Cavitation

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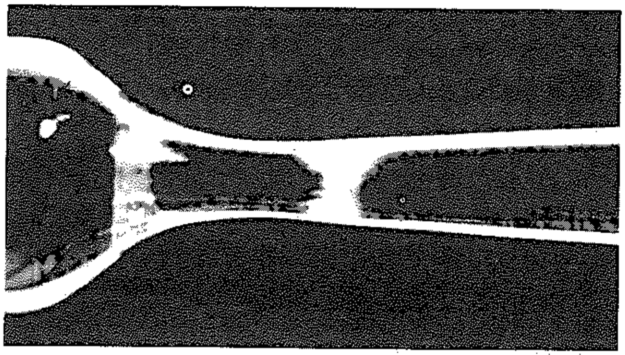
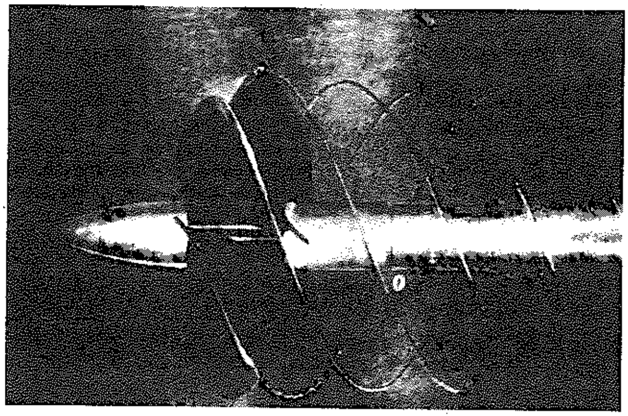
INTRODUCTION

Cavitation is defined as the process of formation of the vapor phase of a liquid when it is subjected to reduced pressures at constant ambient temperature. Thus, it is the process of boiling in a liquid as a result of pressure reduction rather than heat addition. However, the basic physical and thermodynamic processes are the same in both cases.

A liquid is said to *cavitate* when vapor bubbles form and grow as a consequence of pressure reduction. When the phase transition results from hydrodynamic pressure changes, a two-phase flow composed of a liquid and its vapor is called a *cavitating flow*. Cavitating flow may be seen (and heard) as water flows through a glass venturi tube (Fig. 1), an experi-



1. Patches of cavitation bubbles appear just downstream of the throat of a venturi tube.



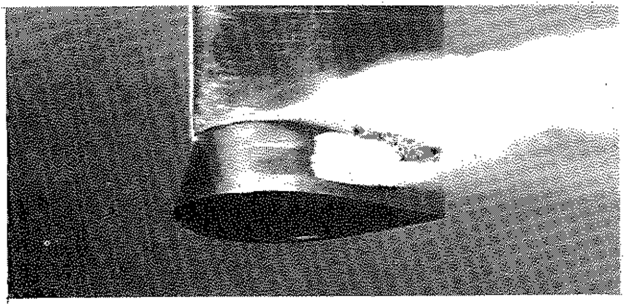
2. Cavitation in the cores of the tip vortices from the blades of a marine propeller forms a helical pattern. Cavitation on the faces of the blades is more easily seen in the close-up of Fig. 7.

ment first exhibited by Osborne Reynolds in 1894. According to Bernoulli's equation, where the velocity is increased, the pressure is decreased. At sufficiently high flow rates, the liquid in the throat, where the velocity is highest and the pressure is lowest, begins to boil. The small bubbles formed there are filled with cold steam and other gases diffused from the liquid. Another example of cavitation occurs in the low-pressure regions on marine propellers at high rotation rates (Fig. 2).

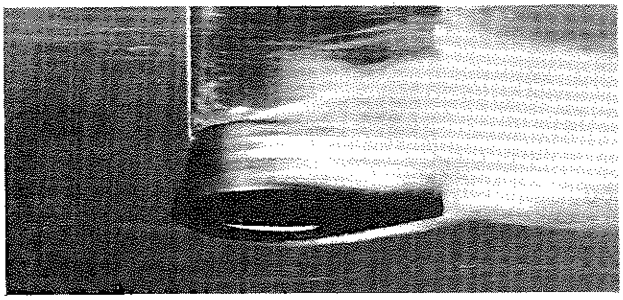
TYPES OF CAVITATION

Flow About Hydrofoils

In the film, experiments are performed in a circulating water channel, where the water speed, absolute pressure, and temperature can be varied independently of each other. A thick, symmetrical hydrofoil is suspended from a strut and set at an angle of attack to lift upward. With the ambient pressure well below atmospheric and held constant, the flow speed is increased until cavitation occurs. Cavitation starts first at the intersection of the strut and hydrofoil (Fig. 3), where the presence of the strut causes a greater pressure reduction than elsewhere on the foil. Cavitation on the foil itself first occurs in the low-pressure core of the laminar boundary layer separation region (Fig. 3). At higher speed, and thus higher Reynolds number, transition from laminar to turbulent boundary layer occurs, and cavitation begins near the minimum-pressure line close to the leading edge (Fig. 4). In Fig. 4, the cavitation region is seen under steady incandescent lighting. Under stroboscopic lighting, we see that the cavitating region is actually made up of individual bubbles (Fig. 5). In the film, high-speed motion pictures reveal that each bubble grows as long as it is in the low-pressure region. The bubbles collapse as they are swept downstream into the high-pressure region near the trailing edge. Individual bubble cavitation is characteristic of forms with gentle pressure gradients, such as those on the foil with a well-rounded leading edge (Fig. 5).



3. As the flow speed is increased, cavitation first occurs at the intersection of the hydrofoil and the vertical supporting strut. With further increase in speed, cavitation on the blade itself occurs first in the low-pressure core of the laminar boundary-layer separation region.

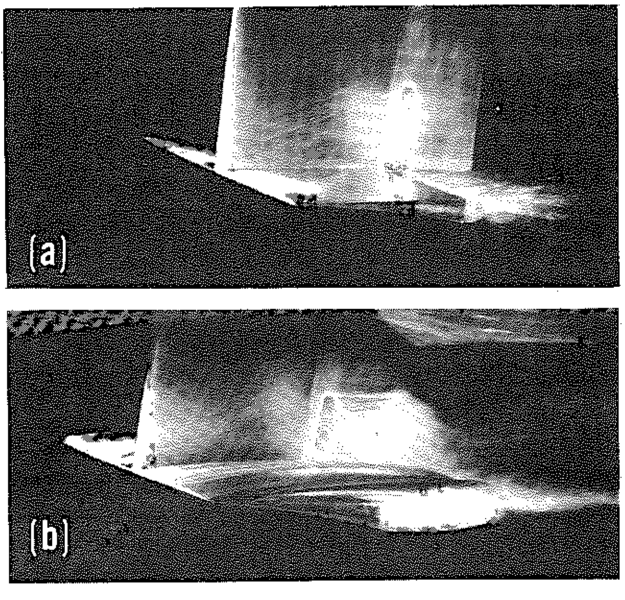


4. At higher flow speeds, cavitation begins near the minimum-pressure line close to the leading edge.

5. The same flow as in Fig. 4, but here seen with stroboscopic lighting. The cavitation region is made up of individual bubbles.

Supercavitating Hydrofoil

When the leading edge of a hydrofoil is sharp, cavitation begins at this edge (Fig. 6a). A continuous,

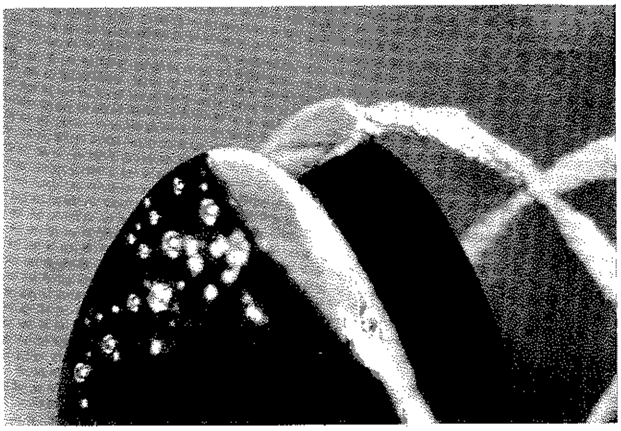


6. When the leading edge of a hydrofoil is sharp (a), cavitation begins first at this edge. When the angle of attack or the flow speed is increased, or the ambient pressure reduced, to the point where the cavitating region extends beyond the trailing edge (b), the flow is called "supercavitating." This type of hydrofoil is designed to operate efficiently in this condition, and is referred to as a *supercavitating* hydrofoil.

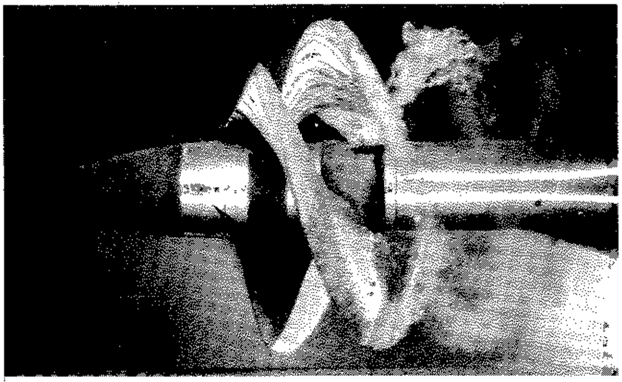
vapor-filled cavity is formed, rather than a mass of small individual bubbles. The cavity grows when the angle of attack is increased, when the ambient pressure is reduced, or when the water speed is increased. When the cavity extends beyond the trailing edge of the hydrofoil, the flow is called a "supercavitating" flow (Fig. 6b).

Flow About Propellers

On a marine propeller cavitation appears on each blade and in the cores of the tip vortices where the pressure is low (Figs. 2 & 7). Figure 8 shows a propeller designed to operate under supercavitating conditions. Note the similarity of the cavity on each blade to that on the hydrofoil with the sharp leading edge.



7. A close-up of a marine propeller under stroboscopic lighting shows cavitation bubbles on the face of the blade and in the cores of the tip vortices.



8. A marine propeller designed to operate under supercavitating conditions has blade cross-sections similar to the hydrofoil of Fig. 6.

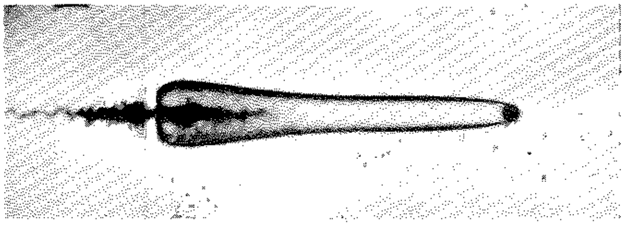
Turbulent Shear Flow

Cavitation can also occur in turbulent shear flows because of the local pressure reduction in intense turbulent eddies. This phenomenon can be observed in the flow behind a disc with its axis of symmetry parallel to the flow direction. At high speeds, the pressure fluctuations in the zone of high turbulent shear at the edge of the wake lead to cavitation (Fig. 9). With further increase in speed, the entire wake appears to be filled with vapor bubbles. Eventually, the flow becomes a true cavity flow (Fig. 17a), as distinguished from a cavitating wake flow. In the film, high-speed photography shows that the flow at the end of the cavity re-enters and moves upstream. The momentum flux in the re-entrant jet is equal to the pressure drag of the body. The jet kinetic energy is dissipated. A similar re-entrant flow can also be seen in the cavity trailing the supercavitating hydrofoil.

9. In the flow past a disc, cavitation appears in the zones of high turbulent shear at the edges of the separated wake.

Water-Entry Cavity

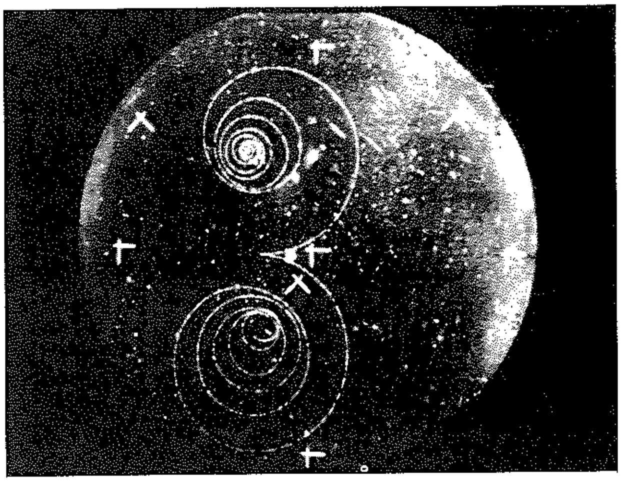
A nonstationary type of cavity flow occurs when a solid body enters water at high speed (Fig. 10). The cavity follows the body into the water and eventually closes off, producing re-entrant jets. Initially, the gas within the cavity attached to the body is air rather than vapor. Progressively, the air is left behind, and if the motion persists long enough, the cavity will contain vapor primarily.



10. With the camera turned so the water surface appears vertical, a round body is shot into water. The cavity follows the body into the water and eventually pinches off at the rear, forming a re-entrant jet directed toward the body. (Courtesy of U.S. Naval Ordnance Laboratory)

Bubble Chambers

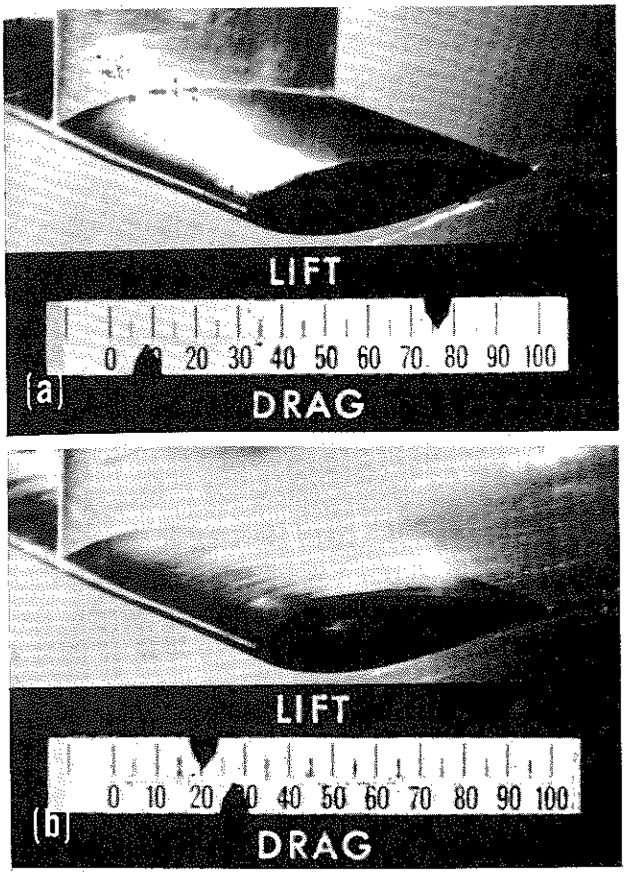
Still another example of cavitation occurs in bubble chambers used for studies of high-energy nuclear particles. In Fig. 11, a positron-electron pair has produced tracks of bubbles in liquid hydrogen which is at a pressure below the boiling point and is therefore unstable.



11. The tracks of a positron-electron pair through liquid hydrogen are made visible by cavitation bubbles.

We have seen that cavitation can take several forms: small, transient bubbles; large, more-or-less steady cavities; nonstationary cavities, and often a mixture of these types.

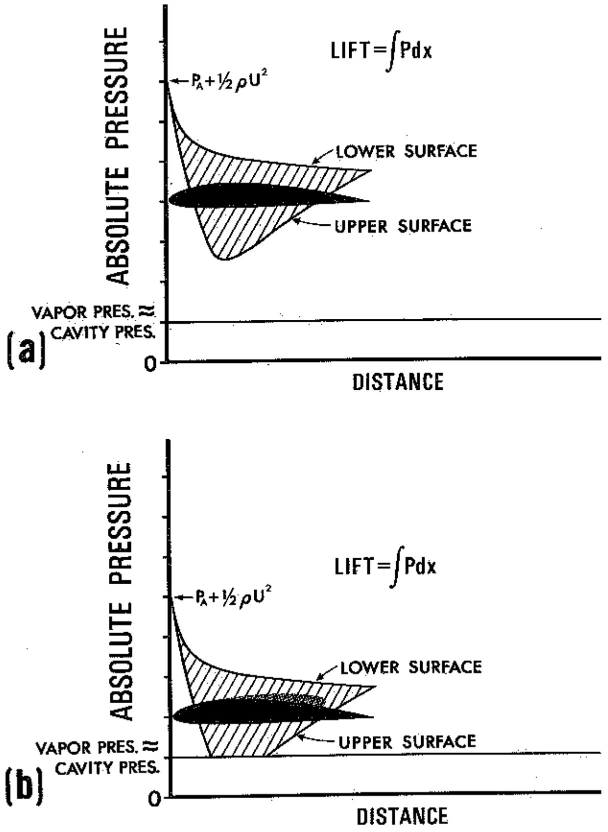
EFFECTS OF CAVITATION AND CAVITATING FLOWS



12. Force gauges measure lift and drag on a suspended hydrofoil. Prior to the inception of cavitation, reduction of the ambient pressure does not change lift or drag (a). When cavitation develops, further reduction in pressure causes a decrease in lift and an increase in drag (b).

Effect on Lift and Drag

Since hydrofoil sections make up so many different types of machines — pumps, turbines, propellers, propeller shaft struts, mixers — the effects of cavitation on such machines can be illustrated by studying the forces on the hydrofoil section itself. At constant flow speed, the lift and drag on a hydrofoil do not vary as the ambient pressure is lowered (Fig. 12a), until cavitation begins. As cavitation develops, the lift decreases and the drag rises (Fig. 12b). The flow becomes quite unsteady and often produces severe vibrations in hydraulic machines.

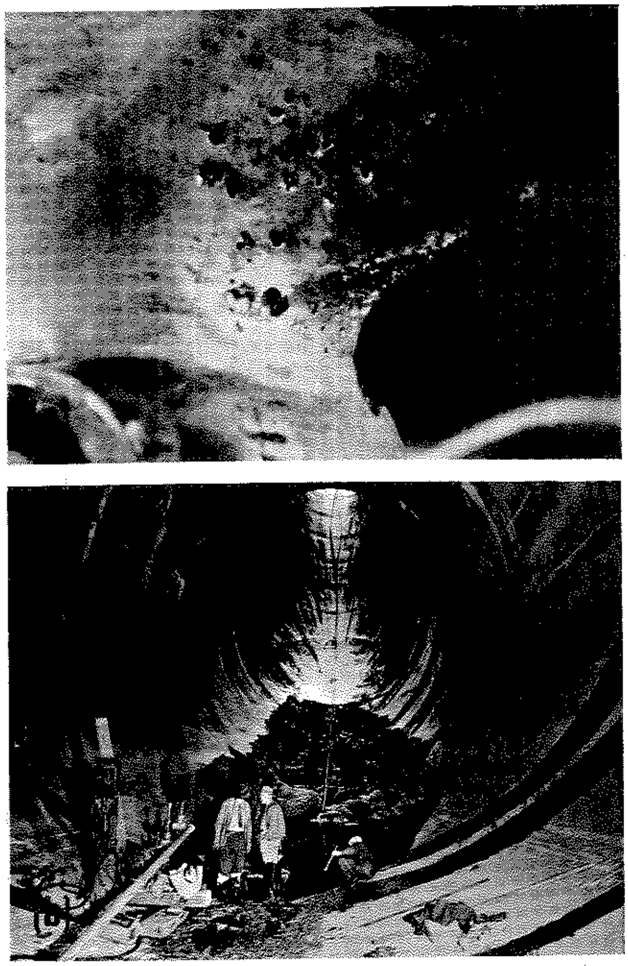


13. Prior to cavitation inception, reduction of absolute pressure does not affect the area between the curves (which is proportional to lift). When cavitation develops, the pressure on the upper surface cannot go below the vapor pressure, and the area (and lift) decreases with pressure reduction.

The loss in lift can be understood by examining the pressure distribution on the hydrofoil section (Fig. 13a). The lift is proportional to the difference in the curves representing the pressure distributions on the upper and lower surfaces of the hydrofoil. As the ambient pressure is decreased, the pressures on the upper and lower surfaces decrease by exactly the same amount until the upper surface begins to cavitate. At this point, the pressure on the upper surface can no longer decrease below the cavity pressure, which is near the vapor pressure. Since the pressure on the lower surface does decrease, the lift drops (Fig. 13b). The shape of the pressure curve changes as cavitation develops; the resultant pressure distribution is such as to cause an increase in drag. Thus, hydrofoils and many hydraulic machines which are designed for efficient subcavitating operation lose efficiency when cavitation occurs. When cavitation is unavoidable and conditions are such that supercavitating flow can be assured, it is possible to use supercavitating hydrofoil profiles designed specifically to achieve high lift-drag ratios.

Noise Produced by Cavitation

Collapsing cavitation bubbles produce noise. In the film, this effect is demonstrated using water in a tube with a partial vacuum in the space above the water surface. By accelerating the tube downward, low-enough pressures can be produced to cause the liquid to cavitate. When the tube is brought to rest, the pressure gradient resulting from the acceleration is removed, the pressure returns to its original value, and the bubbles collapse. The noise produced is the result of shock waves generated upon bubble collapse.

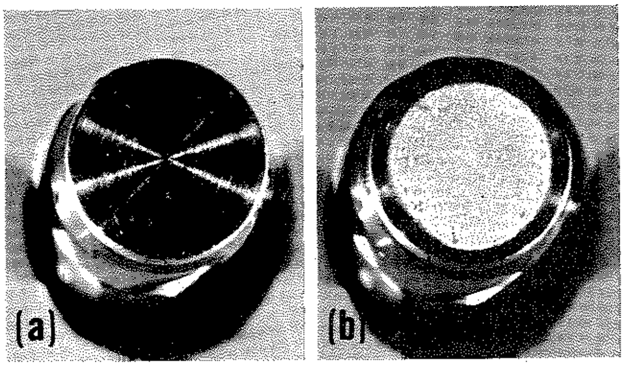


14. Cavitation damage to a marine propeller (a), and to a power dam spillway tunnel (b).

Cavitation Damage

The pressures associated with bubble collapse are high enough to cause failure of metals. Figure 14a shows cavitation damage on a propeller operated under cavitating conditions for a few days. Figure 14b shows cavitation damage in a spillway tunnel of a large power dam.

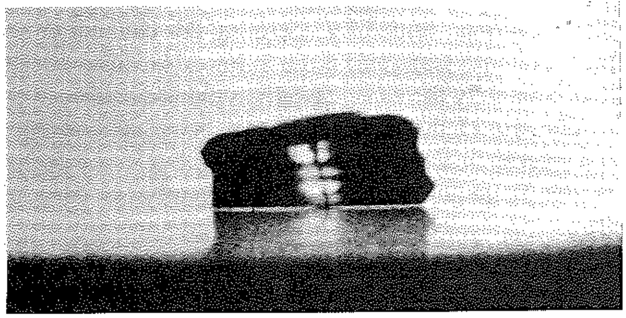
Cavitation can cause damage in a very short time. This effect is demonstrated by oscillating an aluminum specimen in the surface of water, using a magnetostriction oscillator. The specimen is driven vertically at a rate of 14,000 cycles per second. The total amplitude is only .002 inches, but the pressure is changed from below vapor pressure as the button is accelerated upward to a high pressure as it is accelerated downward. After one minute, the highly polished surface has been eroded and considerable weight loss has occurred (Fig. 15).



15. Cavitation erosion (b) to a highly polished aluminum button (a), which was oscillated normal to the page at 14,000 cps for one minute.

DYNAMICS OF TRANSIENT CAVITATION BUBBLES

The life history of the small transient bubbles (Fig. 5) is measured in milliseconds. They grow during their passage through the low-pressure region, and then collapse as they enter the region of increasing pressure. If the bubbles have a relatively high initial



16. A cavitation bubble collapsing on a wall. A re-entrant jet is visible in the center of the bubble.

gas content, they will collapse and then rebound. If such cavitation bubbles remained spherical throughout their life history, extremely high pressures would be developed upon collapse (of the order of thousands of atmospheres). However, distortions occur because of Taylor instability, or if the bubble collapses in an unsymmetrical pressure field (in a gravity gradient or near a wall, for example). In the latter case, an internal jet is formed (Fig. 16), much as in the case of the water entry cavity. The velocity of the jet is very high; the impact on a surface can produce high stresses, and is another mechanism which may account for severe damage.

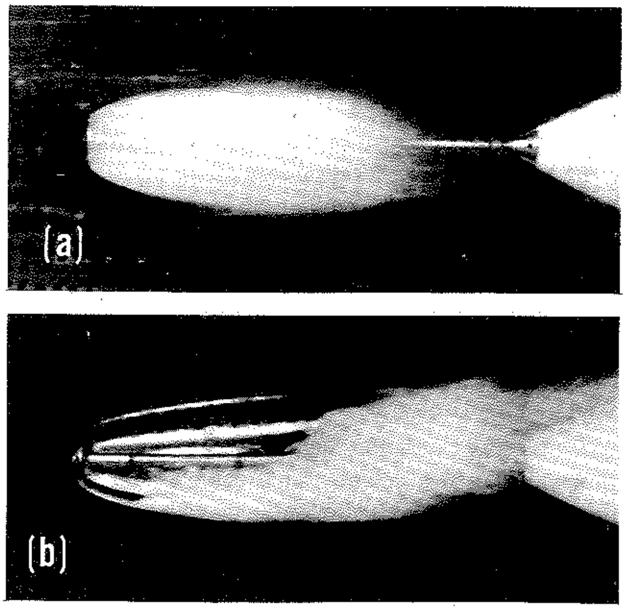
CAVITATION SCALING LAWS

The parameter which describes the conditions for cavitation similarity is the *cavitation number,*

$$\sigma = \frac{P_a - P_c}{\frac{1}{2}\rho U^2}$$

where P_a is the ambient absolute pressure, P_c is the cavity pressure, ρ is the mass density of the liquid, and U is a reference speed characteristic of the flow. It is the basis for scaling cavitation phenomena and for designing model experiments. The cavitation number at which cavitation begins is called the *critical cavitation number*. Above the critical cavitation number, no cavitation occurs; below the critical, it does occur. Operation with a cavitation number well below critical produces a very large cavitated region. In two-phase, one-component flow, the cavity pressure is just the vapor pressure. In a multicomponent flow, the cavity pressure is the sum of the partial pressures of the vapor of the liquid and of any gases that may have been introduced into the cavity. In fact, a cavity developed entirely with gas from an outside source behaves and appears very much like a cavity formed by means of the vaporization process discussed above. This is illustrated in Fig. 17, where a vapor cavity is compared with a cavity caused by introducing air into the wake of the disc. To form the vapor cavity, the water channel was operated at high speed and low pressure. The air cavity was formed by operating the channel at atmospheric pressure and a much lower speed to obtain approximately the same cavitation number.

The size of the physical system being studied does not appear in the cavitation number, but it is a factor in the Reynolds number. Consequently, as long as Reynolds-number effects are taken into account properly, cavitation similarity requires only that the cavitation number be the same for model and prototype. A model experiment can be made at lower speed than that at which the prototype operates if we simultaneously reduce the pressure under which the model is operated. The operation of the cavitation tunnel is based on this principle.

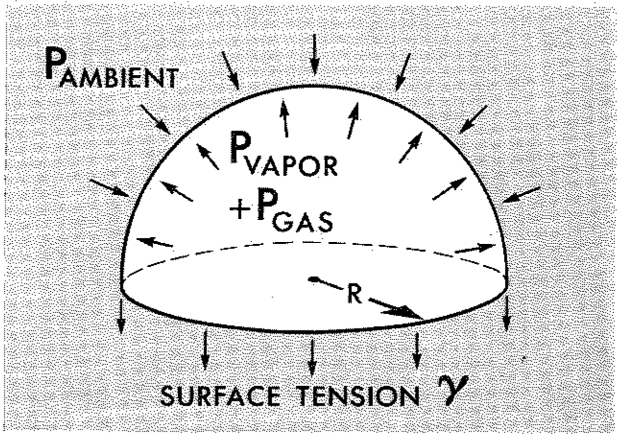


17. (a) shows a cavity behind a disc set normal to a high-speed, low-pressure flow. (b) shows a similar cavity formed by introducing air into the wake of the disc, at low flow speed and at atmospheric pressure.

INCEPTION OF CAVITATION

The Role of Nuclei

How does cavitation, or ordinary boiling for that matter, actually begin? Inception of cavitation in a multi-component liquid at *pressures near the vapor pressure* requires the presence of nuclei which contain minute amounts of vapor, gas, or both. Cavitation will occur only when these nuclei become unstable and grow when subjected to a pressure reduction. The conditions for such growth can be derived from an analysis of the static equilibrium conditions for a spherical nucleus (Fig. 18). The internal forces, produced by

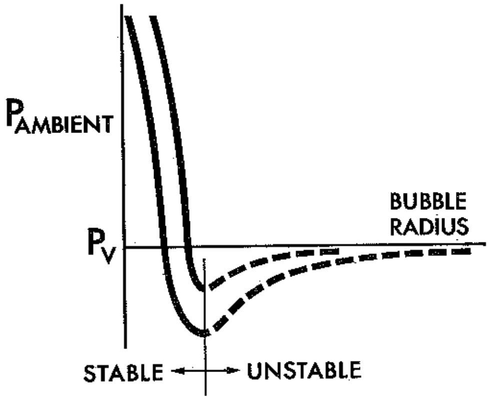


18. The forces on a cavitation bubble nucleus.

the partial pressures of the gas and vapor within the nucleus, must be balanced by the ambient pressure and the surface-tension pressure at the nucleus-liquid interface. Thus, the condition for static equilibrium is that the ambient pressure plus the surface-tension pressure equal the vapor pressure plus the gas pressure

$$P_A + \frac{2\gamma}{R} = P_V + \frac{\text{const.}}{R^3}.$$

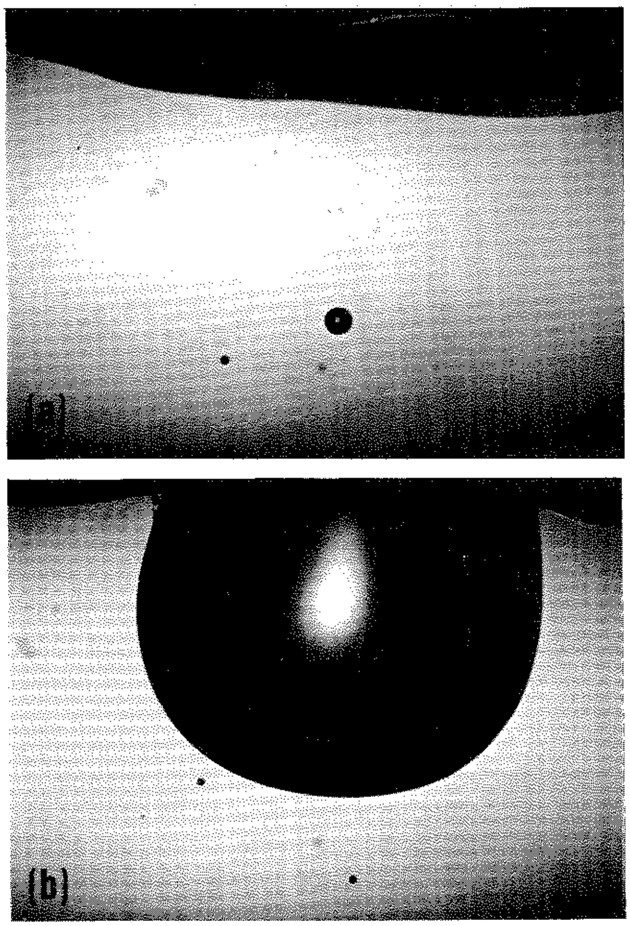
This equation has been plotted in Fig. 19 for two gas contents. The pressure adjacent to the bubble has a minimum value which is below the vapor pressure of the liquid. As long as the ambient pressure is above this minimum, and the initial bubble radius is smaller than the radius associated with it, the nucleus is stable and tends to reach an equilibrium radius along the left-hand portion of the curve, where the slope is negative. If, however, the pressure drops below the critical value, the bubble becomes unstable and grows without bound. If a smaller gas content is available, even lower pressures are required.



19. Plots of the conditions for static equilibrium of cavitation bubble nuclei. The upper curve is for a bubble with a larger gas content than the lower one.

Stable and Unstable Nuclei

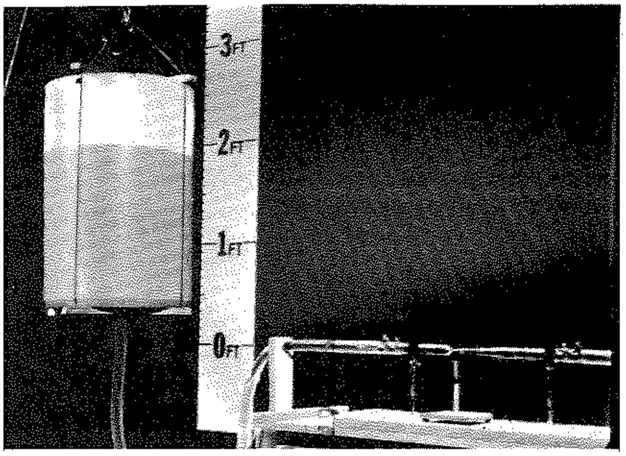
Stable and unstable behavior of nuclei are shown in the film by observing nuclei that have radii just below and just above critical value. Small bubbles of the order of .005 inches in diameter are generated in a tube that is partially filled with water and evacuated to near vapor pressure. This is done by evolving hydrogen from one platinum wire and oxygen from a second wire by means of an electrical impulse generator. The bubbles are unequal in size, the hydrogen bubble being the larger. As they rise toward the free water surface, into regions of lower hydrostatic pressure, the larger hydrogen bubble reaches critical size and grows explosively, while the oxygen bubble does not (Fig. 20). Although the small oxygen bubbles expand as the pressure is reduced, they never reach a size large enough to become unstable. On the other hand, some of the larger hydrogen bubbles, which move along a curve such as the one corresponding to larger gas content in Fig. 19, do expand to a size large enough to slip into the unstable region and grow explosively. Bubbles represented by the portion of the curve of Fig. 19 to the right of the minimum point are already unstable, and cannot exist unless stabilized by some external mechanism.



20. (a) A hydrogen bubble (on the right) and a smaller oxygen bubble (left) rise toward the free surface of water in a partially evacuated tube. (b) As a result of the lower hydrostatic pressure near the free surface, the larger hydrogen bubble reaches critical size and grows explosively, while the oxygen bubble does not. (Courtesy of Albert T. Ellis, University of California.)

Effect of Nuclei Size and Content on Cavitation Inception

A stable nucleus can decrease in size and eventually disappear because its gas content diffuses into the surrounding fluid. This is shown in the film with a venturi experiment, by comparing the cavitation inception pressure for freshly drawn water with that for water which has rested undisturbed for some time (Fig. 21). Because the discharge is to the atmosphere, increasing the driving head increases the velocity and thereby de-



21. With freshly drawn water in the bucket, cavitation begins in the venturi throat at a head of about 2 feet. When the water in the bucket is allowed to rest undisturbed for some time, a higher head (about 3 feet) is required for onset of cavitation.

creases the static pressure at the throat. With freshly drawn tap water, cavitation begins at a head of about 2 feet, and continues to develop as the head is further increased. After leaving the water undisturbed for about an hour and then repeating the experiment, a much higher head is required for onset of cavitation — in this case, about three feet. During the settling period, some nuclei could rise to the surface and vent if they were very large, and some could decrease in size by diffusion of air into the surrounding water. Consequently, a greater pressure reduction was required to cause cavitation in that sample.

A Dilemma

The result of the experiment on nuclei size and content leads to a dilemma. Nuclei in mechanical equilibrium disappear through diffusion of the gas into the surrounding liquid. Unstable nuclei cannot persist. Yet we have seen that nuclei must be present for cavitation to occur at pressures near vapor pressure. How, then, can we account for the persistence of nuclei? We must conclude that some external mechanism is required, such an entrapment of gas in the crevices of solid boundaries or on dust particles, or by the accumulation of some foreign material on the nucleus gas-liquid interface which prevents diffusion.

CONCLUSION

We do not fully understand all of the mechanisms of nucleation, and many basic aspects of cavitation remain to be explained. Nevertheless, we do know a great deal about cavitation, and its effects on performance of machines can be predicted fairly well.

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