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Some experiments on cavities behind disks

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Measurements of cavities behind disks in a water tunnel show that at high enough speeds the cavity pressure is not more than 30–40 % higher than water-vapour pressure, even when at atmospheric pressure the tunnel water is nearly saturated with air. No other hard conclusions can be drawn from the investigations, which showed many puzzling features, discussed below. It is hoped, however, that the qualitative discussion may prove useful to theoreticians who may seek to improve existing mathematical models of cavitation by taking a more realistic account of the physics of the flow.

1. Introduction

The existing mathematical theories of cavitation are in some respects adequate for engineering purposes. They usually assume a constant pressure for some distance along the free streamlines separating from the body. The forces on the latter, and the shape of the cavity near the body, are insensitive to the mathematical conditions used for closing the cavity. Thus the principal disposable parameter is the cavity pressure, which is usually taken to be water-vapour pressure.

Whilst this assumption seems very reasonable for fluid containing no dissolved gases, it is by no means obviously justifiable if dissolved gas is present. Thus Silverleaf & Berry (1962) found that, for a propeller with extensive back-cavitation, the force coefficients were increased significantly as the air content was reduced below the value required to saturate the water at atmospheric pressure. They suggested that this might be due to variations in the cavity pressure with air content. Accordingly, it was decided to investigate the influence of air content in water on what was thought to be a relatively simple type of cavity, namely, that formed behind a circular disk normal to the stream. In reality, however, the flow, even in this case, is very complex, involving water being thrown forward inside the cavity from the rear (with consequent splashing and spray within part of the cavity), and entrainment of water and presumably air out of the cavity into the wake, which in itself has a complicated structure. Buoyancy forces clearly affect the cavity, whose geometry cannot therefore depend, as simple theories often assume, purely on the cavitation number based on cavity pressure, i.e.

$$\sigma_c = (p - p_c)/\tfrac{1}{2}\rho V^2,$$

where p is the free-stream pressure, p_c the cavity pressure, ρ the density, and V the free-stream speed. If air is deliberately blown into the cavity, the cavity pressure is affected, and the cavity must adjust itself so that the wake entrains air from the cavity at a rate which just balances the rate of feeding of air to the cavity. To be fully satisfactory, therefore, a theory of cavitation should take into account not only the pressure in the cavity near the cavitating body, but also buoyancy forces, and the processes which entrain air from the cavity, together with those which, when dissolved air is present in the water, diffuse air into the cavity. In the absence of any such unifying theory, or indeed of a proper understanding of the physical mechanisms underlying these processes of entrainment and diffusion, an account, such as the present, of physical observations on cavities must appear somewhat disjointed. Nevertheless the observations are thought to be worth putting on record in the hope that they may contribute to the ultimate development of a unifying theory.

2. Experimental arrangements

Measurements have been made of the pressures inside cavities formed behind disks normal to the stream in the no. 2 tunnel (Silverleaf 1960) of Ship Division, N.P.L. This tunnel has a working section of 44 in. diameter. Disks of 5, 3½ and 3 in. diameter have been used, the two former being supported as in figure 1 (plate 1) on the upstream end of the 2½ in. diameter shaft normally used for testing model propellers, whilst the 3 in. disk was held on three radial supports, as in figure 2,

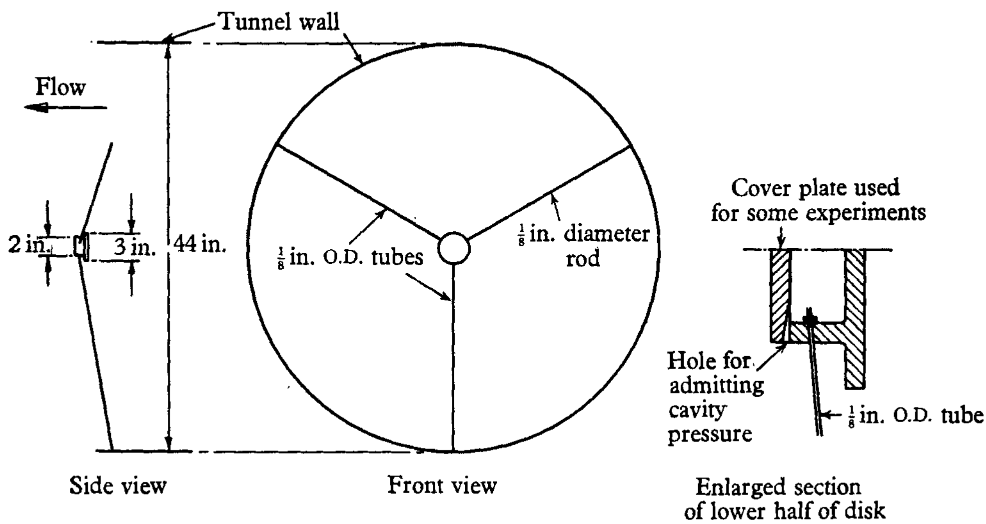

FIGURE 2. Radially supported 3 in. disk.

so that the downstream end of the cavity was unobstructed. For each disk, two tubes communicated with the cavity, their openings being just behind the disk. The pressure was measured through one tube, connected to a mercury U-tube manometer which could measure pressures in the range 0–6 in. of mercury absolute. The other tube could be used to blow air into the cavity, in investigations of the way in which cavity pressure and length vary with blowing rate. The air content of the water could be maintained at any value between about 3 and

26 parts per million (ppm) by weight,† as the tunnel incorporates a return limb buried deep under the ground, to re-dissolve some of the air bubbles that come out of solution in cavitation. The main object of the natural-cavity measurements, without blowing, was to see how water speed and air content affected the cavity pressure and size.

The reader is warned against attempting to correlate too closely the results, which will be presented below, with theoretical predictions or with other experimental results. This is because the pressures in the tunnel contraction were affected by the disks, so that the tunnel speed and pressure, V and p_T, which were derived from the contraction pressures, did not correspond exactly with the true undisturbed stream conditions. Thus such quantities as cavitation number have purely nominal values in the present work. Since, however, this paper is concerned mainly with trends of variation, such errors do not greatly matter.

3. Technique for measuring cavity pressures

When cavity pressures were being measured in natural, unventilated cavities, the tunnel was usually run up to a high speed, and the pressure-measurement tube was then cleared of water by blowing air through it. The tube was connected to the manometer and the reading taken. If the tunnel speed was then reduced, the manometer reading often remained approximately unaltered. If the manometer was then sealed off, a burst of air blown through the tube, and the manometer re-connected to it, with the tunnel speed and pressure remaining constant, a new higher manometer reading was often obtained. The reverse often happened if the manometer was sealed again, the pressure tube temporarily connected to a vacuum pump, and the manometer then re-connected. The new pressure was often the water-vapour pressure at room temperature. At first it was thought that these differences in manometer reading corresponded to real differences in cavity pressure, which might lie anywhere between an upper and a lower bound. However, it was observed that no corresponding changes in cavity length occurred, and it became evident that a more probable explanation was that, when changing from a high speed to a low speed, or attaching the vacuum pump to the pressure tube, a drop of water was drawn into the tube. This would be quite likely at the lower speeds when the cavity was largely frothy, with water being thrown forward from the tail of the cavity right up to the disk. A drop of water could, due to surface tension, remain blocking the tube despite a pressure difference across it, and the pressure on the manometer side of the drop could be as low as room-temperature vapour pressure. Thus the 'lower-bound' pressure would be quite spurious. Confirmation that this was so was obtained by fitting a cover plate as in figure 2 to the 3 in. disk, shielding the pressure-tube opening from the direct impingement of water drops. It was then found that 'lower-bound' pressures could not be obtained.

We conclude, therefore, that if cavity pressures are to be measured by conventional manometers it is best to clear the pressure line by a short burst of air

† All figures refer to total air content, none being available for the fraction of air that was truly dissolved. At the usual temperature (16 °C) of the tunnel water, the saturation air content at atmospheric pressure is about 25 ppm.

prior to each reading. The pressure measurements given in this paper were all obtained in this way.

At low tunnel speeds the cover plate on the 3 in. disk had some effect even on the 'upper-bound' pressures, tending to reduce them. This was probably because of water-drop impact on the uncovered pressure tube increasing the average pressure within the tube and manometer. Correspondingly at low speeds, with a largely frothy cavity, water impact on the back of the disk may cause its mean base pressure to be higher than the mean pressure along the free streamlines springing from the disk edge.

4. Unsteadiness in the cavities

The experimental results obtained in these investigations present many puzzling features. For example, with the 3½ in. disk, if the tunnel was set going at a high speed and a low pressure a long, largely clear and glassy cavity would at first be formed. However, the frothy region at the downstream end of the cavity would gradually extend forward, and the cavity pressure would rise above its original value, the tunnel speed and pressure remaining constant all the while. Then it would suddenly become impossible to hold the tunnel pressure at its original low value: a rise would occur, and with it a sudden shortening of the cavity and rise of cavity pressure. At this, the flow would become unsteady and noisy, due to cavitation collapse on the walls of the tunnel.

With this 3½ in. disk the cavities springing from the struts supporting the shaft (cf. figure 1) may have been as large in total cross-sectional area as the cavity from the disk itself. It may have been that air, coming out of solution in the cavitation, gradually accumulated in these secondary cavities, enlarging them at the expense of the main disk cavity. It was to minimize such effects that the experiments with the radially supported 3 in. disk were performed.

Even with this disk it is likely that under some conditions of tunnel running secondary cavities formed at other parts of the tunnel circuit. The tunnel pressure is reduced by extracting a small quantity of water from the tunnel. At any particular speed there is a minimum pressure at which the tunnel will run. If it is attempted to reduce the pressure further, either the speed falls, presumably due to cavitation on the impeller, or, despite the extraction of water, the pressure remains constant, presumably due to the creation of secondary cavities at low-pressure parts of the circuit. Thus there is evidence that the tunnel can never be completely filled with water as intended, but that instead it always contains a trapped bubble of air. Although this is probably less than a cubic foot in volume at atmospheric pressure, it will of course expand when the pressure is reduced. Further, when the wake from a cavitating body extends into the diffuser, downstream of the working section, little pressure recovery may occur in the diffuser, and cavitation may occur at the top of it. In such conditions a violent oscillation of the disk cavity sometimes occurred, with a period usually of about ½ sec. Thus figures 3 and 4 (plate 1), which extend over a length of 3 ft., show the maximum and minimum length phases of a cavity from the 3 in. disk,† the

† The disk itself is out of sight to the right of the pictures, as it is supported in the end of the tunnel contraction, some 3 ft. upstream of the windows.

tunnel speed and pressure being constant at 40 ft./sec and 162 lb./ft.^{2} absolute (giving a nominal cavitation number σ_v based on vapour pressure of 0·080), and the air content being 4·2 ppm. However, if the tunnel pressure was reduced more cautiously when starting the tunnel, a steady cavity could be obtained at the same speed and tunnel pressure. Sometimes it was in fact impossible to make the cavity oscillate. The length of the steady cavity was intermediate between the maximum and minimum lengths of the pulsating cavity.

5. Surface appearance of the cavities

A feature of the cavities from the 3 in. disk was their rough, frosted-glass appearance when photographed by a short duration 10–30 μsec flash, as in figures 3 and 4. The downstream end of the cavity was evidently full of bubbles and spray, but the more upstream part appeared not to be so. This was perhaps clearer to the naked eye, or when photographed by a longer duration flash, than it is from figures 3 and 4. Thus figure 5 (plate 2), which shows the same condition as figure 3 (apart from a slightly higher air content), but taken with a millisecond flash, shows that whilst the downstream end of the cavity is opaque, it is translucent further upstream. However, the cavity never attained the smooth glassy surface that the 5 in. disk cavity had at the higher speeds, as for example in figure 6, taken with a millisecond flash at 46 ft./sec, 590 lb./ft.^{2} tunnel pressure (i.e. nominal $\sigma_v = 0{\cdot}269$), and 3·2 ppm air content. It is not at all clear what causes the roughened surface of figures 3 and 4. It may be caused by a rain of fine spray from inside the cavity impinging on its walls. Alternatively, it may be due to the water flow over the cavity surface being turbulent, perhaps because of the radial supports of figure 2, though one might have expected such disturbances to be confined to narrow stripes along the cavity surface. (In figures 3 to 5 there are streaks which suggest that they might mark the wake of the uppermost starboard strut.) Unfortunately, the upstream end of the 3 in. disk cavity could not be viewed, so it was not possible to see if any part of the cavity surface was glassy clear. It is interesting to note that the cavitation from the shaft-support struts in figure 6 (plate 2) is rough and striated: this is due to very small particles adhering to the leading edges of the struts, so evidently a very clean edge is required to give a glassy cavity. However, well-finished fully-cavitating propellers produce cavities which, viewed in stroboscopic light, have surfaces like figure 3 rather than figure 6. Towing-tank experience with hydrofoils forming cavities ventilated from the free surface shows that sometimes a glassy cavity will occur, when on a repeat run the cavity surface will be rough and striated. It is only fair to point out that a hydrofoil may represent a particularly sensitive case, since the free streamlines at the leading edge are at a very small angle to the upper surface, and if this angle changes slightly, so that they osculate the surface, a striated appearance is likely to result. On a disk the streamlines leave the edge at a much greater angle to the solid surface. Nevertheless, it appears that the nature of the cavity surface is a general feature of cavitation which is far from being well understood.

6. Pressure measurements in natural cavities

We now consider the pressure measurements made with natural, unventilated cavities. Figure 7 shows $p_c - p_v$ plotted against V for the 5 in. disk at 15·3 ppm air content, where p_c and p_v are the cavity pressure and water-vapour pressure in inches of mercury, and V is the tunnel speed in ft./sec. The tunnel temperature, which affects p_v, was, in the present experiments, between 17 and 15 °C, a range for which p_v varies between 0·57 and 0·51 in. of mercury. The tunnel was run at approximately its minimum pressure at each speed. Figure 8 shows a similar curve for the 3 in. disk at 13·4 ppm. For this disk it is not possible to indicate the cavity régimes as in figure 7, since at the lower speeds the cavity is largely out of sight, the 3 in. disk being 3 ft. upstream of the windows. Apart from a lone spot

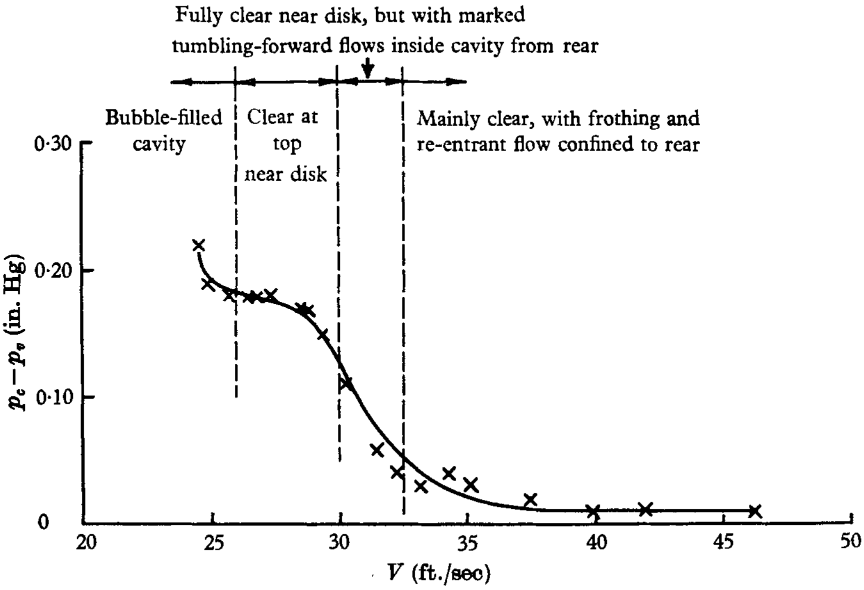

FIGURE 7. Cavity pressure variation with 5 in. disk.

at 43 ft./sec in figure 8, obtained immediately after starting up the tunnel when the cavity was pulsating, the cavity pressures for the 3 in. disk asymptote at high speeds to a value much higher than the corresponding value for the 5 in. disk. The lone spot is puzzling: a similar measurement was obtained at 17·7 ppm, again just after starting up the tunnel when the cavity was pulsating. On many other occasions, however, pulsating cavities were accompanied by cavity pressures indistinguishable from those obtained with steady cavities at about the same speed and tunnel pressure. Figure 9 shows the asymptotic limit values of p_c/p_v (disregarding the lone spots) plotted against air content for both the 5 in. and the 3 in. disk. Although at high enough speeds the cavity pressure is always very roughly of the same order as the vapour pressure, even at high air contents, there are clearly significant differences between the 5 in. and the 3 in. disks. These differences may perhaps be associated with the difference, already noted, between the glassy surface of the 5 in. disk cavity and the roughened appearance of the 3 in. one. If the latter appearance denotes turbulence, it might well be accompanied by a more vigorous diffusion of air from the water through the cavity wall than occurs with a glassy surface. Alternatively, it may be that no appreciable diffusion occurs across the external walls of the cavity: instead, diffusion may take place mainly within the cavity towards the rear, where there are turbulent, seething water motions with spray formation. Such spraying into a low-pressure

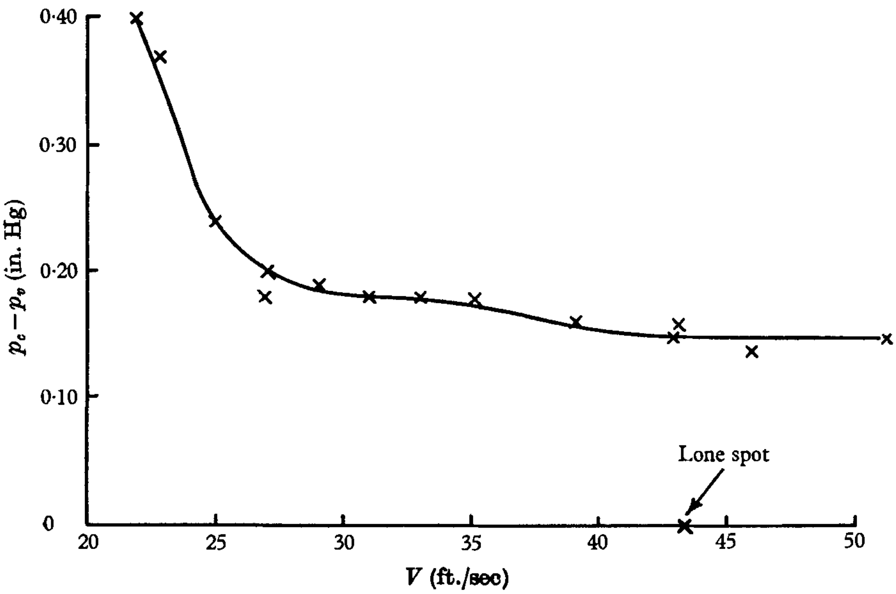

FIGURE 8. Cavity pressure variation with 3 in. disk.

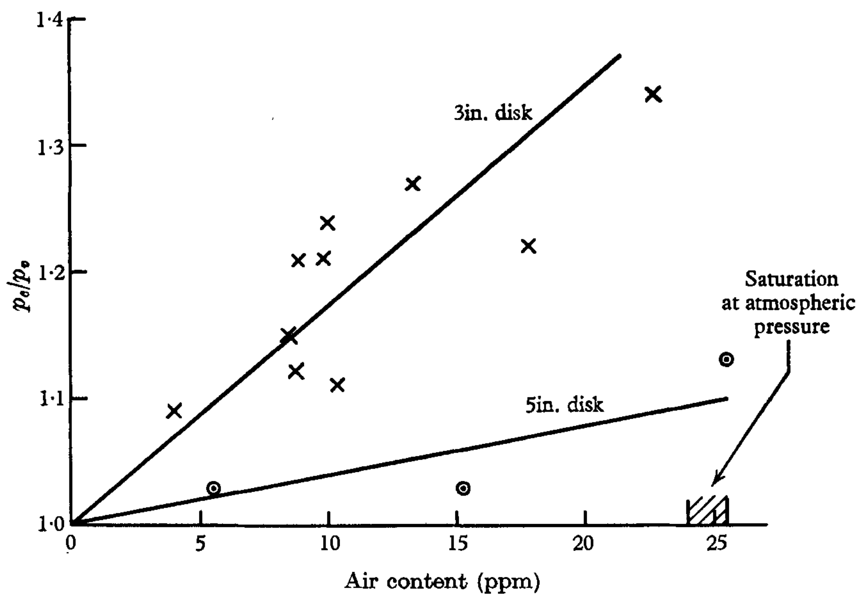

FIGURE 9. Limiting values of p_c/p_v.

region is similar to what happens inside the familiar Van Slyke air-content measuring apparatus. If such spraying is the cause of air diffusing into the cavity, it may still be associated with the roughened appearance of the external cavity surface, since that appearance may, as mentioned above, be caused by a rain of spray hitting the surface from within. It seems not unlikely that the spraying processes would occur more vigorously within the 3 in. disk cavity, whose downstream end is unobstructed, than for the 5 in. disk, where the flow was affected by the shaft and shaft support struts.

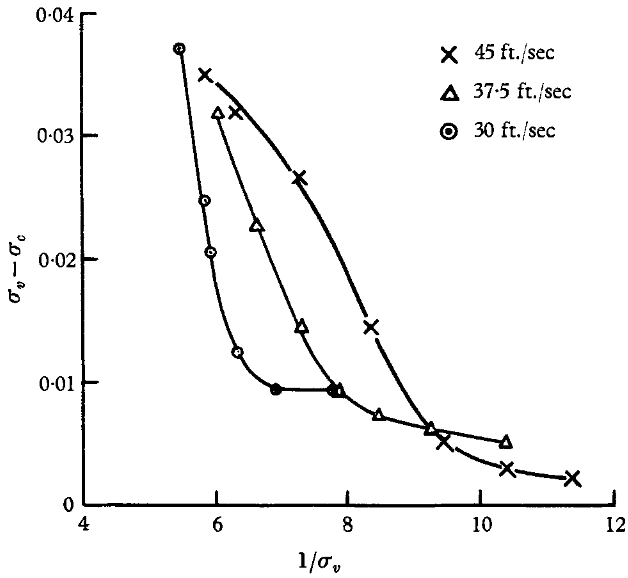

FIGURE 10. Cavity pressure variation at different speeds, 3 in. disk.

Any diffusion of air into the cavity, whether it occurs across the walls of the cavity or from the spray droplets within it, must of course be balanced by an equal entrainment out of the cavity to the wake. These entrainment processes might, in the case of the 5 in. disk, have been influenced by the presence of the shaft and shaft support struts. Tunnel blockage effects are of course more important with the 5 in. than with the 3 in. disk, but it is hard to see why this should drastically affect the influence of air content on cavity pressure.

The curves of figures 7 and 8 were obtained with the tunnel running at approximately its minimum pressure at each speed. The 3 in. disk was also run at a series of constant speeds, the pressure being varied. Typical results are presented in figure 10 for 8·7 ppm air content. Here $2(p_c - p_v)/\rho V^2$ or $\sigma_v - \sigma_c$, is plotted against $\rho V^2/2(p_T - p_v)$, or the reciprocal of the cavitation number σ_v based on vapour pressure. The ordinates represent the increase in cavity pressure above vapour pressure divided by the dynamic head, which is presumably a measure of the pumping action tending to entrain air out of the cavity. The abscissae represent the dynamic head divided by the suction required to vaporize the water. The resulting curves, though far from being collapsed on to one another, are much closer together than if simply $p_c - p_v$ had been used as the ordinate.

7. Lengths of natural and ventilated cavities

Cavity lengths l were measured for the 3 in. disk and are plotted in figure 11 against $2(p_T - p_c)/\rho V^2 = \sigma_c$, the cavitation number based on cavity pressure. The natural cavity measurements in figure 11 were obtained at two different air contents, 8·7 and 22·7 ppm. The points all plot onto one curve approximately, and there appears to be no significant trend of variation of cavity length with air content.

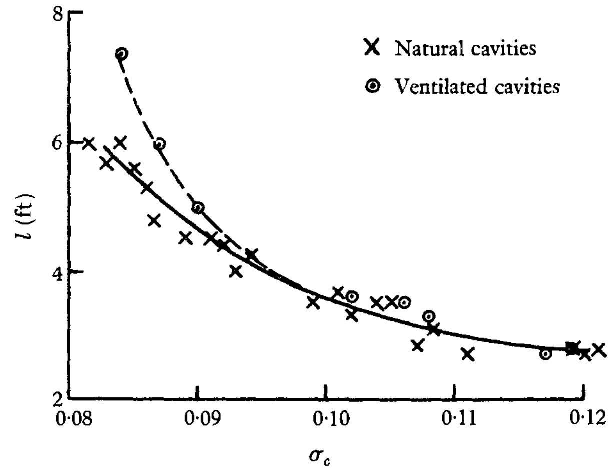

FIGURE 11. Cavity length against cavitation number, 3 in. disk.

Figure 11 includes results obtained with continuous blowing through the cavity ventilation tube. It appears that ventilated cavities have much the same lengths as natural cavities at the same cavitation numbers. There are, however, some differences. Thus for a slighly higher blowing rate than that corresponding to the longest ventilated cavity in figure 11, the cavity could be made to lengthen till it extended right through the working section into the diffuser. No further reductions of tunnel pressure at this tunnel speed were then possible, presumably because any attempt to reduce pressure simply enlarged the cavity still more. This situation is analogous to the choking of a transonic wind tunnel. The very similar phenomenon of cavitation-tunnel choking which occurs as a result of secondary cavities in other parts of the tunnel circuit has already been mentioned. With natural cavities, choking as a result of undue enlargement of the primary disk cavity did not occur.

8. Pressures within ventilated cavities

The effect of blowing on cavity pressure for the 3 in. disk is illustrated in figure 12, where $\sigma_c = 2(p_T - p_c)/\rho V^2$ is plotted against a blowing parameter β_1, defined as the ratio (volume flow of air at tunnel pressure) to (volume flow of water in free stream through disk area). It can be seen that where the cavitation number σ_c without blowing (i.e. the intercept of the curve with the vertical axis) is roughly the same for two different tunnel speeds, as for

$$v = 45\,\text{ft./sec}, \quad p_T = 408\,\text{lb./ft.}^2 \quad \text{and} \quad v = 30\,\text{ft./sec}, \quad p_T = 210\,\text{lb./ft.}^2,$$

the curves are roughly the same. At high blowing rates the curves flatten out, and further increase of blowing has no appreciable effect on either the cavity pressure or the cavity length. At the lowest pressure for the highest speed (310 lb./ft.^{2}, 45 ft./sec), the flattening out is associated with the cavity extending through the working section, as mentioned above, but this is not so at the lower speeds. With the 5 in. disk, operating at conditions where no cavitation occurs without blowing, a similar flattening occurs and its onset is associated with the bubbly cavity,

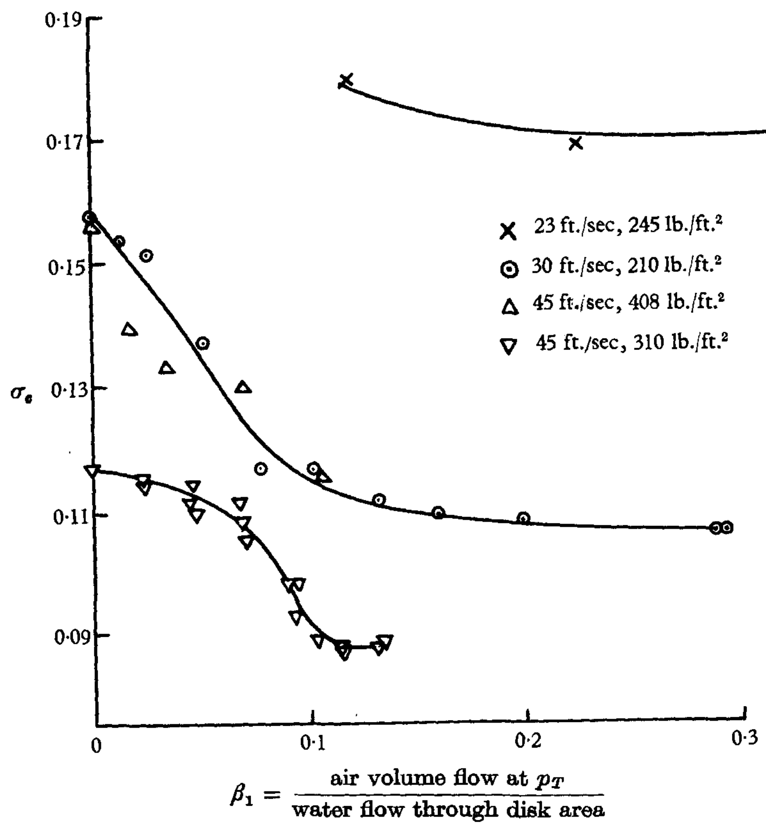

FIGURE 12. Effect of blowing on cavitation number, 3 in. disk.

which is formed with moderate blowing, suddenly clearing to form a largely glassy-clear cavity. At this juncture too, the nominal cavitation number σ_c is usually in the region of 0·27, which due to choking, is probably about the minimum obtainable for the 5 in. disk in the tunnel. Results obtained with speeds in the range 17–25 ft./sec, and tunnel pressures in the range 370–2000 lb./ft.^{2}, are shown in figure 13, the crosses being cavities that are entirely bubbly in appearance, and the circles ones that are largely glassy clear. In figure 13 cavitation number has been plotted, not against β_1 as in figure 12, but against a quantity β_2, proportional to the ratio (volume flow of air at cavity pressure) to (volume flow of water in free stream through disk area). Thus $\beta_2 = p_T \beta_1 / p_c$. Both methods of correlating the results give a large scatter, as is only to be expected, since geometrical similarity for the motion of volumes of air as they pass from the cavity into the wake downstream cannot be expected if p_T/p_c is not the same. Moreover, Froude number is certainly a relevant parameter affecting the buoyancy force on the cavity which, as can be seen from the cavity photographs, is appreciably inclined upwards. Differences in Froude number may account for the difference in limiting pressure achieved at the high blowing rates in figure 12 for the different tunnel speeds. Another cause of scatter may be the fact that figures 12 and 13 contain results for various different air contents. However, the differences occasioned by this are probably much smaller than the other types of scatter.

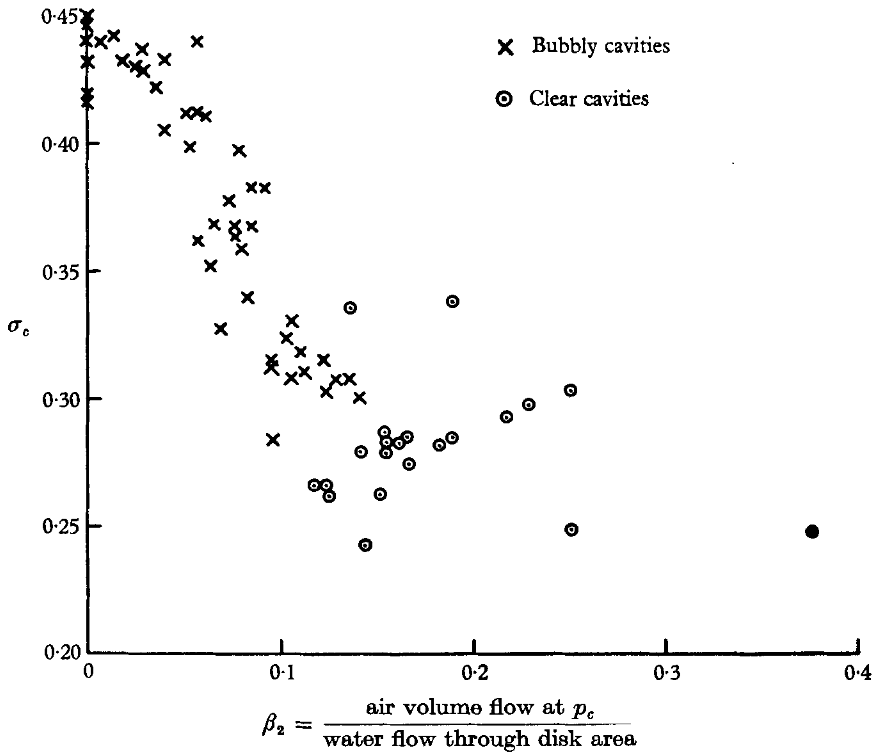

FIGURE 13. Effect of blowing on cavitation number, 5 in. disk.

9. Appearance of the wake

Despite the evident influence of buoyancy on the cavity, no clear sign was seen of the twin trailing vortices observed by Cox & Clayden (1956) with ventilated cavities. They ascribed these vortices to the lift circulation induced round the cavity. The wake flow behind our cavities was always more confused and turbulent looking than that behind theirs. This may well have been due to the larger sizes of our disks and the higher tunnel speeds at which they were run.

There was an influence of air content on the appearance of the wake behind a natural cavity. Thus figures 14 and 15 (plates 2 and 3) show 10–30 μsec flash pictures of the wake behind the 3 in. disk cavity at $V = 27$ ft./sec, p_T being 135 lb./ft.^{2} for the former case (nominal $\sigma_v = 0{\cdot}137$), when the air content was

4·2 ppm, and 168 lb./sq.ft. for the latter case (nominal $\sigma_v = 0{\cdot}184$), when the air content was 9·8 ppm. There are clearly more bubbles present at the higher air content, despite the slightly higher tunnel pressure which would be expected to reduce their size. Nevertheless, it is perhaps surprising that at the low air content so much visible cavitation persists so far behind the cavity, into a region where the mean pressure would be expected to have returned to something like the pressure of the undisturbed stream. The occurrence of cavities here bears witness to the vigour and persistence of the turbulent eddying motions in the wake. This point is seen still more clearly from figure 16 (plate 3), which shows the wake behind the natural cavity (not pulsating) formed by the 3 in. disk at 35 ft./sec, 144 lb./ft.^{2} (nominal $\sigma_v = 0{\cdot}109$), and 4·2 ppm. This is in fact a composite of two photographs taken on separate occasions through the two windows of the tunnel, but the pictures happen to overlap well. The upstream and downstream ends of the composite picture are respectively about 3 and 9 ft. downstream of the disk. There appears to be a periodicity in the wake similar to that in a two-dimensional vortex street, but it is hard to see what is happening in detail in such a complicated flow.

10. Concluding remarks

No definite conclusions can be drawn from these experiments, which as we have seen, present many puzzling features. That this should be so, for what at first sight appears a very simple class of cavity, is an indication that the physics of cavitation is very imperfectly understood. In view of this it is perhaps surprising that mathematical free-streamline models, involving drastic simplifications, should succeed nevertheless in giving useful answers. However, the way to improvement of these models probably lies in taking a more realistic account of the physics of the flow. If this paper suggests any ideas in this respect, or proves helpful to other experimenters in the field, it will have served its purpose.

Mr M. P. Lewis assisted with the ventilated cavity experiments on the 5 in. disk. The technique for securing the 3 in. disk was devised by Mr A. Dolman, Mr H. Sharp, and Mr P. S. Cook. Mr Silverleaf drew the authors' attention to the different natures of the 3 in. and 5 in. disk cavity surfaces.

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