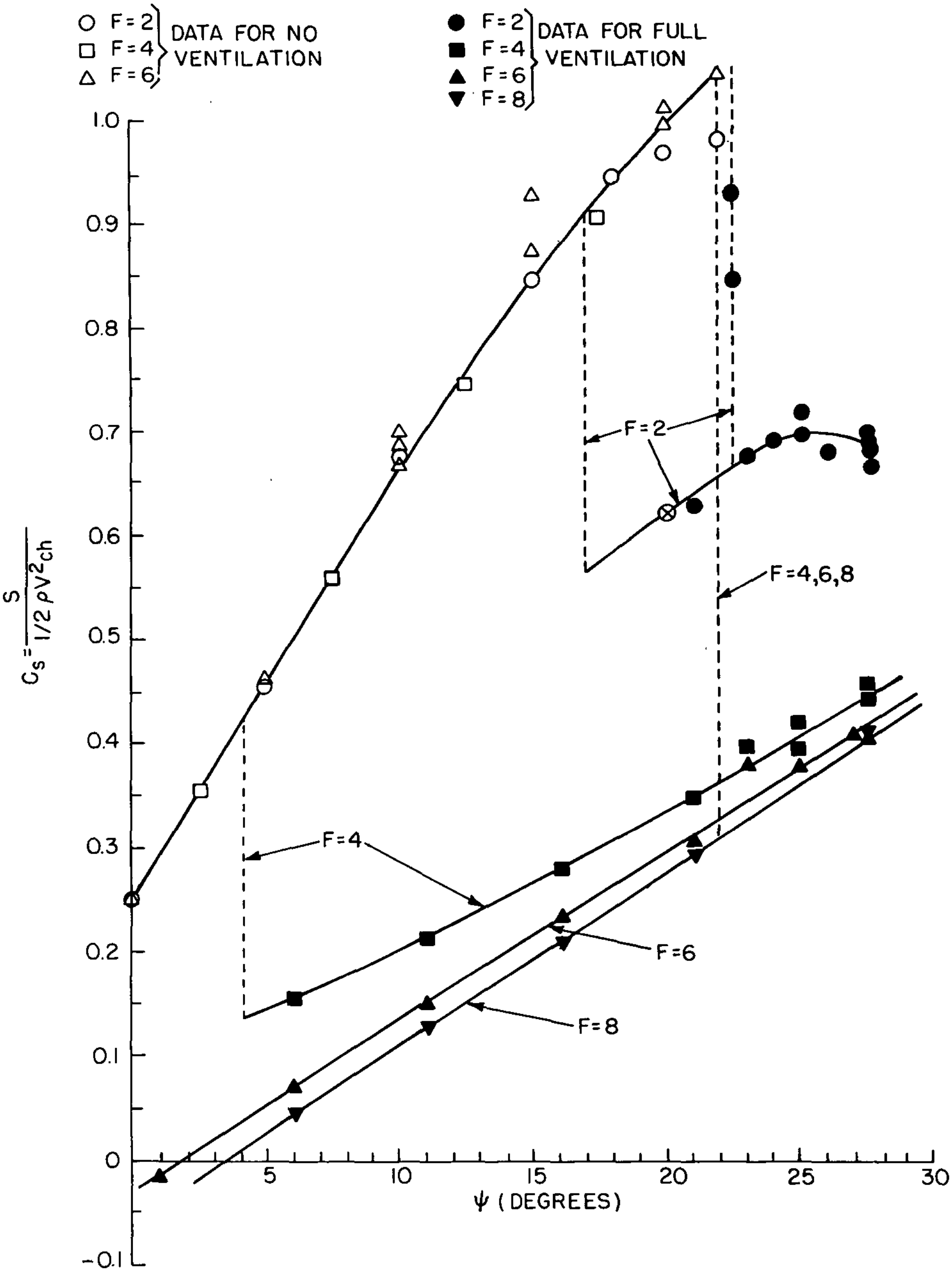

Fig. D2 - Side-force coefficients

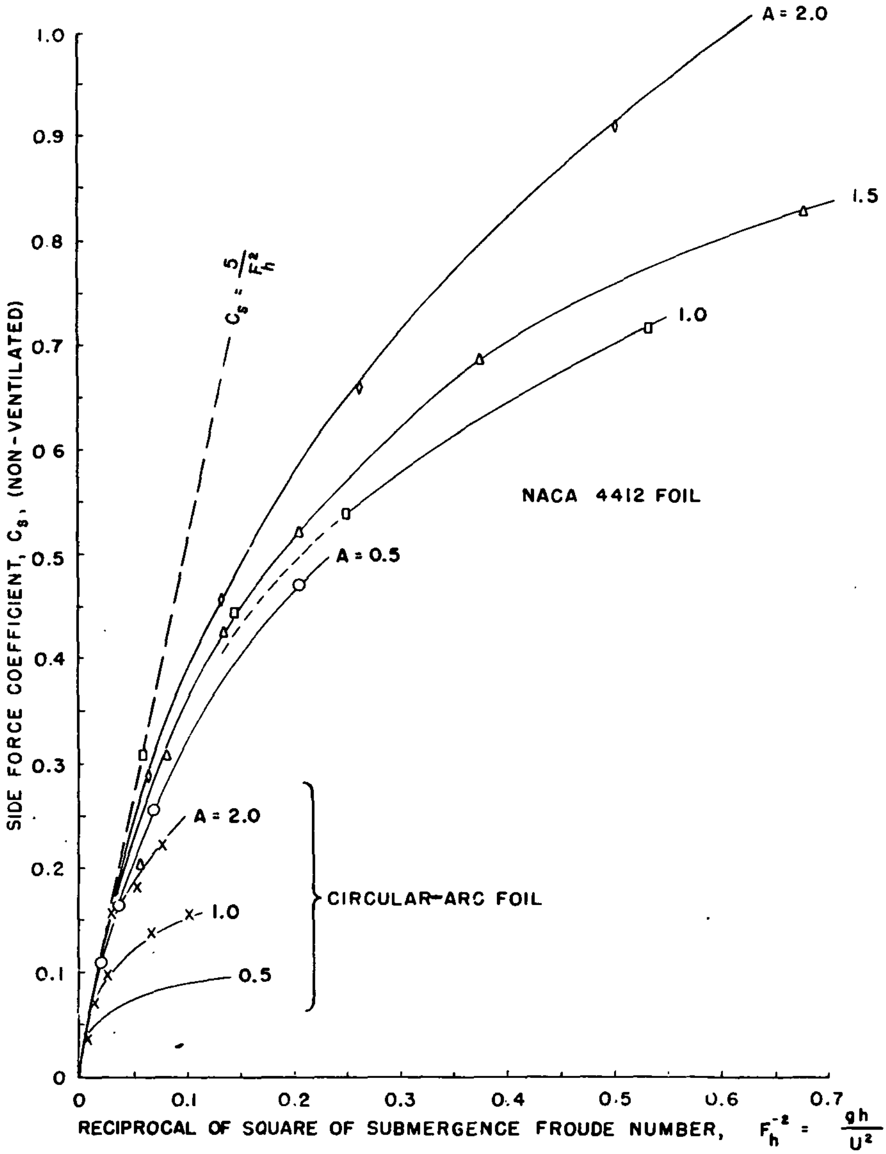

Fig. D3 - Side-force coefficient bounds, below which ventilated cavities are not sustained, as a function of submergence Froude number

U is the free-stream speed, or speed of advance,

u_3, v_3, w_3 are x-, y-, and z-components of velocities produced by presence of body and cavity in three dimensions,

x, y, z are coordinate axes taken in such a way that the free stream is parallel to the negative x-axis and the z-axis is positive upward,

p_∞ is the reference pressure at infinity,

p_v is the vapor pressure,

p_a is the atmospheric pressure, and

σ is the cavitation index.

For points which are not near the extremities of the ventilated cavity, i.e., where $\partial\zeta/\partial x$ is negligible, the flows may be expected to be quite similar. Thus, the flows may be matched if we take

$$\sigma(\zeta) = -\frac{2}{F_\zeta^2} = -\frac{2g\zeta}{U^2}, \qquad -h < \zeta < 0, \qquad \text{(D5)*}$$

which certainly imposes the condition that $u_2 = u_3$ in all regions where the quadratic terms are negligible.

Employing this relationship a bit freely leads to a formulation for the effective two-dimensional side-force coefficient of a ventilated strut as

$$C_{s_2}(\psi, F_h) = \frac{1}{h}\int_{-h}^{0} C_L(\alpha, \sigma)\, d\zeta \qquad \text{(D6)}$$

which through use of (D6) yields

$$\begin{aligned} C_{s_2}(\psi, F_h) &= \frac{F_h^2}{2}\int_0^{2/F_h^2} C_{L_2}(\alpha, \sigma)\, d\sigma \\ &= \bar{C}_{L_2}(\alpha) \text{ for } 0 \le \sigma \le \frac{2}{F_h^2} \end{aligned} \qquad \text{(D7)}$$

where C_{L_2} is the two-dimensional lift of the cavitating section, and $\bar{C}_{L_2}$ is the mean of C_{L_2} between the limits $\sigma = 0$ and $\sigma = 2/F_h^2$. (It is clear that for $F_h \to \infty$, $C_{s_2} = C_{L_2}(\alpha, 0)$.)

To account for aspect-ratio effects, in the main, we arrive at the side-force coefficient for finite span (3-dimensions) in the form:

$$C_{s_3} = \frac{C_{s_2}(\alpha - \alpha_o)}{E + \frac{a_2}{\pi A}} = \frac{\bar{C}_{L_2}(\alpha - \alpha_o)}{E + \frac{a_2}{\pi A}} \qquad \text{(D8)}$$

*This result was obtained by Perry† who did not, however, indicate restrictions imposed by three-dimensional effects.

†B. Perry, "Experiments on Struts Piercing the Water Surface," Cal. Tech. Hydrodynamics Lab. Report E-55-1, December 1954.

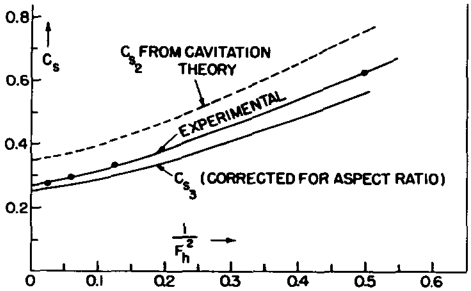

Fig. D4 - Measured and computed side-force coefficients for fully ventilated strut

where

- E is the Jones' edge-correction factor which is computed as perimeter less the chord length at the water surface divided by twice the span,
- a_2 is the cavitating section lift-slope at $\alpha = \psi$,
- A is the geometric aspect ratio,
- and α_o is the angle of zero lift.

Evaluation through the use of Wu's* results for the lift of a cavitating plate in the case of the NACA 4412 strut at aspect ratio 2.0 and yaw angle $\psi = 20$ degrees yields the curves shown in Fig. D4. It is seen that the dependence of the side-force coefficient upon Froude number is well represented over the entire test range by the use of the cavitation analogy. It is also clear how large F_h must be before the flow may be likened to that at zero cavitation index ($\sigma = 0$).

F. S. Burt (Admiralty Research Laboratory)

At A.R.L. we had the advantage of a preview of Dr. Wadlin's paper, but we are not entirely convinced of the proposition that boundary layer separation is needed before ventilation can begin. It seems rather like the problem of which came first, the chicken or the egg. You can just as easily argue that low pressure produces ventilation which produces separation as the proposition that separation causes ventilation. In fact, Fig. 5† of Wadlin's paper, showing the ventilation boundary, could quite well be explained at the lower incidences, without necessarily postulating the existence of a laminar bubble at the lower incidences, by saying that lower incidences produce lower peak suctions; hence, higher speeds would be necessary to produce given values of suction. Whether the flat plate used to obtain the data in Fig. 5 had a laminar bubble would depend largely on the nose shape of the leading edge, and no details of this are given. It would be of interest to know if this particular section has been tested in a wind tunnel and the existence of the laminar bubble under these conditions has been demonstrated. The oil picture of the strut in Fig. 8 would appear to show the laminar bubble, but it would be of interest to know what the Reynolds number of the tests were and whether they tied up with the Reynolds number at which ventilation occurred.

The author suggested that the surface-piercing foil could be considered as the simplest case of ventilation, yet he showed that the effect of the free surface flow conditions are such as to inhibit the prime requisite for ventilation, namely, the free entry of the air. It would seem to be much simpler to consider a fully submerged foil and to repeat the result of Fig. 5 to see if there is any similarity in the test points at the lower incidences.

---

*T. Y. Wu, "A Free Streamline Theory for Two-Dimensional Fully Cavitated Hydrofoils," Cal. Tech. Hydrodynamics Lab. Report 21-17, July 1955.

†Note: All figure numbers are from Wadlin's paper.

P. DuCane (Vosper, Ltd., England)

Referring to the type of flow described in Wadlin's Fig. 2, I have recently observed what would seem to be a rather unusual example of such flow - at least it is an example which has not been seen previously and the explanation of which, it must be confessed, was not immediately obvious.

During the course of functioning trials in the case of an installation of roll damping fins aboard a fast type of round form torpedo boat of the Swedish Navy we were employing the technique known as "forced rolling" to test the installation. This consists of reversing the signal from the controlling gyros in such a manner that the fins will at all times be ordered to increase the roll velocity rather than to reduce it, which is the normal "modus operandi" of such installations.

In this way a roll amplitude is built up each side of the vertical, the magnitude of which is dependent upon the fin forces developed as well as the natural damping of the hull and its statical stability expressed in the form GM.

Such forced rolling is a useful test of many features of the installation, especially if heavy weather is required for a trial and is liable to lead to much delay before the desired conditions are realized.

While observing the mechanism in the engine room we were informed from a deck that "jets" of spray were emerging from the surface by the fins. The "jets" emerged as the fin neared the surface and rose to some ten or fifteen feet for a few seconds while the ship was heeled to the maximum away from the side from which the spray was emerging.

It should be understood that in "forced rolling" the fin will still be trying to lift the ship even as it approaches the surface as in Fig. D5. It therefore seems quite reasonable to suppose that a flow approximating that shown in the lower illustration of Wadlin's Fig. 2 causes this spray to emerge in the manner and at the angle described.

This type of flow associated with a submerged lifting foil approaching the surface is sometimes referred to as Green's flow or Green's solution. It will be interesting to measure the change in lift as the surface is approached and ventilation occurs.

T. Kiceniuk (California Institute of Technology)

Mr. Wadlin's finding that low pressure is necessary, but not sufficient, to induce ventilation behind a surface-piercing body corroborates the findings made in the Free-Surface Water Tunnel at the California Institute of Technology.*† Figures D6 and D7, taken from these earlier reports, show some details of the flow which may give added insight to the mechanism for ventilation inception. The electronic flash photographs reveal what appear to be ventilated vortices shed downstream of the model. These vortices provide a feasible mechanism for the deep penetration by air into the body of a dense liquid in motion. These photographs, as well as visual observations, indicate that real understanding of this problem must await careful and

*B. Perry, "Experiments on Struts Piercing the Water Surface," CIT Hydro. Lab. Report No. E-55.1, Dec. 1954.
†T. Kiceniuk, "A Preliminary Experimental Study of Vertical Hydrofoils of Low Aspect Ratio Piercing a Water Surface," CIT Hydro. Lab. Report No. E-55.2, Dec. 1954.

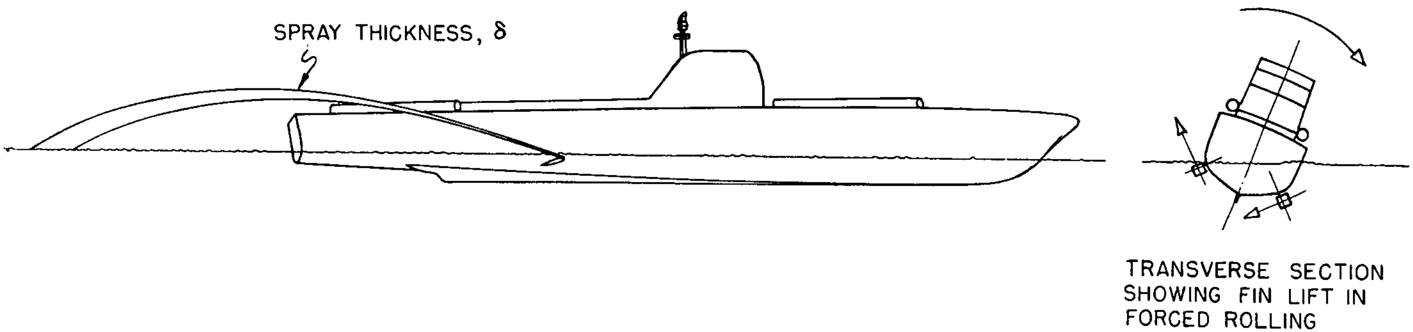

Fig. D5 - High-speed patrol craft in forced rolling showing Green's flow, from leading edge of fin, developing lift

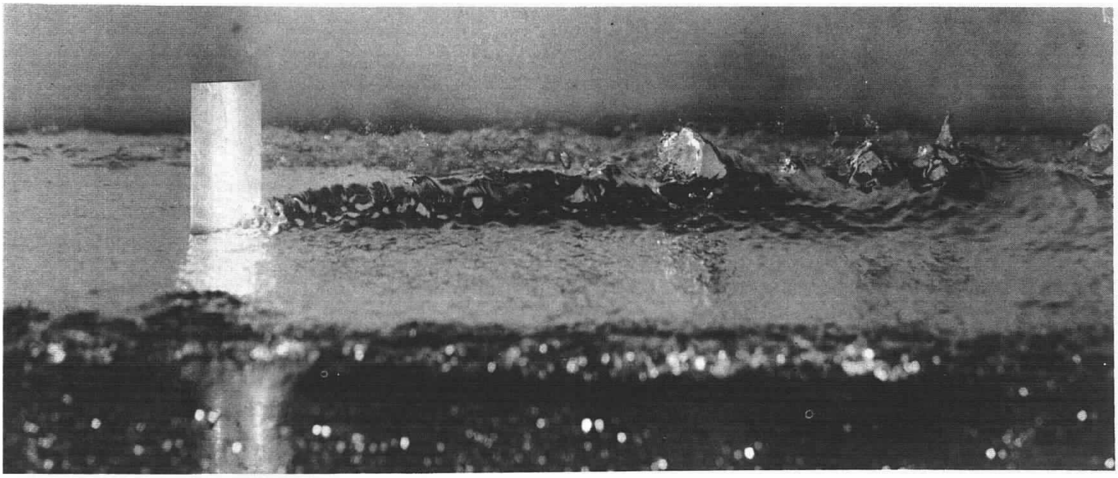

Fig. D6 - Electronic flash photograph of the ventilation behind a surface-piercing body

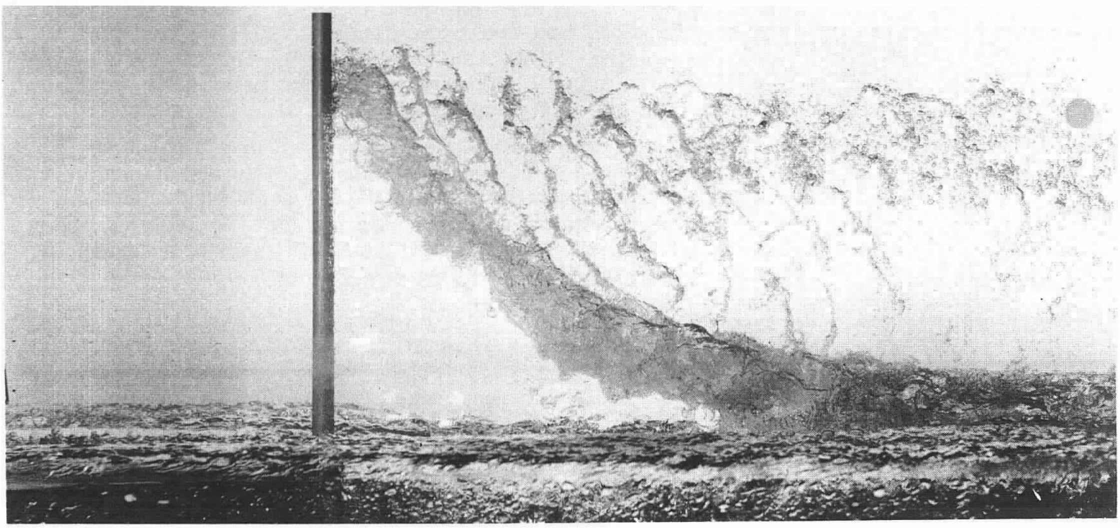

Fig. D7 - Electronic flash photograph of the ventilation behind a surface-piercing body showing possible vortices

detailed observations and measurements of the physical processes taking place in the wake of the body. The use of time-averaged measurements such as the usual pressure coefficient, for example, may be irrelevant in a separated flow situation where the instantaneous low pressures existing at a point on the body or within a vortex core triggers the ventilation. High-speed photographs taken in the wake region of surface-piercing bodies may reveal other phenomena which must be reconciled with any proposed theory.

The vortices in Fig. D7, if they are indeed vortices, are being shed at a frequency which compares very well with those computed by Roshko* for a bluff body.

B. Perry (California Institute of Technology)

In answer to Mr. Burt's question, some unreported experiments performed a few years ago in the Free Surface Tunnel at the California Institute of Technology may be of interest. In connection with experiments on air-inflated cavity flow on cylindrical bodies with flat noses, we tried to induce a full cavity flow by introducing air through a probe at various points. We found that air introduced several diameters aft of the nose, as at A in Fig. D8, was swept away as bubbles, while the introduction of air at B opened an air cavity attached to the rear of the body as shown. Only by putting the air supply probe forward to a location such as C, i.e., into a zone of viscous separation, could a full cavity be formed. Once established, however, the cavity could then be supplied with air with the probe placed anywhere inside it. As I recall it, the flow velocity was of the order of 15 fps and the body diameter was about 2 inches. These tests seem to be in complete agreement with the ideas put forward here by Mr. Wadlin, and earlier by Hoerner.

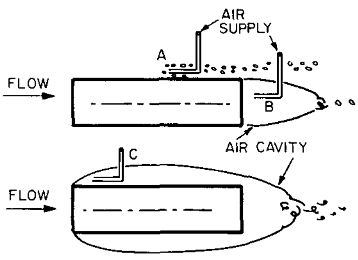

Fig. D8 - Introduction of air at various points near a body in a flow stream

With the mechanism of ventilation now understood, at least in a general way, it may be pertinent to consider an inherent difficulty which faces the designer of high speed craft. If any zone of potential ventilation is available, some inadvertent disturbance to the flow may cause a cavity to open up which will then, so to speak, provide its own passage for air supply. Since this may cause a catastrophic change in flow pattern, one is led to the conclusion that in many instances the only safe design procedure will be to assume that ventilation will occur.

M. C. Eames (Naval Research Establishment, Halifax)

The essential connection between ventilation and a separated boundary layer, or wake, has been suspected for some time. It is perhaps unfortunate that a newcomer to the subject might obtain the impression that this was being claimed as an original idea. Actually, in Ref. 9 of Wadlin's paper, for example, Hoerner refers to "an accumulation of boundary-layer material and a negative pressure within the separated region" as prerequisite for ventilation.

To my mind the extreme value of the more recent work lies in the experimental approaches which have been developed to demonstrate this relation. The use of an oil film is a particularly nice technique, and the results are most gratifying.

There is one point to which I should like to add emphasis. Experience in the full-scale operation of hydrofoil craft suggests that significant retardation of ventilation

*A. Roshko, "On the Drag and Shedding Frequency of Two-Dimensional Bluff Bodies," NACA TN 3169, July 1954.

by the influence of the constant-pressure water surface can only be obtained under laboratory conditions. In open water even the smallest ripples appear to be sufficient to initiate ventilation at the water surface. This of course is an advantage to full-scale operation since ventilation proceeds smoothly as speed is increased. The explosive type of phenomenon which results when large negative pressures are supported in calm water and subsequently tripped by a small disturbance could represent a very dangerous situation for a hydrofoil craft.

The fact that only a small disturbance is necessary would appear to add circumstantial evidence to Mr. Wadlin's ingenious explanation of the mechanism behind surface ventilation. The high velocity gradients in the vertical direction provide a highly unstable situation requiring little deviation of the surface to initiate powerful eddying and thus give rise to the requisite low energy paths.

Finally, I would like to ask Mr. Wadlin whether he has carried out any experiments using anti-ventilation "fences." In an "ad hoc" search for the smallest effective fence we have found that on a particular section designed for uniform pressure distribution it is only necessary to extend the fence over the leading 50 percent of the chord. (Maximum thickness occurs at 50 percent chord.) I would have expected most of the low energy paths to exist behind this, and therefore the success of the half-fences surprises me. Perhaps Mr. Wadlin could clarify my thinking on this point.

* * * * *