VENTILATION OF BODIES PIERCING A FREE SURFACE

J. M. Wetzel
St. Anthony Falls Hydraulic Laboratory
Minneapolis, Minnesota

* * * * *

Experimental studies were conducted at the St. Anthony Falls Hydraulic Laboratory to investigate the scale-effect problem associated with the ventilation of vertical, semisubmerged cylindrical rods and streamlined lifting surfaces. Two types of ventilation--creeping or partial and a flash or delayed vent formation--have been observed for these shapes. Data for the large-diameter rods can be correlated with the Froude number and submergence ratio, whereas uncoated rods of small diameter require consideration of several parameters. The use of Teflon-coated rods improved the Froude number correlation for the rods of small diameter.

Ventilation of vertical, lifting struts is primarily a function of velocity, yaw angle, submergence, and strut shape. Ventilation data of several strut shapes at high yaw angles can be correlated with the Froude number based on chord.

* * * * *

INTRODUCTION

As a surface-piercing body moves through a liquid, at a certain velocity an air pocket will form that will expose part or all of the rear portion of the body to the atmosphere. The formation of this pocket of atmospheric air will be called ventilation, although in some references it is also referred to as air leakage. Knowledge of the inception and mechanism of ventilation is of considerable importance as ventilation creates a distinct change in the hydrodynamic characteristics of the body.

To investigate the ventilation phenomena, it was considered desirable to conduct experimental studies on models and extrapolate the model data to prototype conditions by means of suitable modeling parameters. During the course of model tests on inclined, streamlined bodies piercing a free surface, it was found that a scale effect existed; i.e., the extrapolated data from the model did not agree with the data from the prototype. As scale effect is a serious design problem, an additional series of tests was initiated to study the ventilation of elementary body shapes, such as circular cylinders in a vertical position. In these tests with circular cylinders, the effect of gravity, surface tension, and viscous forces on ventilation was investigated.

The studies were later extended to include vertical, yawed struts of streamlined shape. This paper summarizes the results of this series of tests, which were part of a fundamental research program conducted at the St. Anthony Falls Hydraulic Laboratory under the sponsorship of the Office of Naval Research.

GENERAL CONSIDERATIONS

A relatively large amount of data has been published on the flow about semisubmerged cylinders of finite length. Hay (1) has done considerable work in this field, although his primary interest was the resistance of cylinders rather than the mechanics of ventilation or the scale effect associated with ventilation. However, some of the data presented can be extrapolated to a useful form for comparison purposes. Several papers are also available from NASA (2) and the California Institute of Technology (3,4) regarding ventilation of streamlined shapes in the presence of a free surface; the latter papers describe preliminary tests on struts.

In general, two distinct types of ventilation on a vertical, semisubmerged body can be observed: (a) a "creeping" or partial ventilation where the air pocket gradually increases in depth with increasing velocity, and (b) a "flash" ventilation or "delayed vent formation" where the air pocket forms very suddenly at a certain velocity, with little or no previous depression being observed behind the body. The size, submergence, and orientation of the body will generally determine which type of ventilation will normally occur.

In the case of the vertical, yawed strut, ventilation can usually be obtained for a given angle by increasing the velocity of the strut. For high yaw angles, as the velocity is increased to a certain value (which is dependent on foil shape and submergence) a pocket opens on the suction side but does not extend completely to the bottom of the strut. A relatively large amount of aerated water is present in the lower portion of the pocket. As the velocity is further increased, the pocket will eventually extend to the bottom of the strut and full ventilation is attained.

For the low yaw angles, air enters the suction side of the strut suddenly, creating a very marked change in the lift force. The water separates completely from the strut near the leading edge and forms a rather well-defined spray sheet. If the velocity of the strut is reduced slowly, the sheet will not reattach itself until a relatively low velocity is obtained, indicating a considerable hysteresis effect. The yaw angle that separates the partial and delayed ventilation is primarily dependent on strut shape but may change slightly with submergence. By consideration of well-known modeling parameters, it is possible to correlate ventilation data for various body sizes and submergences, although best results are obtained for the creeping ventilation.

EXPERIMENTAL FACILITIES

The studies were conducted in a circular steel tank of 10-foot diameter and 2-foot depth. The tank was equipped with a rotating-arm mechanism as shown in Fig. 1. The rotating arm was driven by a 5-hp hydraulic motor through a Vickers transmission, with fluid at high pressure being provided by a hydraulic test stand. Such an arrangement provides a wide range of velocities up to a velocity of about 20 fps with an arm length of 3.5 feet. The maximum velocity is restricted because of excessive turbulence and waves created by the moving body. The velocity was determined by a calibrated flowmeter on the hydraulic test stand and also by a tachometer generator driven by a gear fastened to the drive shaft of the arm mechanism. The rotating arm

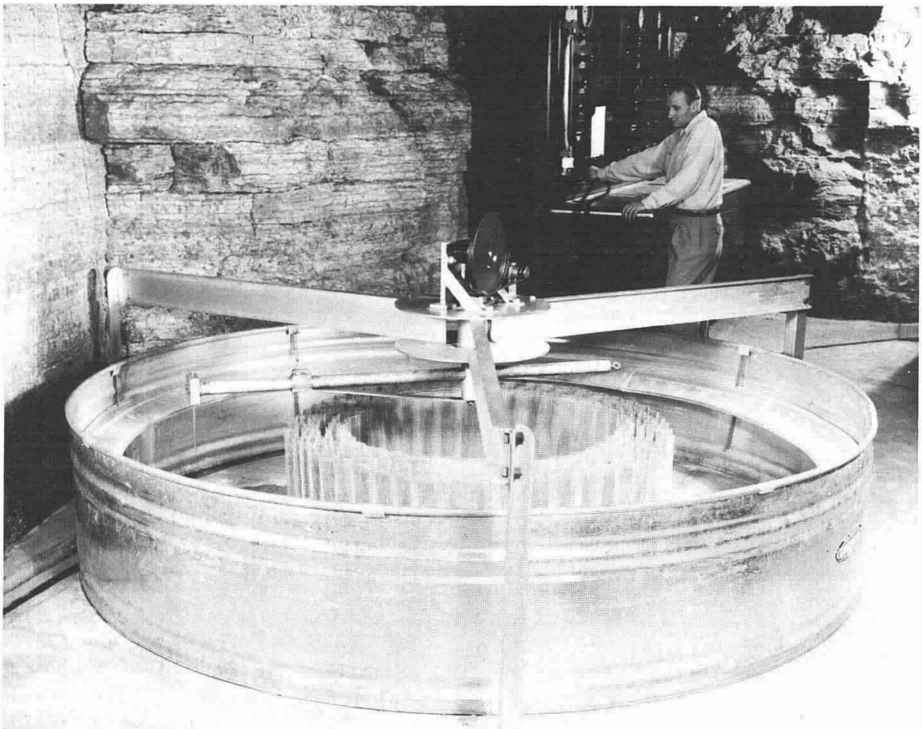


Fig. 1 - Photograph of rotating-arm tank

can be adjusted to various lengths, and the outer end is constructed to receive a variety of test-body shapes.

Table 1

Rod Diameters (in.)
and Materials Used

Steel	Brass	Lucite	Teflon
0.031	0.124	1.500	0.052
0.050	0.187	2.000	0.064
0.062	0.250		0.127
0.078	0.500		0.254
0.095	1.000		0.503
			0.753

The streamlined struts used in the ventilation studies were of NACA 0012 and NACA 0024 profiles. Two- and 3-inch chord struts were available for the NACA 0012 section, and a 2-inch chord for the NACA 0024 section. The foils were made of aluminum with a special milling cutter, hand finished and polished. An NACA 0012 strut of 2-inch chord sprayed with Teflon was also used for the tests. The strut was fastened to a mounting bracket attached to the end of the arm. The bracket was constructed to permit adjustment of the yaw angle (to within 1/2 degree) and submergence.

EXPERIMENTAL PROCEDURE

Data were taken by visual observation of the complete ventilation to the bottom of the body, and the velocities for this condition were noted. Repeat tests have indicated that this point could be observed accurately and data could be reproduced satisfactorily. Cylindrical rods with nominal diameters of less than 1/4 inch were braced to reduce lateral vibrations. Most of the rods were tested in tap water and also in water with altered surface tension and viscosity. The surface tension was reduced by addition of commercial detergents, such as Alconox or A11. By varying the concentration of detergent, the surface tension could be reduced from about 72 to 35 dynes/cm (0.00495 to 0.0024 lb/ft). The solutions were carefully mixed, and surface tension measurements were made several times during the test by the ring method, using a Du Noüy tensiometer. The viscosity was changed by heating the water with heating coils placed on the bottom of the tank. With this method, the kinematic viscosity could be reduced by a factor of nearly one-third.

With the struts, a submergence and a yaw angle were set for a particular shape and the velocity increased in small increments until complete ventilation was attained. The occurrence of complete ventilation was determined visually with little difficulty. Attempts were made to obtain the data for smooth-water conditions in the tank; therefore, in most cases boom rotations were confined to one or two. A brief series of spot checks was made with the towing carriage to verify the data taken in the rotating-arm facility.

DISCUSSION OF RESULTS—CIRCULAR CYLINDERS

Effect of Froude Number

The velocities for complete ventilation were used to compute the Froude number based on either the rod submergence, H, or the rod diameter, D. Data showing the relationship of the Froude number and a dimensionless submergence ratio, H/D, for the uncoated rods are plotted in Figs. 2 and 3. The vertical broken line is taken from results by Hay (1). His results indicate that the ventilation velocity for certain rod submergences and diameters can be computed with sufficient accuracy by $V/\sqrt{gH} = 1.7$. The St. Anthony Falls data, particularly for the larger rods at all but the smallest submergences, appear to verify Hay's data. Data for the smaller diameter rods do not agree so well except at the large submergence ratios; a definite scale effect exists for the lower submergence ratios when plotted in this manner. The Froude number of approximately 1.7 must be approached from the decreasing side before complete ventilation of either basic type would occur for most of the rods tested.

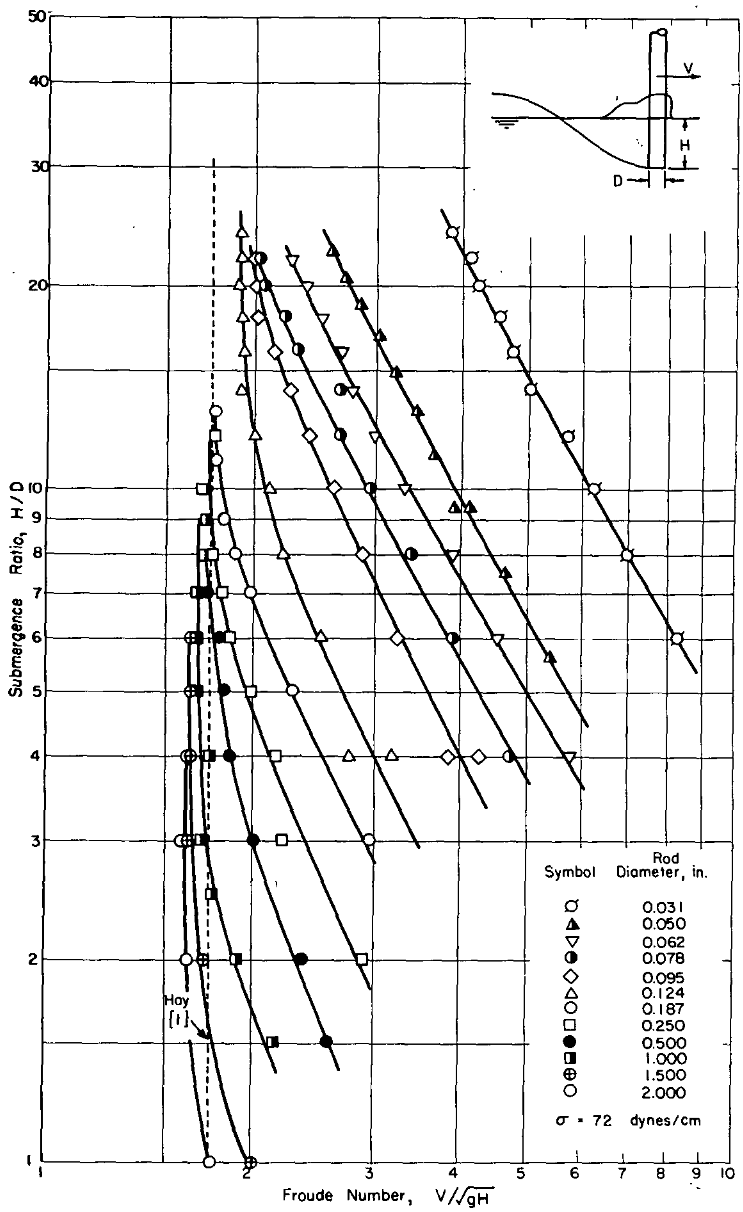


Fig. 2 - Rod ventilation as function of Froude number based on submergence

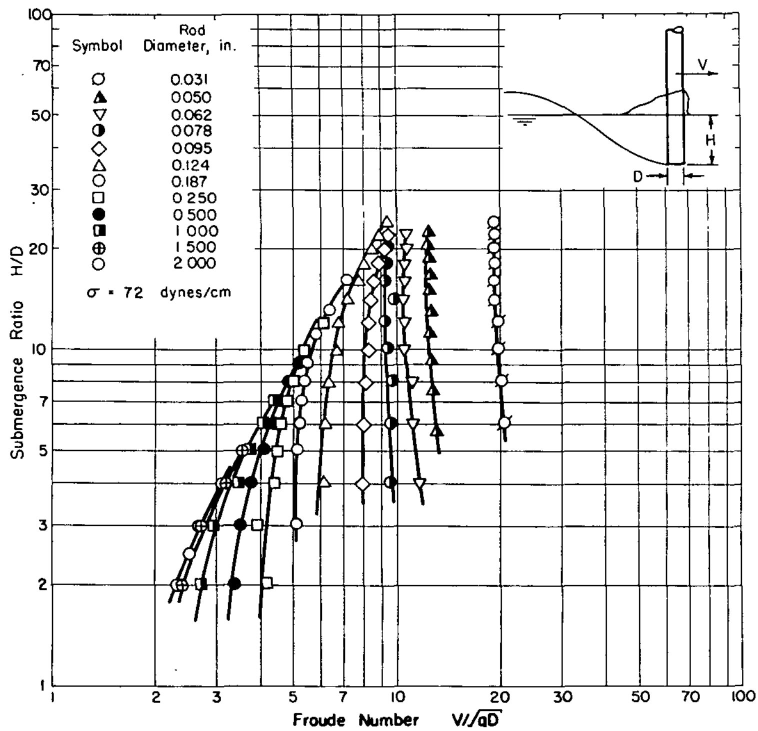


Fig. 3 - Rod ventilation as function of Froude number based on diameter

Figure 3 illustrates the same data plotted as a function of the Froude number based on diameter. For the smaller rods, the ventilation Froude number is nearly independent of the submergence ratio, i.e., for a rod of given diameter, the velocity for complete ventilation remains essentially constant. As the rod diameter increases the same trend is true, but over a smaller range of submergences (low submergences). During the tests it was observed that the ventilation of the small-diameter, uncoated rods occurred in general as flash ventilation, with an increasing tendency for creeping ventilation as the diameter and submergence increased. For the large rods, no flash ventilation was observed. Relating this observation to the data of Fig. 3, it is apparent that the velocity for creeping ventilation is dependent upon the submergence ratio, whereas the velocity for flash ventilation is relatively independent of the submergence ratio.

Effect of Weber-Number Correction

As the data for all rod diameters and submergences were not successfully correlated with the Froude number, it was decided to determine the significance of surface tension. The effect of surface tension on ventilation was investigated by adjusting the surface tension of the water to maintain a constant ratio of the Froude number to the Weber number for a particular group of rod diameters ($D_r^2 = \omega_r$, where D_r = diameter ratio and ω_r = kinematic capillarity ratio). Rods with nominal diameters of less than 1/4 inch were used more extensively in these tests, as the small-diameter rods exhibited a relatively large-scale effect. The results of this study are shown in Figs. 4 and 5. As shown in Fig. 4 for the smaller rods, a reduction of surface tension decreases the ventilation velocity to some extent, but the reduction is not sufficient for satisfactory data correlation. For example, consider the data for the 0.095-inch rod in Fig. 4. Two sets of data are shown for this diameter; one set (solid symbol) represents data for a lowered surface tension, the other (open symbol) represents data taken with tap water. The latter set of data is included to compare directly the effect of lowering the surface tension on the ventilation velocity for a rod of given diameter. To satisfy the assumption that surface-tension forces are significant (constant Froude/Weber number ratio), the data for the 0.095-inch rod and $\sigma = 42$ dynes/cm (closed symbol) should agree favorably with the data for the 0.125-inch rod in tap water with $\sigma = 72$ dynes/cm. It is evident that this assumption is not completely correct, as the data do not form a common curve. The reduced surface tension did not lower the ventilation velocity of the 0.095-inch rod sufficiently to make the Froude numbers equal. Figure 5 contains data for larger diameter rods. It is evident that surface tension has less effect on the ventilation velocity, particularly for the larger submergences. This is in agreement with the Froude number correlation previously found for the larger diameter rods.

Effect of Reynolds-Number Correction

To scale the inertia, viscous, and gravity forces simultaneously, it was necessary to maintain a constant ratio of the Froude and Reynolds number ($D_r = \nu_r^{2/3}$, where ν_r = kinematic viscosity ratio). This was accomplished by adjusting the viscosity of the water in the tank as described previously. Again the smaller diameter rods were used, as ventilation of the larger rods was correlated with the Froude number alone for most submergences. Figure 6 illustrates the typical effect of the

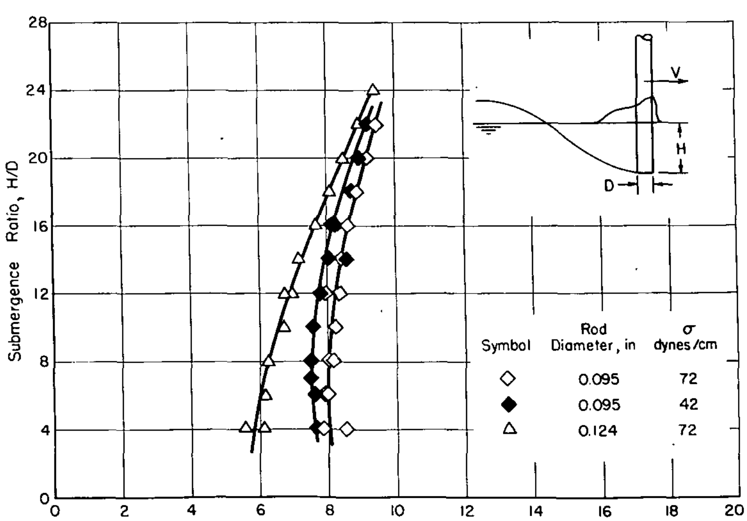


Fig. 4 - Effect of constant Froude/Weber ratio on rod ventilation (0.095-inch and 0.124-inch rods)

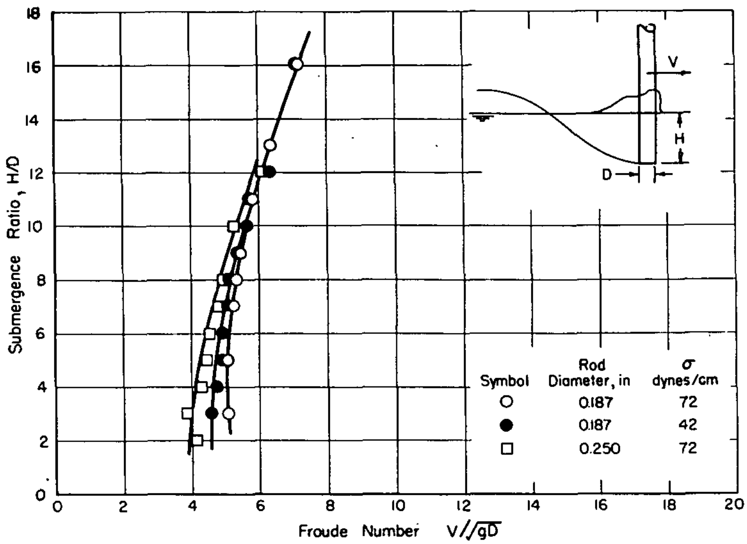


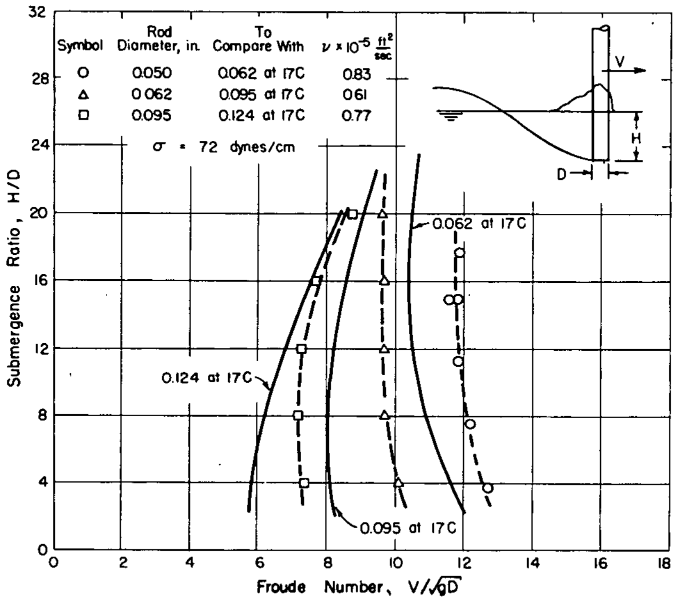
Fig. 5 - Effect of constant Froude/Weber ratio on rod ventilation (0.187-inch and 0.25-inch rods)

viscosity correction. For most rods two sets of data taken in water with different viscosities are shown for a particular diameter. The solid line is faired through data taken in unheated water at 17°C. The broken line is faired through data taken in water heated to maintain a constant Froude/Reynolds ratio. As an example, consider the 0.062-inch rod. The data for this rod with a lowered viscosity (open triangles) should agree favorably with the 0.095-inch rod in unheated water, as the ratio of the Froude to the Reynolds number has been kept essentially constant. It is evident that the ventilation velocity has been reduced, as shown by the broken and solid faired lines for the 0.062-inch rod, but not sufficiently to permit satisfactory Froude-number correlation with a larger diameter rod as determined from the original assumption.

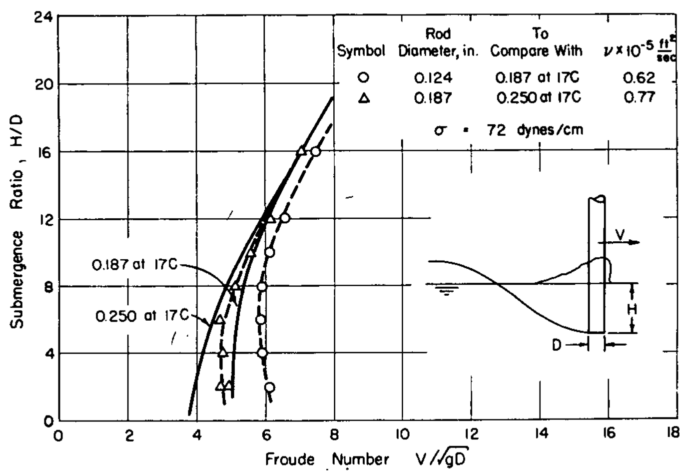
Teflon Rods

In an attempt to reduce further the existing discrepancy between data for rods of different sizes, several of the rods were coated with Teflon. Plots of faired curves of the data for the submergence ratio H/D against the Froude numbers are shown in Fig. 7. The data for rod diameters above 0.254-inch fall on essentially the same line for most submergence ratios, indicating that the Froude numbers can be considered the proper modeling parameter for these particular submergence ratios and diameters. From comparison of Fig. 7 with Fig. 2 or Fig. 3, it is evident that the use of Teflon greatly improved the Froude-number correlation.

One of the most significant ventilation characteristics of the Teflon rod was that delayed vent formation was practically nil, whereas with the uncoated rods of small diameter it was the predominating type of ventilation. It would be expected that the effect of the Teflon would become less apparent for the large rod diameters, as above 0.254 inches. This also can be noted from a comparison of the previous graphs.

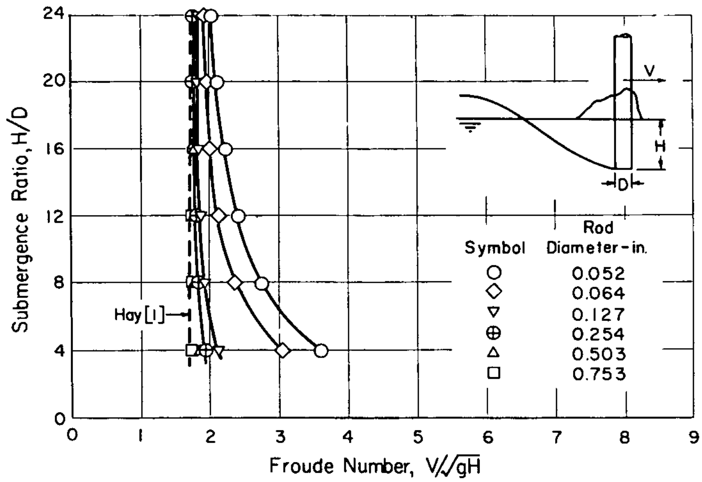


(a)

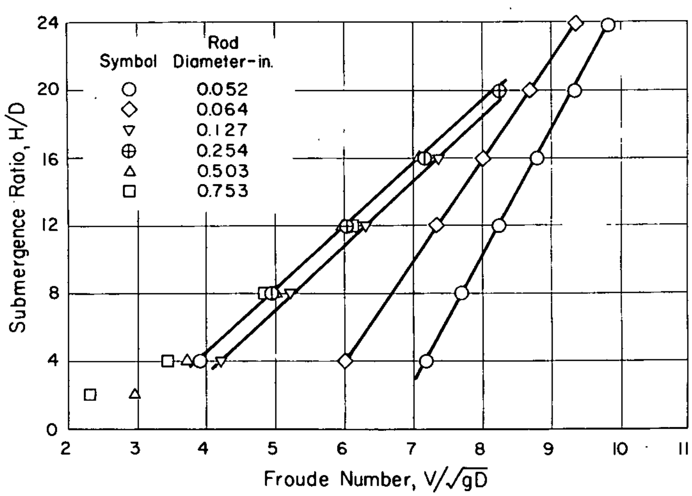


(b)

Fig. 6 - Effect of constant Froude/Reynolds ratio on rod ventilation



(a)



(b)

Fig. 7 - Ventilation of Teflon rods as a function of the Froude number and submergence ratio

In observing the ventilation of the cylindrical rods, it was noted that a considerable hysteresis effect existed for the uncoated rods of small diameter, as is typical of flash ventilation. The Teflon rods exhibited no hysteresis, as the ventilation appeared and disappeared at essentially the same velocity. It also was found that the velocity at which the vent closes was independent of the rod material.

DISCUSSION OF RESULTS— YAWED STRUTS

The basic data that have been obtained include the velocity for complete ventilation for a particular submergence, and yaw angle. Typical data are shown in Figs. 8 and 9 for various submergence ratios. In the course of the ventilation studies it was noted that a wide range of scatter was present for ventilation of the struts at all but the very high yaw angles. This scatter was believed to be caused by the condition of the water surface or turbulence in the rotating-arm facility. It appeared that if the foil struck any surface disturbance, provided the foil was moving at a sufficient velocity, it would immediately ventilate, even though ventilation would not occur for smooth-water conditions. It was also found that a minimum velocity could be obtained for which the strut would not ventilate under any conditions. The difference in magnitude of this minimum velocity and the velocity required for ventilation in smooth water was very considerable, the difference increasing with decreasing yaw angle. This can be readily seen from Figs. 8 and 9.

The rough-water curve represents the minimum ventilation velocities that could be obtained by forcing the ventilation to occur. The ventilation was forced by creating a disturbance through which the strut passed. It also was possible in many cases to start ventilation by creating a disturbance in the wake of the strut, thereby permitting air to enter this region and move forward to the foil. With these artificial disturbances it was possible to obtain ventilation at relatively low yaw angles, as compared to smooth water. In a sense, the difference between the rough- and smooth-water curves represents the hysteresis effect for the struts, as the forced-ventilation data are essentially the points where complete ventilation disappears.

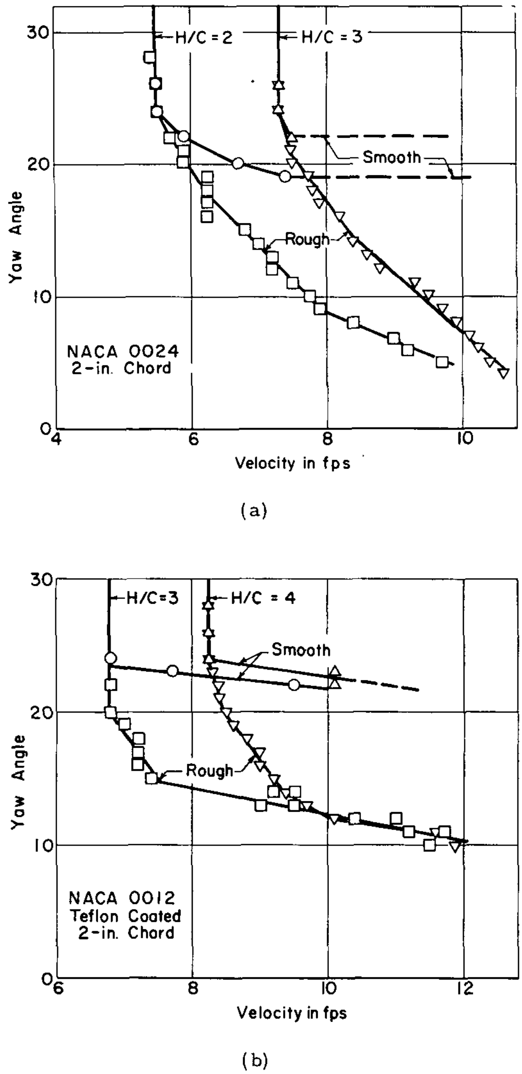
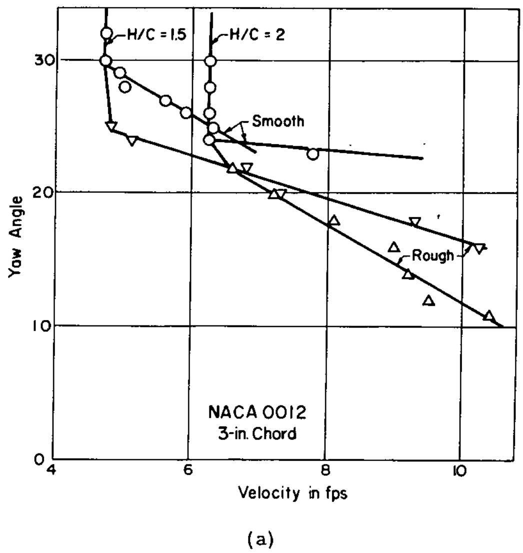


Fig. 8 - Effect of water-surface conditions on ventilation velocity (2-inch chord)

The effect of surface tension has also been briefly investigated in the rotating-arm tank. The surface tension was lowered and repeat runs were made with the



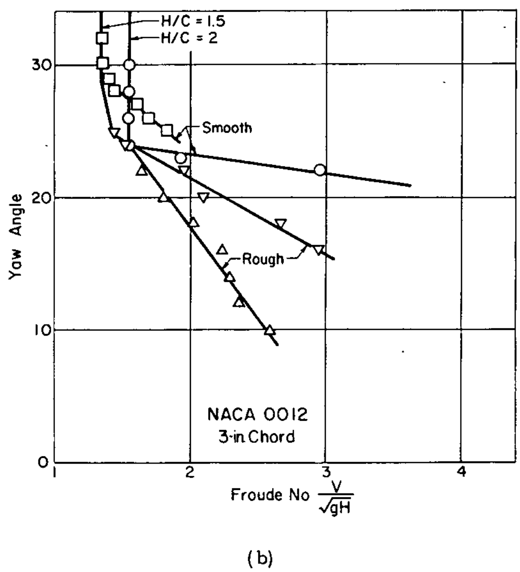
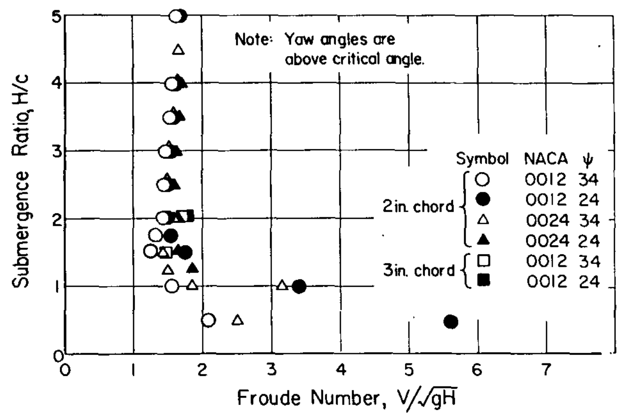


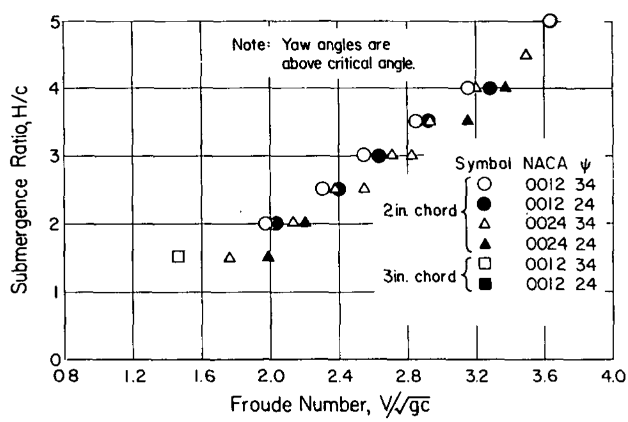
Fig. 9 - Effect of water-surface conditions on ventilation velocity (3-inch chord)

same strut geometry. In general, it appears that the ventilation velocity was reduced slightly for the sizes of struts used in the tests. However, this was rather difficult to ascertain carefully as the conditions of the water through which the strut passes have also been shown to have a very marked effect on the ventilation velocity. The reduction of surface tension did create a different pattern in the spray formation about the strut but apparently did not greatly influence the factors that are responsible for the triggering of ventilation. Surface tension may effect ventilation of surface-piercing bodies in several ways. It may permit air to leak into the low-pressure side of the strut more easily, or it may permit air to enter the wake area more easily through the trailing vortexes. In both cases, it would be expected that lowering the surface tension would reduce the velocity for complete ventilation. More tests appear necessary to separate completely the effects of surface tension and rough-water or turbulent conditions on the aeration of the flow in the region of the strut.

Preliminary analysis has been directed toward correlating data for the sections utilized. Attempts at correlating data over the entire range of yaw angles have not been successful, but better results have been obtained by dividing the ventilation into two types which are determined by the yaw angle for a given strut geometry. As seen in Figs. 8 and 9 for a particular submergence ratio, the ventilation velocity is essentially constant for the high angles of yaw. As the angle is decreased, a position is found where the velocity becomes very sensitive to small angle changes. The sharp break in the curve occurs over a relatively small range of yaw angles. For yaw angles below the break in the curve, ventilation was very difficult to obtain in relatively smooth water at the velocities available in the rotating-arm facility. The high-angle ventilation (angles above the break) is essentially independent of yaw angle and can be correlated by the Froude number based either on submergence



(a)



(b)

Fig. 10 - Correlation of high-angle strut ventilation data

or on chord and the submergence ratio (depth in chords). This correlation is shown in Fig. 10 for the NACA 0012 and NACA 0024 sections and for two chord sizes. Also note that the data for three foils tend to group together for the higher submergence ratios at a submergence Froude number of about 1.6. Foil thickness or shape apparently has little effect for this range of yaw angles. Struts of a rectangular cross section have been used in preliminary tests and have exhibited essentially the same properties.

Some work of a preliminary nature has been done regarding the relationship of the stall angle to high- and low-angle ventilation. A brief series of tests was conducted to measure the lift force with a dynamometer and thereby determine the wetted-flow stall angle for the particular sections. In general, it was found that the angle that separated the two regions of ventilation was approximately the stall angle for the strut. Therefore, in the case of smooth water, it was difficult to obtain ventilation below the stall angle at the available velocities. However, if the flow pattern was disturbed by some external conditions, ventilation was achieved.

CONCLUSIONS

Based on the tests described in the preceding sections, it is possible to derive the following conclusions:

1. Two distinct types of ventilation occurred—creeping and flash ventilation. The predominating type was determined by body size, submergence, and, for struts, angle of yaw.

2. Creeping ventilation predominated for large-diameter, uncoated rods and also for Teflon-coated rods. Flash ventilation predominated for the small, uncoated rods at all but very large submergences.

3. Creeping-ventilation data could be correlated with the Froude number and submergence ratio. In general, flash-ventilation correlation necessitated consideration of other parameters.

4. Little hysteresis effect existed for creeping ventilation. A very pronounced effect was found for flash ventilation as the formation of the air pocket was considerably delayed.

5. The two distinct types of ventilation that occurred for vertical, lifting struts were dependent on the angle of yaw. Above a certain yaw angle, ventilation was primarily a function of submergence and body shape, and the ventilation velocity was essentially independent of the yaw angle. Below this angle, the ventilation velocity became increasingly dependent on yaw angle, and less dependent on submergence. High-angle ventilation data were successfully correlated with the Froude number and submergence ratio.

REFERENCES

1. Hay, A.D., "Flow About Semi-Submerged Cylinders of Finite Length," Princeton University, October 1947

2. Ramsen, J.H., "An Experimental Hydrodynamic Investigation of the Inception of Vortex Ventilation," National Advisory Committee for Aeronautics Technical Note 3903, April 1957

3. Kiceniuk, T., "A Preliminary Experimental Study of Vertical Hydrofoils of Low Aspect Ratio Piercing a Water Surface," California Institute of Technology, Hydrodynamics Laboratory Report E-55.2, December 1954

4. Perry, B., "Experiments on Struts Piercing the Water Surface," California Institute of Technology, Hydrodynamics Laboratory Report E-55.1, December 1954

* * * * *

DISCUSSION

J. P. Breslin (Stevens Institute of Technology)

This experimental investigation should be of paramount importance to all concerned with small model studies of ventilation and cavitation phenomena. Mr. Wetzel's results reveal the major effect of surface tension forces on the character and degree of ventilation of rods up to a diameter of 3/4 inch. The use of Teflon apparently prevents the development of highly curved junctures between the body and the cavity. Consequently, the relatively large surface-tension forces are avoided. Mr. Wetzel's Figs. 2 and 7(a) should be presented side-by-side and to the same scale to do justice to the remarkable difference in behavior which the use of Teflon provides.

The discovery of this large effect opens the question of the influence of surface tension on the equilibrium location of vapor cavities on curved sections and bodies. It may be that the extent of cavitation will be found to be remarkably affected since the radii of curvature at the forward cavity body juncture should be very small. Perhaps there are researchers who have done such experiments. In any event the effect of a non-wetting material will be investigated in a study of ventilation of small scale dihedral foils at the Experimental Towing Tank.

In regard to the remaining scale effects exhibited in Fig. 7(a), possibly the curvatures at the bottom of the ventilated pocket are small enough for the smallest rods to provide sufficiently large surface fractions to inhibit full cavity development. In addition, the effect of viscosity at low Reynolds numbers may also be expected to prevent scaling of the velocity distribution about the fore part of the smallest cylinders.

T. Kiceniuk (California Institute of Technology)

There were no photographs of the two regimes of operation. I was wondering if the two could be distinguished visually once ventilation was established, or whether they remained different.

Although the effect on the surface tension of the added detergent was reported, no mention was made of the contact angle between the water and the model before and after the detergent was added. Also were the surface-tension values or contact angle affected by change in water temperature which was being used to secure Reynolds Number variation?

In past studies at the C.I.T. Hydrodynamics Laboratory we tried waxing the surface of planing cylinders to determine what effect this would have on the spray-sheet formation and on the forces acting on the model. Surprisingly, the spray sheet still clung to the cylinder and trailed aft, and no significant change in the force picture could be detected.

P. Eisenberg (Office of Naval Research)

It may be of interest to reveal how Mr. Wetzel was led to examine the effects of a material such as Teflon on the surface-tension influences found to be of importance in the ventilation process. Some years ago, I was told of the discovery of a material or coating that was purported to allow slip at a fluid boundary and, therefore, to lower the frictional resistance below expected values for a hydraulically smooth surface. The evidence cited was the remarkable acceleration of a hydroplane racing boat on which the planing surfaces had been coated with this material.

Doubting the slip hypothesis, I naturally looked for a more rational explanation of such exceptional performance. It occurred to me that, if the step in the planing surface could be ventilated at a lower speed than would normally happen, it would be possible to achieve the full-planing condition much earlier, and, therefore, to accelerate more rapidly since the hump resistance would thus have been lowered.

It was found subsequently that Teflon did indeed exhibit small, interfacial tension relative to water at the air-water interface. I believe it was Mr. Tulin, then in ONR's Mechanics Branch, who suggested that we could both test my hypothesis of the effect of a material such as the one mentioned above and, at the same time, show perhaps that the surface tension effects could be eliminated in this way, thus making it possible to test at small Froude numbers models for which ventilation phenomena are important on the prototype. We therefore arranged for Mr. Wetzel to carry out the tests described in his paper, with the results fully confirming the postulated behavior and so ably reported. We selected Teflon only because we were already acquainted with its properties in some detail.

K. L. Wadlin (National Advisory Committee for Aeronautics)

Mr. Wetzel has carried out a comprehensive study of the principal parameters influencing the inception of ventilation. The answers to many of our questions about the mechanics of the inception process are undoubtedly available in the data obtained by him. It is interesting to note that flash ventilation and hysteresis only occurred when the Reynolds number was low. Also the effects of viscosity, surface tension, and Teflon were noticeable only at low Reynolds numbers. That is, only these influenced ventilation inception when conditions were such that the flow probably was close to the transition from fully attached flow around the cylinder to separated flow. These effects then probably influenced the separation point on the cylinder, particularly in the region of the water surface. This would lead to separated regions being available to provide paths for the air as soon as the pressure gradients were sufficient to draw the air down. This results in creeping ventilation instead of flash ventilation occurs when the pressure gradient is present before separation.

E. R. Tinney (State College of Washington)

The careful experimental work performed by Mr. Wetzel has clarified many points particularly with regard to some of the "scale effects" that can be expected in laboratory tests on ventilation. The writer suggests that a different manner of presenting the data on cylinders (particularly Fig. 2 of Mr. Wetzel's paper) would add to the understanding of the ventilation phenomenon.

At incipient ventilation it is a necessary, though undoubtedly not a sufficient, condition that the pressure be atmospheric in the ventilation region. That is,

$$\rho g H + C_p \frac{\rho V^2}{2} = 0 , \tag{D1}$$

from which

$$\frac{V}{\sqrt{gH}} = \sqrt{\frac{2}{-C_p}} . \tag{D2}$$

For the Reynolds numbers at which the author conducted his tests (R_e between 1.5 × 10^3 and 1.5 × 10^5, based on diameter), the value of c_p at a point on the cylinder 90 degrees from the line of the approaching flow is approximately -0.8 for long cylinders deeply submerged. Substituting this value into Eq. (D2) gives

$$\frac{V}{\sqrt{gH}} = 1.58. \tag{D3}$$

This value of 1.58 agrees well with the minimum value of 1.6-1.7 which the author finds as the asymptotic value for all cylinders deeply submerged.

The value of c_p is affected by the free surface to a degree that is probably dependent upon Reynolds number. It seems logical, therefore, to plot $V/\sqrt{gH}$ as a function of Reynolds number for constant values of H/D. This is done in Fig. D1 which shows that Eq. (D3) applies for all the cylinders tested, if the Reynolds number is greater than 5 × 10^4. This provides a lower limit for laboratory tests if "scale effect" due to viscosity is to be avoided. The limiting value of Reynolds number is seen to depend on the value of H/D.

At lower values of Reynolds number an empirical relation can be developed which indicates the relative significance of both Reynolds number and submergence. This relation is

$$\frac{V}{\sqrt{gH}} = 1.6 + \frac{1.8 \times 10^6}{\left(\frac{H}{D}\right)(R_e)^{3/2}}. \tag{D4}$$

This equation is plotted in Fig. D2 together with all the data given by the author on his Fig. 2. From Fig. D2 it appears that the influences of submergence and Reynolds number on ventilation are insignificant for values of the parameter $H/D\,(R_e)^{3/2}$ greater than 10^8.

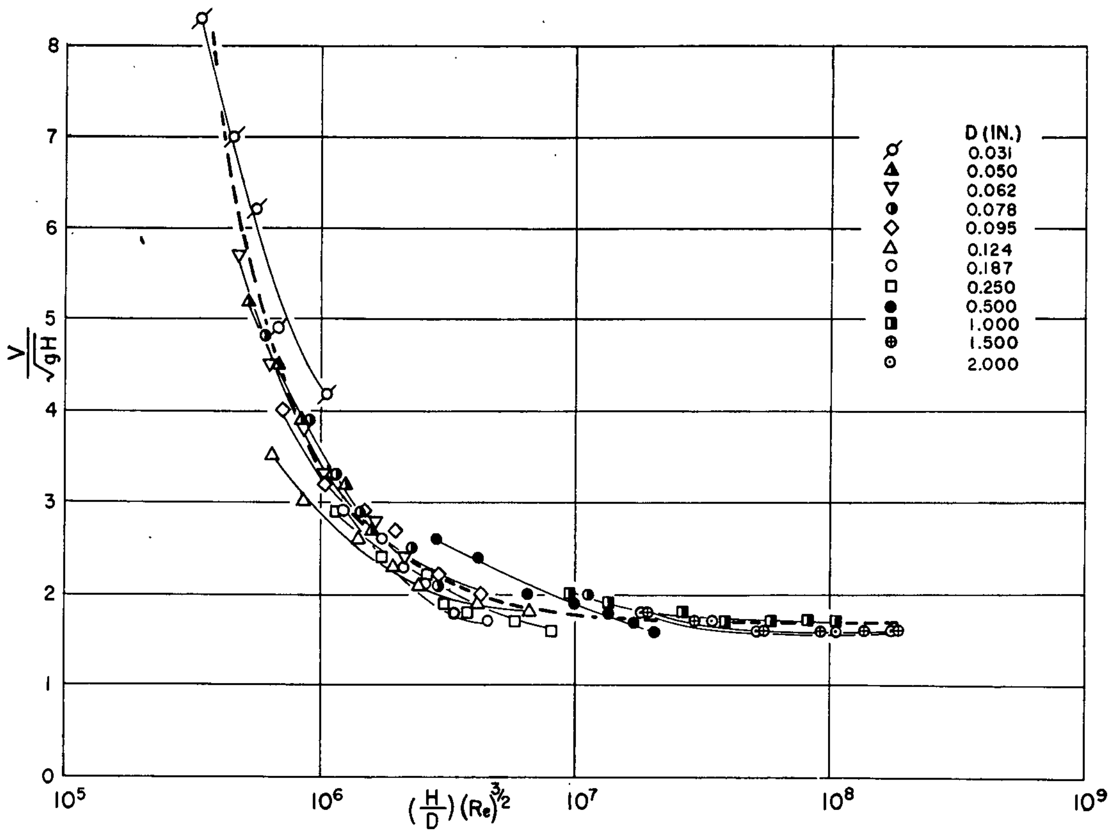


Fig. D1 - Plot of $V/\sqrt{gH}$ as a function of Reynolds number for constant H/D values

* * * * *

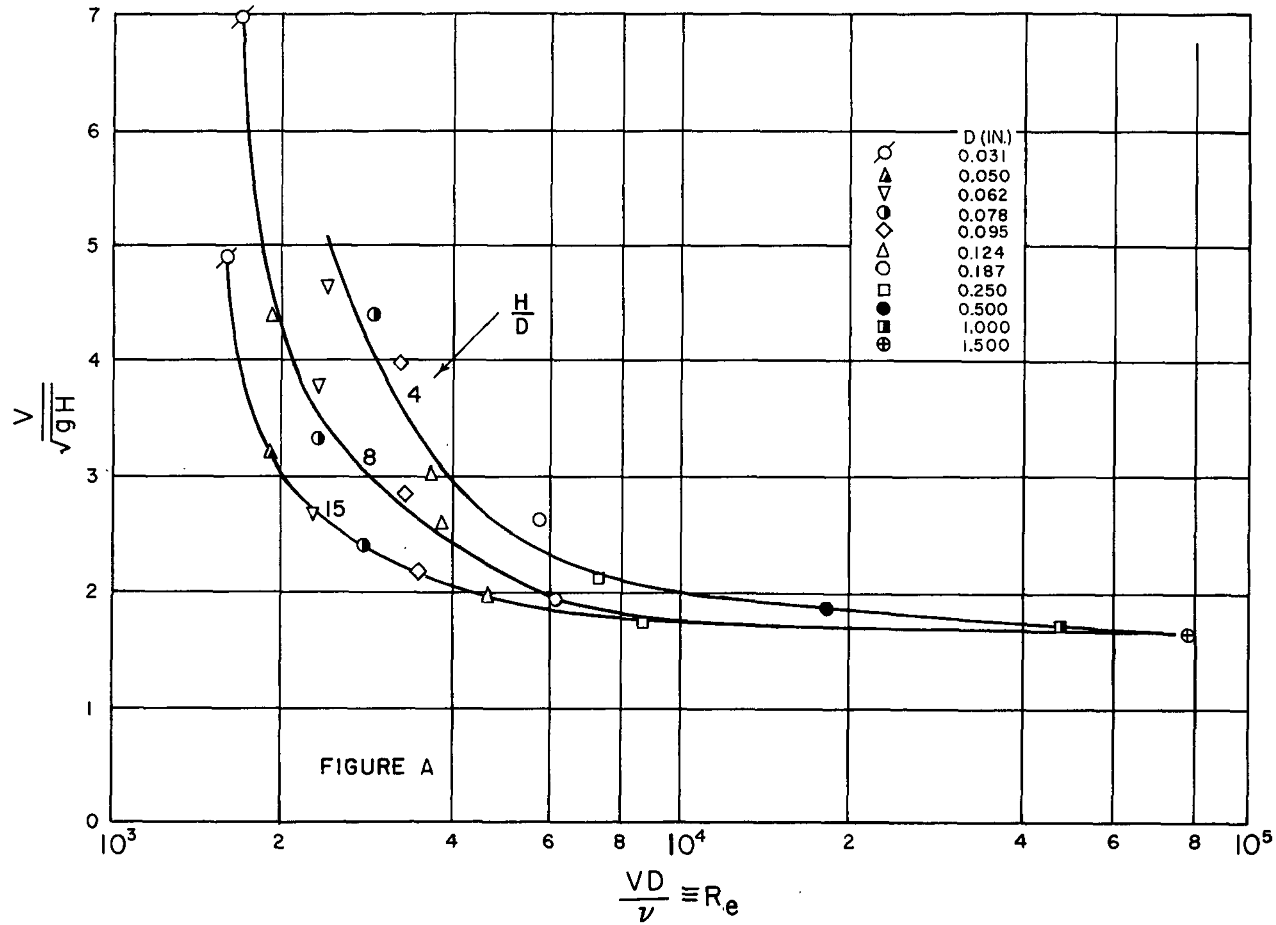


Fig. D2 - Influence of submergence and Reynolds number on ventilation