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THE INFLUENCE OF AIR-FILLED NUCLEI ON CAVITATION INCEPTION

by

M. Strasberg, Ph.D.

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ABSTRACT

The need for nuclei in the cavitation inception process is discussed. It is shown that the characteristics of the nuclei in the water determine the critical pressure for cavitation, and accordingly, that a variation in the nuclei content may introduce scale effects into tests of cavitation inception. Evidence is presented that the nuclei in water are cavities of undissolved air. The critical pressure for the onset of cavitation is given for several forms of air nuclei. It is shown that negative pressures are required for inception if the nuclei are small enough. Some measurements made with ultrasonic apparatus are described which seem to verify the theoretical deductions. The significance of the ultrasonic measurements and the theoretical deductions to hydraulic cavitation is discussed.

INTRODUCTION

A primary objective of most cavitation testing is to determine the conditions required for the onset of cavitation. It is the purpose of this report to discuss some of the factors influencing the inception of cavitation and, more specifically, to examine the effect on inception of the presence of air-filled nuclei in the water.

The most straightforward cavitation inception test is concerned only with the prediction of the onset of cavitation for conditions identical with those of the test. Examples of this simple form of prediction are sea tests of ship propellers, full-scale tests of turbines, and self-propelled full-scale tests of torpedoes. Such tests give the desired answer directly, without requiring any assumptions or additional information (except, perhaps, an understanding of exactly what constitutes "identical" conditions).

In the more general cavitation inception test, however, the results are used to predict the onset of cavitation for conditions which may differ considerably from those of the test. For example, an observation made on a model submarine propeller in a water tunnel containing water at some specific test pressure, temperature, and air content,may be used to predict the onset of cavitation on a large prototype propeller at various submergences in the sea.

In order that such a prediction may be possible, a rule of similitude must be known indicating how the inception speed varies with the scale, the static pressure, etc. According to elementary theory, cavitation occurs whenever the local pressure drops to the vapor pressure of the water, so that the inception speed for a given shape of body or propeller depends only on the static pressure and the vapor pressure. The variation of inception speed with these pressure variables is conventionally taken into account by expressing the test results in terms of a dimensionless cavitation number K, defined as

$$K = \frac{P_0 - P_v}{\frac{1}{2}\rho\, U_0^2}$$

where P_0 is the free-stream static pressure,

P_v is the vapor pressure,

ρ is the water density, and

U_0 is the free-stream velocity of flow.

According to the elementary theory, the onset of cavitation occurs at a critical cavitation number K_c whose value is a characteristic of the cavitating shape and does not depend on either the scale or the static pressure.

However, comparisons between model and prototype made in the past decade have indicated, on the contrary, that the cavitation number K_c at inception does indeed vary with the scale and test pressure. In general, the prototype cavitates at a higher cavitation number, i.e., at a lower speed, than does the model. Furthermore, the cavitation number at inception decreases with decreasing test pressure.

The reasons for this failure of the critical cavitation number to remain constant are only now beginning to be understood. In this report certain of these reasons, associated with the behavior of the water itself, will be discussed. Before entering this discussion, however, it may be useful to review the conventional derivation of the law of similitude for cavitation onset in order to indicate explicitly the basic assumptions involved.

THE LAW OF SIMILITUDE FOR CAVITATION INCEPTION

Three assumptions are required for the derivation of the scaling law for the inception of cavitation. They are:*

1. The flow maintains geometric similarity, i.e., the ratio of the velocity at any two points in the flow is fixed. In particular, if U_1 is the velocity at some point in the flow near or on the body or propeller, and U_0 is the free-stream velocity, then the ratio

$$\frac{U_1}{U_0} = a$$

is constant and independent of the scale, the magnitude of U_0, and the static pressure.

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*This analysis follows that given by Schlaifer in his thought-provoking albeit caustic commentary on Numachi's early cavitation experiments.[1]

[1] References are listed on page 23.

2. The flow is steady and friction losses are negligible, so that Bernoulli's law may be used to relate the velocities with the pressures. Accordingly, if P_1 is the static pressure at the same point in the flow, and P_0 is the free-stream static pressure, then

$$P_1 + \frac{1}{2}\rho U_1^2 = P_0 + \frac{1}{2}\rho U_0^2$$

so that

$$P_1 = P_0 + \frac{1}{2}\rho U_0^2 (1-a^2) \qquad [1]$$

Since $(P_1 - P_0) / \frac{1}{2}\rho U_0^2$ defines a pressure coefficient C_p , Equation [1] can be rewritten as

$$C_p = \frac{P_1 - P_0}{\frac{1}{2}\rho U_0^2} = (1 - a^2) \qquad [2]$$

Accordingly, assumptions 1 and 2 can be combined into the single assumption that the value of the pressure coefficient at any point in the flow is independent of the scale, the free-stream velocity, or the pressure.

3. Cavitation will occur at any point in the flow where the static pressure falls to the vapor pressure P_v of the water. If P_1 is chosen at the point of lowest pressure, where the pressure coefficient is $C_{\min}$, cavitation begins when P_1 equals P_v. By substituting P_v for P_1 in Equation [2], the following relation is obtained:

$$\frac{P_0 - P_v}{\frac{1}{2}\rho U_0^2} = -C_{\min} \qquad [3]$$

The ratio at the left is the conventional cavitation number K. Equation [3] expresses the rule that at cavitation inception, the cavitation number equals the negative of the most negative value of the pressure coefficient in the flow.

The extent to which the rule is obeyed depends on the degree to which the three assumptions are obeyed in any real flow. The first two assumptions, or their combination represented by Equation [2], are common to most model testing and are not at all limited to cavitation measurements. They imply that Reynolds-number effects do not exist. Their validity may be estimated by determining how nearly independent of Reynolds number are the coefficients of pressure, drag, or thrust (measured under noncavitating conditions at high free-stream pressure). Unfortunately, under certain conditions cavitation inception may be more sensitive to a change of Reynolds number than are these coefficients. For example, some theoretical calculations indicate that tip-vortex cavitation on a propeller should be much more dependent on the Reynolds number than is the thrust coefficient.[2] Some experimental data indicate that body cavitation may be very sensitive to the thickness of the boundary layer.[3] Accordingly, it may not always be possible to estimate, from measurements of pressure or force coefficients, how nearly the first two assumptions are satisfied with respect to cavitation.

The third assumption, that cavitation occurs at vapor pressure, is peculiar to cavitation tests. This assumption may intuitively seem to be quite reasonable and, in fact, some early experiments seemed to verify it.[4,5]

However, it is now generally recognized that the pressure at which cavitation occurs is variable. Indeed, under certain conditions, particularly those found in water tunnels, inception may require a negative pressure or tension.[6,7]

If the inception pressure had a fixed critical value for any given batch of water, this fixed value, even though different from vapor pressure, could be substituted for the vapor pressure in the statement of assumption 3 above, and a relation similar to Equation [3] obtained with this fixed critical pressure P_c in place of P_v. If a modified cavitation number were defined with P_c instead of P_v, then the law of similitude would be that the modified cavitation number

$$\frac{P_0 - P_c}{\frac{1}{2}\rho U_0^2}$$

is constant at cavitation inception. For example, in some observations on the onset of tip-vortex cavitation on a propeller, it was found that if a modified cavitation number was defined with P_c equal to -7 feet of water, then this modified index remained constant at cavitation inception over a wide range of test pressures.[8] For this reason it is of interest to determine if the critical pressure P_c does have a fixed value for any batch of water, and to determine what factors cause the value to change.

Measurements of the pressure at which vapor cavities form in water have been made under static conditions by applying a steady suction or tension to undisturbed water. Such measurements have resulted in an amazing range of values, ranging from vapor pressure to minus 300 atmospheres. On the other hand, theoretical estimates of the physicists, based on calculations of the inherent strength of water, predict even more negative pressures of from -500 to $-10{,}000$ atmospheres for inception.* However, such large negative values have never been observed experimentally.

To explain why the measured inception pressures are so variable, and always less negative than the theoretical values, it has been postulated that cavitation starts on microscopic nonhomegeneities or nuclei in the water.[10] The nuclei are generally assumed to be

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*A comprehensive review of the various measurements and theoretical estimates of the pressure required for cavitation is given by Blake.[9]

undissolved air cavities whose sizes range from 10^{-3} to 10^{-5} inches. The cavitation process is considered to be the growth of these air-filled nuclei to visible size. The variation of the inception pressure is attributed to variations in the size of these nuclei.

THE ROLE OF NUCLEI

The need for nuclei in a cavitation process may be illustrated by the following simple analysis. Consider a spherical bubble in a body of water. The pressure inside the bubble is larger than the pressure in the water near the bubble because the surface film around the bubble tends to contract like an inflated rubber balloon. If the internal and external pressures are P_i and P_e respectively, then the balance of static pressure requires that

$$P_e = P_i - \frac{2\sigma}{R_0} \qquad [4]$$

where σ is the surface tension and R_0 is the bubble radius.

If the bubble consists of water vapor, the pressure inside the bubble must equal the vapor pressure P_v. Accordingly, the conditions on the external pressure that the bubble grow is

$$P_e \leq P_v - \frac{2\sigma}{R_0} \qquad [5]$$

Before the cavity grows, it must first form. At formation, the cavity radius will be very small, so that the external pressure P_0 must be very negative. For example, if R_0 at formation is 10^{-7} cm, which is several times larger than molecular dimensions, P_0 must be about -1500 atmospheres to cause growth. Only if relatively large bubbles, larger than 0.01 cm, already exist in the water will bubble growth occur at positive external pressures.

AIR-FILLED NUCLEI

A nucleus can grow to visible size in two ways: (1) by the relatively slow diffusion of dissolved air out of the water into the nucleus, or (2) by its sudden explosive expansion into a large cavity. The slow growth by diffusion results in a permanent bubble filled primarily with air, and is accordingly called ''gaseous cavitation.'' The sudden explosive expansion, on the other hand, results in a cavity filled primarily with water vapor, since diffusion of air cannot keep up with the expansion, and is accordingly called ''vaporous cavitation.'' In vaporous cavitation, the cavities collapse and disappear due to condensation of the water vapor after leaving the low-pressure cavitating region, although sometimes a small air bubble may be left behind, as a result of the diffusion of some air into the vapor cavity during its short life.[11]

The simplest form of air-filled nuclei are simply small free bubbles of undissolved air. Photographs of bubbles acting as nuclei for cavitation have been published by Daily and Johnson.[12] For such bubbles, it is possible to estimate theoretically the critical pressure for the onset of either vaporous or gaseous cavitation.

VAPOROUS CAVITATION

The critical pressure for vaporous cavitation was first calculated by Blake[13] using the requirement that the pressure inside and outside the bubble be in static equilibrium. This equilibrium is expressed by Equation [4] previously discussed, but with P_i now equal to P_v plus the air pressure P_g. It is possible to show that for a bubble containing a fixed amount of air, a minimum external pressure exists below which static equilibrium can not be maintained. If the external pressure is reduced below this value, the bubble becomes unstable and grows without limit. This value is accordingly the critical pressure for the onset of vaporous cavitation.

The critical pressure is given by

$$P_c = P_v - \frac{2}{9}\sqrt{3}\left[\frac{2\sigma}{R_0}\right]\left[1 + (P_0 - P_v)\frac{R_0}{2\sigma}\right]^{-1/2} \qquad [6]$$

where R_0 is the original radius of the bubble at an external water pressure P_0. As R_0 becomes larger, the critical pressure approaches, but never exceeds, the vapor pressure. If R_0 is small enough, smaller than about 10^{-3}cm, the critical pressure is negative.

The derivation of Equation [6] assumes that inertial or other time-dependent factors do not influence the growth of the bubble. Accordingly, the equation is rigorous only if all pressures are steady or quasi-static. However, in hydraulic cavitation the nucleus experiences a transient pressure reduction only for a short time as it moves through the cavitation zone. Intuitively it would seem that a transient reduction would be less effective than a quasi-static reduction in causing instability; however, this turns out to be incorrect, for conventional conditions.

The influence of time-dependent factors on bubble growth can be investigated by reviewing the results of Noltingk and Neppiras,[14] who solved the differential equation for the growth of an air bubble due to a fluctuating pressure $p(t)$:

$$\rho\left(R\ddot{R} + \frac{3}{2}\dot{R}^2\right) - \left(P_0 - P_v + \frac{2\sigma}{R_0}\right)\left(\frac{R_0}{R}\right)^3 + \frac{2\sigma}{R} = P_v - p(t) \qquad [7]$$

with $p(t)$ as one cycle of a negative sine function. Although this function was chosen to represent the pressure of a sound wave, it is similar to that experienced by a bubble passing a cylinder or sphere. In the equation, R is the instantaneous radius of the bubble and the dots indicate derivatives with respect to time.

The solutions of the differential equation can be represented by plotting the maximum size of the growing bubble as a function of the magnitude of $p(t)$, for some initial bubble size. Such a plot has a sudden break at a particular critical pressure; if $p(t)$ never drops to this value, the bubble does not change size appreciably, but if $p(t)$ falls even momentarily below the critical value, the bubble grows to many times its initial size.

The critical pressure obtained from such a plot agrees quite well with the value calculated from the quasi-static Equation [6]. This is an important result, for it indicates that the onset of vaporous cavitation does not depend on the duration of the transient pressure.*

The duration of the transient does, however, influence the maximum size to which the bubble grows. The maximum size is given by the approximate relation

$$R_{\max} = bT_x\left(\frac{\Delta p}{p}\right)^{1/2} \qquad [8]$$

where Δp is the peak positive value of $P_v - p(t)$,

T_x is the time that $P_v - p(t)$ is positive, and

b is a numerical constant whose value depends on the way the pressure around the bubble changes as the bubble moves through the cavitation zone.

Comparison of this simple expression with measured and calculated values of $R_{\max}$ for conventional pressure fields,[14,15] indicated that if b is set equal to unity, the values of $R_{\max}$ will be accurate to 50 percent. The maximum size thus depends on the duration of the transient but not significantly on the nucleus size; whereas the critical pressure, determining whether the bubble starts to grow at all, depends on the nucleus size but not on the duration of the transient.

In another investigation[16] of the effect of time, based on Equation [7], the "onset" of cavitation is defined to be bubble growth to the particular radius of 0.1 cm. With such a criterion time effects would, of course, exist in accordance with Equation [8]. However, the previous definition of critical pressure based on bubble instability appears to be more fundamental. With the alternate definition, there does not seem to be any basis for choosing some arbitrary maximum bubble size; particularly for bodies of different dimensions.

It has been suggested in the past that the time required for bubble growth will cause the onset of cavitation to depart from the conventional law of similarity discussed on page 2.

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*This result is valid only within certain limits, of course. The limit set by Noltingk and Neppiras is that the duration of the transient must be longer than the natural period of oscillation of the nucleus bubble. The natural period T_0 of an air bubble in water is given by the numerical relation $T_0/R_0 = 3 \times 10^{-3}$ sec/cm. For example, a bubble nucleus of radius 10^{-3} cm has a natural period of 3 microseconds, and smaller nuclei have even shorter periods. Accordingly, cavitation on nuclei no larger than 10^{-3} cm should not depend on the duration of the transient, provided it last at least 3 microseconds.

According to the argument, at higher speeds less time is available for growth, thus causing a departure from similarity. However, Equation [8] can be used to show that this argument is fallacious. On the contrary, the time changes by just the correct amount to maintain similarity. The time T_x in Equation [8] may be expressed as L/U_0, where L is a characteristic length of the body and U_0 is the free-stream velocity. The most negative value of $p(t)$ can be expressed as

$$[p(t)]_{\min} = P_0 + \frac{1}{2}\rho U_0^2 C_{\min}$$

where $C_{\min}$ is the most-negative pressure coefficient in the flow. Then the maximum size of the cavitating bubble is given by

$$R_{\max} = \frac{L}{U_0}\left[\frac{P_v - P_0 - \frac{1}{2}\rho U_0^2 C_{\min}}{\rho}\right]^{½}$$

which can be rewritten in terms of the conventional cavitation number K as

$$\frac{R_{\max}}{L} = \left[-\frac{1}{2}(K + C_{\min})\right]^{½} \qquad [9]$$

(Note that $C_{\min}$ is negative). Accordingly, at any given cavitation number the cavity will grow to a fixed proportion of the body dimension L. Similitude is thus maintained, at least to the extent that Equation [8] is valid.

GASEOUS CAVITATION

It has already been mentioned that cavitation need not be of the vaporous type, but under certain circumstances gaseous cavitation can occur by diffusion of air into the nucleus bubble. The two types differ significantly in appearance. Vaporous cavitation results in the sudden and intermittent formation of transient cavities which either disappear completely or leave tiny air bubbles much smaller than the original transient cavities. Gaseous cavitation, on the other hand, results in permanent air bubbles which grow slowly until they are carried by the flow out of the cavitation region.

Blake[13] showed that the oscillating pressure of a sound wave can cause diffusion of air into a bubble by a process which he called "rectified diffusion." This is not generally of interest in hydraulic cavitation, and will not be discussed here, except to mention that it is a possible mechanism for the slow growth of bubbles in a highly turbulent region, where the large-amplitude pressure fluctuations may act like sound pressures and cause rectified diffusion. In steady hydraulic flows, or flows without excessive turbulence, only steady diffusion need be considered.

The condition for steady diffusion of dissolved air out of water is simply that the water should be in contact with air at a lower pressure than the equilibrium or saturation pressure for the air dissolved in the water. However, growth by diffusion is relatively slow. Even if the water is supersaturated by a factor of ten at the existing static pressure, about 0.15 second is required for growth of a nucleus to 10^{-3} cm, and about 15 seconds for growth to 10^{-2} cm (Reference 17).

In most hydraulic flows, bubbles moving with the water do not remain in low-pressure regions long enough for appreciable growth. However, if the bubble is trapped on a fixed boundary it can grow before being carried away by the flow.

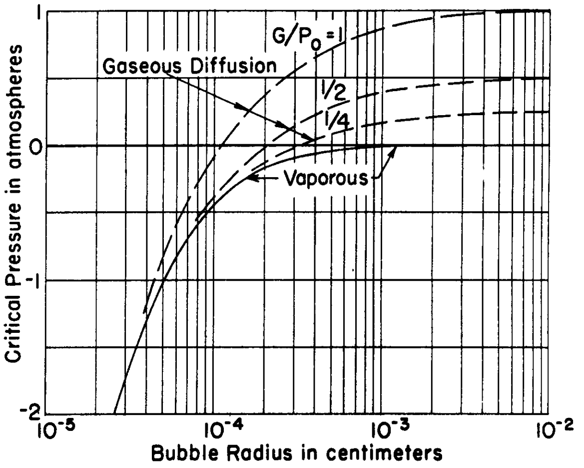

Figure 1 - The Critical Pressure for Gaseous and Vaporous Cavitation as a Function of the Radius of the Air-Filled Nucleus

The nucleus size is the size at atmospheric external pressure. The critical pressure is given relative to the vapor pressure. The three curves for gaseous cavitation are for three values of air content, the saturation pressure of the dissolved air being indicated on the curves.

If the bubbles are small, the surface tension increases the internal pressure sufficiently to prevent growth by diffusion, even if the external pressure is somewhat below the saturation pressure. Accordingly, the critical pressure for gaseous cavitation will be lower than the saturation pressure. The variation with nucleus size is shown in Figure 1 by the dashed lines, with the gas saturation pressure *G* as parameter.

For comparison, the critical pressure for vaporous cavitation is also shown in the figure, calculated from Equation [6]. If the bubbles are small enough, both gaseous and vaporous cavitation require negative pressures of about equal magnitude. For the larger nuclei, gaseous cavitation can occur at pressures above the vapor pressure, provided, of course, that the bubble is at the required pressure long enough to accommodate the slow diffusion process. Vaporous cavitation, in contrast, always requires pressures below vapor pressure, but the growth is rapid. Although the critical pressure for gaseous cavitation varies with the equilibrium air pressure, the pressure for vaporous cavitation is independent of dissolved air (except insofar as the dissolved air may influence the size of the nucleus bubbles).

Photographs of cavities growing rapidly by vaporous cavitation are now quite common, those of Knapp and Hollander [18] being typical. More recently, Parkin and Kermeen[3] obtained some photographs showing the slow growth typical of gaseous cavitation, the bubbles being trapped in the boundary layer on a surface.

VAPOROUS-GASEOUS INTERACTION

So far, the onset of vaporous and gaseous cavitation have been treated as independent, either one or the other occurring. However, the phenomenon can be complicated by an interaction between the two forms. It is possible that a nucleus originally too small to undergo vaporous cavitation at the existing pressure could nevertheless grow by gas diffusion until it became large enough to go into vaporous cavitation.[19] For example, suppose a nucleus bubble of radius 10^{-4} cm moved through a zone where the most-negative pressure was −0.2 atmosphere. Referring to Figure 1, it is seen that this pressure is not sufficiently negative to cause vaporous cavitation. However, the existing pressure *is* sufficiently negative to cause gaseous diffusion. If the bubble remained at the pressure long enough, it would grow by diffusion until it reached a size of about 2×10^{-4} cm, at which point it would burst into vaporous cavitation.

Since time is required for diffusion, it is of interest to estimate how the reduction in the critical pressure for cavitation depends on the time available for growth of the nucleus. The calculation is outlined in Appendix A, and only the result will be given here. Consider a nucleus originally of such a size that its critical pressure for vaporous cavitation is P_c, moving through a zone where the local pressure P is too high for vaporous cavitation. The time required for the nucleus to grow sufficiently so that it will cavitate at the existing pressure P is given in Table 1 for two values of the equilibrium pressure G of the dissolved air in the water. The time is expressed in terms of the product TP^2, and also directly in terms of the time T for specific values of G and P.

TABLE 1

Growth Time Required for a Decrease of Critical Pressure for Vaporous Cavitation Associated with Air Diffusion

P_c/P	TP^2 in sec-atm^2		T in millisec for $G = 1$ atm	
	$G/P = 4$	$G/P = 8$	$P = -1/4$ atm	$P = -1/8$ atm
1.01	4.5×10^{-5}	2.0×10^{-5}	0.7	1.3
1.05	1.8×10^{-4}	8.1×10^{-5}	2.9	5.2
1.4	1.4×10^{-3}	5.6×10^{-4}	22	36
1.7	2.5×10^{-3}	8.5×10^{-4}	40	54
2.1		1.3×10^{-3}		83

The table indicates, referring to the last column for example, that if a nucleus originally requiring a pressure of −0.175 atm remained in a region where the local pressure was −0.125 atm, it would break into vaporous cavitation after about 36 millisec. At a velocity of 30 ft/sec, such a growth time corresponds to a growth distance of nearly 1 foot. Accordingly, in a large cavitation zone such as exists on a ship propeller, diffusion growth may cause the inception pressure to change appreciably. On a small model, however, the nucleus would not remain in the cavitation zone long enough for any significant change.

Accordingly, the growth of nuclei by diffusion may be a cause of the scale effect for the onset of cavitation.

THE SIZE OF THE NUCLEUS AIR BUBBLES

The postulate of air bubbles as nuclei thus permits calculation of the thresholds for either vaporous or gaseous cavitation as a function of the size of the nucleus bubbles. However, it is not yet clear what determines their size.

In water standing undisturbed, such as water in a towing tank or in the depths of the sea, air bubbles are unstable and tend to disappear, either by dissolving or by rising to the surface.[20] An air bubble of radius 10^{-3} cm dissolves in only about 8 seconds in air-saturated water; solution is even faster if the bubble is smaller or the water undersaturated.[17] On the other hand, bubbles existing in supersaturated water will grow by diffusion of air, and rise to the surface as they grow. Accordingly, if bubbles are to persist in water, it is necessary that new bubbles be formed continuously, or else some mechanism must prevent them from dissolving or rising.

In circulating hydraulic systems, several mechanisms may prevent bubbles from disappearing. Bubbles trapped on the walls can be swept into the main stream and recirculated. The flow itself, or eddies associated with the flow, can prevent bubbles from ever reaching the surface. If a free surface is present, as in an open-section water tunnel or in a water channel, surface disturbances can entrain new bubbles. Cavitation can generate new bubbles which, upon recirculation, act as nuclei for additional cavitation. In such systems, a complicated equilibrium will exist between the various mechanisms forming and removing bubbles. The size and quantity of the existing bubbles depends on this equilibrium.

However, if the water is undersaturated with air, none of these mechanisms can prevent the bubbles from dissolving. Since solution occurs relatively fast, it is unlikely that new bubbles could be generated as fast as they dissolve. This would be especially true in a water tunnel with a resorber, or in the depths of the sea where, despite the greater static pressure, the water contains only enough air to be saturated at the surface. Accordingly, it would seem that undersaturated water should be completely free of air bubbles.

Nevertheless, cavitation certainly does occur in undersaturated water, indicating that nuclei are indeed present. Moreover, there is convincing evidence that the nuclei contain air. Among the evidence may be cited Crump's measurements[6] showing that the inception pressure for cavitation in a venturi varies with air content, and some measurements of acoustically induced cavitation to be described subsequently. Perhaps the most convincing evidence is the demonstration of Harvey et al[10] that water can not be made to cavitate after it is temporarily subjected to a high pressure; the only explanation of this phenomenon is that the air nuclei are removed as the high pressure forces them into solution.

Accordingly, cavitation theory is faced with the following dilemma: the results of measurements and theory indicate the presence of undissolved air nuclei in undersaturated water, yet diffusion theory indicates that such nuclei should spontaneously disappear by dissolving in the water.

STABILIZED AIR CAVITIES

To resolve this dilemma, some explanation must be found for the failure of the air cavities to dissolve in undersaturated water. Two alternate mechanisms have been suggested. Harvey et al[10] postulated that the air is trapped in cracks on the surface of solid particles suspended in the water. More recently, Fox and Herzfeld[21] have suggested that solution does not occur because the bubbles are surrounded by a skin of organic impurities existing in the water.

The trapping of air in a crack requires that the crack wall be "hydrophobic", i.e., not wetted by water. If, on the contrary, the wall were wetted, water would creep into the crack and displace the air. If the wall is not wetted, the angle of contact between the water and the wall is larger than 90 degrees, measured through the water, so that the air-water interface is concave on the water side. Accordingly, the surface-tension pressure is directed toward the water, so that the pressure in the trapped air is lower than the pressure in the water. The trapped air can then be in diffusion equilibrium with the air dissolved in the water even if the water is undersaturated at the ambient water pressure.

The organic skin is another mechanism by which the air pressure inside the bubble can be maintained below the ambient water pressure, thus maintaining diffusion equilibrium in undersaturated water. A skin surrounding a bubble may act like a rigid spherical shell supporting the pressure difference. If the water is saturated at a pressure below the ambient pressure, air diffuses out of the bubble through the skin. Because the skin is relatively rigid, the bubble maintains its size as the internal air pressure drops. When the internal pressure drops to the saturation value, diffusion equilibrium is established and no more air dissolves. There is experimental evidence that mono-molecular skins of organic impurities form spontaneously on air-water interfaces; such skins may also form around bubbles.

With either of the mechanisms, it is possible to calculate the critical pressure for vaporous cavitation as a function of the ambient pressure and the air content of the water. Surprisingly, the functional relationships are of the same form for both mechanisms, despite the difference in the physical processes involved. A characteristic dimension of the air cavity turns out to be inversely proportional to the difference between the maximum external pressure to which the cavity has been subjected and the saturation air pressure. The critical pressure for cavitation can be shown to be[22]

$$P_c = a_1 G - a_2 P_m \qquad [10]$$

where G is the equilibrium or saturation pressure of the air dissolved in the water,

P_m is the maximum external water pressure to which the cavity has been subjected, and

a_1 and a_2 are numerical constants, whose values cannot be determined with present knowledge, except that $a_2 + 1 > a_1 > a_2 > 1$.

Equation [10] indicates that the critical pressure should decrease linearly with decreasing equilibrium air pressure. The only external pressure influencing the critical pressure is the maximum pressure to which the cavity has been subjected. This "memory" for past high pressure is the pressurizing effect observed by Harvey et al.[10]

These theoretical deductions have been given some support by some measurements performed by the author on cavitation inception induced by ultrasonics. The paper will be concluded with a brief description of these results, not only to support Equation [10], but also to indicate the convenience and utility of ultrasonic equipment for the investigation of cavitation nuclei.

INVESTIGATION OF AIR NUCLEI WITH ULTRASONICS*

The experimental investigation had two objectives:

1. To detect, by means of ultrasonics, undissolved air cavities in the water.
2. To determine the critical pressure for vaporous cavitation in undisturbed water as a function of its air content and the static pressure.

A complete description of the experiment and the apparatus is given elsewhere.[22] In this paper, those results of interest in the study of hydraulic cavitation will be summarized.

DETECTION OF AIR CAVITIES

Air cavities in water absorb sound energy, and it is this property that is used to detect them. When an air cavity is in a sound field, the cavity pulsates in response to the sound pressure. The resulting expansion and contraction of the air converts some of the sound energy into heat. This occurs whether the cavities are bubbles or air trapped in cracks.

The amount of absorption of a body of water containing air cavities may be determined by putting some sound energy into the water and measuring the rate at which sound energy decays, i.e., by observing the reverberation decay. The principle of the method may be illustrated by a simple experiment. If a glass of water is tapped, it will ring with a clear tone of perhaps one-second duration. If bubbles are now formed in the water by inserting an "Alka-Seltzer" tablet, tapping will only result in a dull thud. The difference is due to the absorption of the sound energy by the bubbles. This principle, in refined form, is utilized in our apparatus.

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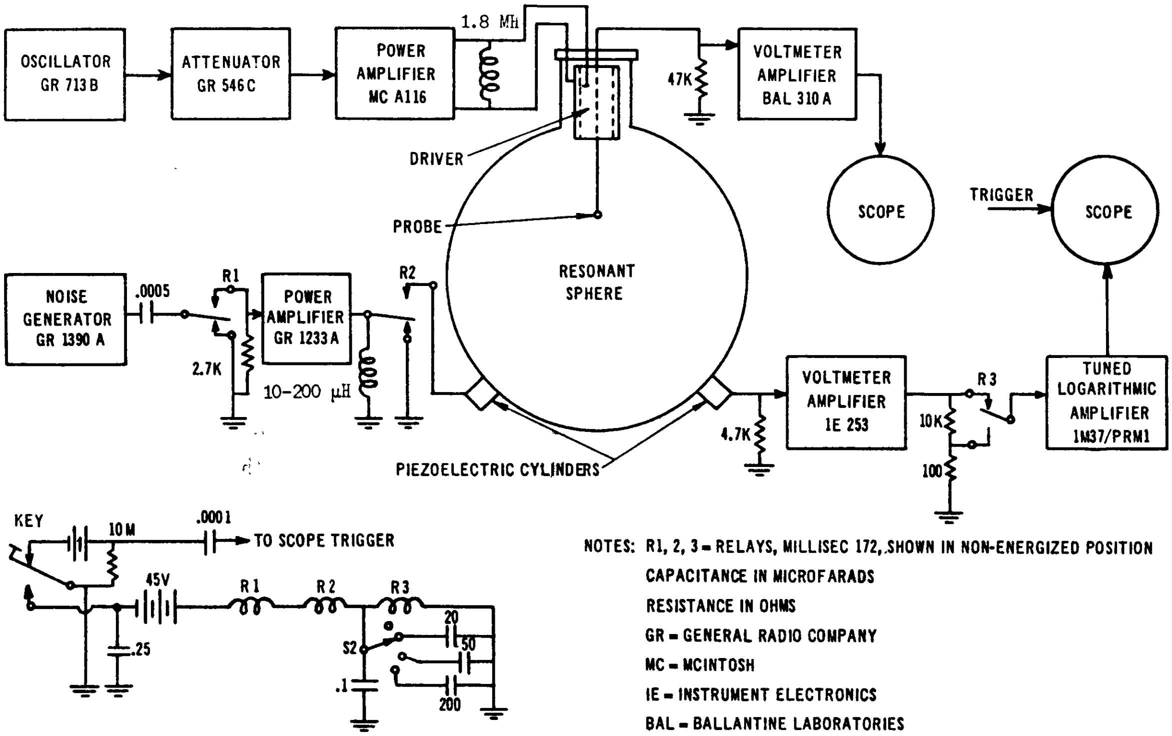
*These measurements were performed in partial fulfillment of the requirements for the Ph.D. at the Catholic University of America.



NOTES: R1, 2, 3 - RELAYS, MILLISEC 172, SHOWN IN NON-ENERGIZED POSITION
CAPACITANCE IN MICROFARADS
RESISTANCE IN OHMS
GR - GENERAL RADIO COMPANY
MC - MCINTOSH
IE - INSTRUMENT ELECTRONICS
BAL - BALLANTINE LABORATORIES
1M37/PRM1 IS A U.S. NAVY RADIO INTERFERENCE FIELD INTENSITY METER. MODIFIED SOMEWHAT.

Figure 2 - Block Diagram of the Electronic Equipment for Ultrasonic Cavitation Measurements

The lower portion shows the equipment for detecting air bubbles in the water, whereas the upper line shows the equipment for causing cavitation with high-intensity ultrasonics.

Our equipment is shown schematically in Figure 2. The water sample is contained in a 12-liter spherical Pyrex flask about 12 inches in diameter. Two small piezoelectric ceramic cylinders, ¼-inch diameter and ¼-inch long are cemented to the outer wall of the sphere. One of these cylinders acts as the sound source and is supplied with electrical random noise from a noise generator and power amplifier. The second piezoelectric cylinder acts as sound receiver. Its output is amplified, passed through an attenuator and then rectified into a DC signal by a tuned logarithmic amplifier. The DC output of this amplifier, which is proportional to the logarithm of the AC voltage from the sound receiver, is observed as a trace on a DC cathode-ray oscilloscope. Three relay switches are arranged in the circuit so that depressing a hand key turns on the noise signal to the sound source and inserts attenuation into the receiving circuit. Releasing the key cuts off the noise source, triggers the horizontal time base of the oscilloscope and, after an adjustable time delay, removes the attenuation from the receiving circuit. When the key is released, the resulting display on the scope shows the

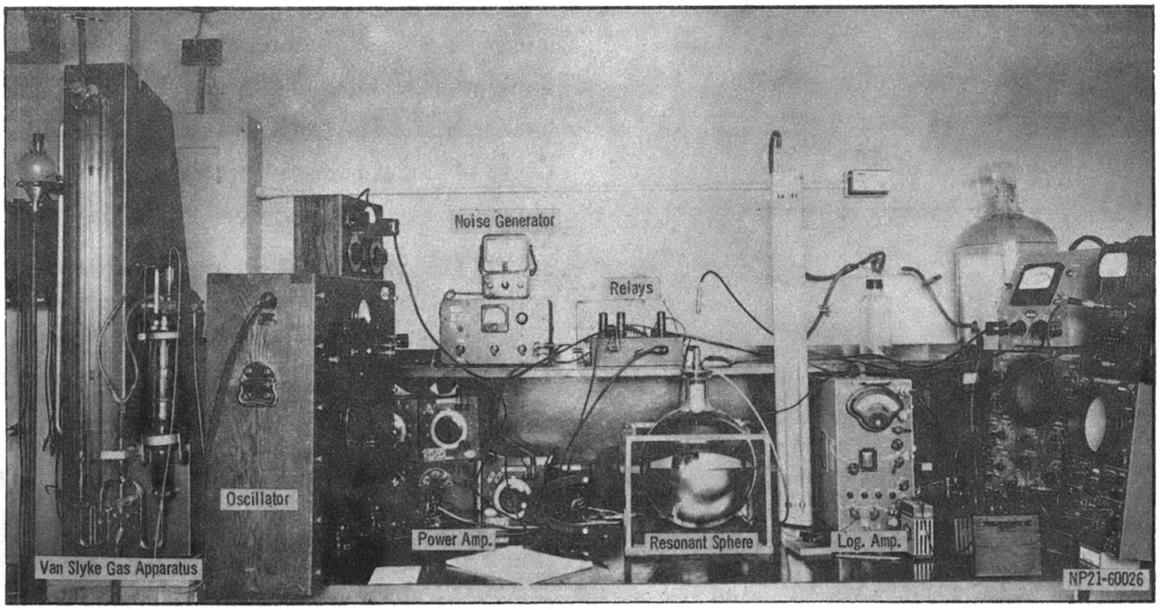


Figure 3 - Apparatus for Ultrasonic Cavitation Measurements

decay of the sound in the sphere. Since the sound decays exponentially with time, the logarithm of the sound amplitude falls linearly with time, so that the logarithmic amplifier provides a decay trace on the scope which is approximately a straight line. The decay rate is given by the slope of the trace, in terms of the known sweep rate of the horizontal time base and the known logarithmic sensitivity of the vertical axis. A photograph of the apparatus appears as Figure 3.

Absorption of sound at a given sound frequency is associated primarily with bubbles which resonate near that frequency. The resonant frequency f_r of an air bubble in water is given by the numerical relation

$$f_r R = 330 \text{ cm/sec} \qquad [11]$$

where R is the bubble radius. Accordingly, by varying the frequency it is possible to detect bubbles of different sizes. The rate of sound decay caused by gas bubbles resonating at a frequency f_r is given by the approximate numerical relation

$$d_r = 10^{14} N_r / f_r^2 \qquad [12]$$

where f_r is the frequency in c/sec, and N_r is the number of bubbles per cm^3 resonating in the frequency range $1/2\ f_r$ to $3/2\ f_r$. The decay rate d_r is in decibels per second, an increment of 10 decibels corresponding to a factor of 10 in sound energy; e.g., 50 decibels per second means that the energy drops to 10^{-5} of its original value in a second.

Sound decay is caused in the apparatus not only by bubbles but also by sound absorption inherent to the water itself and in the walls of the sphere. Accordingly, the total decay

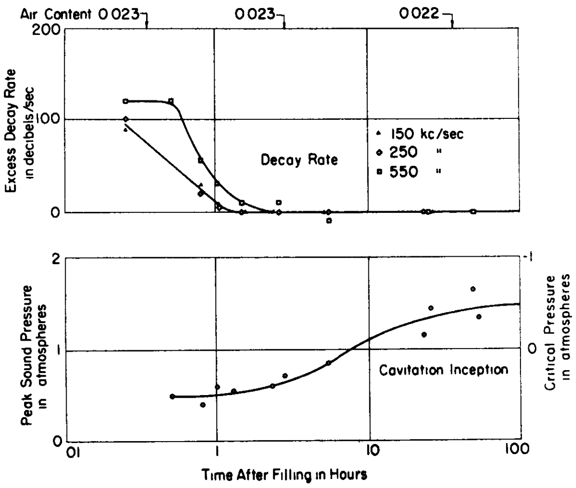


Figure 4 - The Decay Rate and the Inception Pressure for Ultrasonic Cavitation, as a Function of the Time after Filling the Sphere with Fresh Tap Water

rate d is equal to $(d_r + d_0)$, where d_0 is the minimum or background decay rate of the apparatus in the absence of bubbles. This background decay sets a limit to the sensitivity of the apparatus for detection of bubbles. The background decay may vary erratically from day to day by as much as 10 percent. To detect bubbles with certainty, enough bubbles must be present to increase the decay rate by a substantial amount, say by 25 percent over the average background rate. The number of bubbles which will cause such an increase can be estimated by equating d_r in Equation [12] to 1/4 d_0. Accordingly, the minimum detectable number of bubbles, or threshold of detectability, is given by

$$(N_r)_{\min} = 2.5 \times 10^{-15} f_r 2d_0 = 3 \times 10^{-10} \frac{d_0}{R^2} \qquad [13]$$

where again N_r is the number of bubbles per cm^3 with radii ranging from 1/2 to 3/2 R, R being in cm, and f_r is the resonant frequency of the bubble in centimeters per second. If fewer bubbles are present than the quantity given by Equation [13], they will not be detected.

For the present measurements, tap water is drawn directly from the city supply into a spherical flask about 12 inches in diameter. The decay measurements are made as the water stands undisturbed in the flask. Results of a typical set of measurements on a sample of supersaturated water are shown in the upper portion of Figure 4, where the excess decay rate $(d - d_0)$ at several sound frequencies is plotted against the time after filling.

After one or several hours, depending on the sample, the decay rate falls to the minimum value detectable by the apparatus. This means that the content of air cavities has become too small to be detectable. The minimum detectable number of cavities N_r and volume concentration V_r, calculated from Equation [13] and the measured values of the background decay rate d_0, are indicated in Table 2 for several sound frequencies. Also shown is the radius of each cavity, assuming it is a spherical bubble (or its "equivalent radius" if it is not spherical, such as air in a crack).

TABLE 2

Thresholds of Detection for Air Bubbles

Frequency kc/sec	Background Decay Rate db/sec	Resonant Radius R_r 10^{-3} cm	N_r* cm^{-3}	V_r**
150	20	2.4	0.001	5×10^{-11}
250	40	1.4	0.005	7×10^{-11}
550	200	0.6	0.2	1.4×10^{-10}

*N_r is the number of bubbles with radii ranging from 1/2 to 3/2 R_r per cm^3 of water.

**V_r is the volume at normal temperature and pressure (NTP) of bubbles in the same size range as for N_r per unit volume of water.

Accordingly, it is possible to say that water which has been standing undisturbed for several hours contains fewer than one bubble per cm^3 with radii in the range 3×10^{-4} to 9×10^{-4} cm, and that the total volume of undissolved air in this size range is less than 2×10^{-10} cm^3 per cm^3 of water. This condition exists despite the fact that the water is supersaturated.

These results verify the conclusion reached on page 11 that bubbles should gradually disappear from undisturbed water by rising to the surface. However, it should be noted that extremely small bubbles, smaller than 3×10^{-4} cm and therefore not detectable by the apparatus, may still be present. Such tiny bubbles would take weeks to reach the surface if the water were not moving; thermal currents in the water may prevent them from ever drifting up. Indeed, the ultrasonic cavitation measurements to be described indicate that they are present.

MEASUREMENT OF CAVITATION INCEPTION PRESSURE

It is possible to cause cavitation of the water in the same spherical flask by setting up a high-intensity sound field. If the sound pressure has an amplitude p_s, the instantaneous total pressure is $P_0 + p_s \sin 2\pi ft$, where P_0 is the static pressure. If this oscillating pressure drops to the critical pressure P_c, cavitation occurs. Accordingly, the critical pressure is given in terms of the sound pressure at cavitation by the relation $P_c = P_0 - p_s$.

The sound field is generated by a large driver consisting of a 1½-inch diameter piezoelectric ceramic cylinder held in the neck of the spherical flask as indicated in the upper portion of Figure 2. The open bottom end of the driver cylinder projects below the water surface. The sphere is filled with water just to the neck, to keep the shape of the water as nearly spherical as possible. The driver receives its electrical power from a 30-watt power amplifier excited at a frequency of about 25 kc/sec by a controllable oscillator. This section of the equipment is similar to that used by Galloway[23] for cavitation studies.

By proper choice of the sound frequency, a sound field is generated with maximum sound pressure at the center. This has the advantage of causing cavitation only at the center of the sphere, away from any solid boundaries. The spherical body of water is highly resonant at these frequencies. The large amplification at resonance results in high sound pressures with relatively small electrical power.

The sound pressure in the water is measured with a sound probe. The probe consists of a tiny piezoelectric cylinder, 1/16 inch in diameter, at the end of a brass tube. The electrical output of the probe is measured with an electronic voltmeter and also observed on an oscilloscope. The sensitivity of the probe is known from a calibration performed by conventional acoustic techniques, so that its voltage output can be converted to sound pressure. The probe is not placed at the center of the sphere, for this would cause the cavitation to form on the probe rather than in the water. The probe is held several inches off center, and the indicated pressure at this point is multiplied by a correction factor to obtain the pressure in the cavitation zone at the center.

It may be well to consider how the value of critical pressure for ultrasonic cavitation is related to the critical pressure for hydraulic cavitation. In hydraulic cavitation the water is at a low pressure for a time which may vary from 1 to 100 milliseconds, depending on the velocity and the size of the cavitating region. In ultrasonic cavitation, on the other hand, the water is at low pressure for very short periods, which repeat periodically; at 25 kc/sec, for example, the low pressure exists for periods shorter than 0.012 milliseconds. However, as pointed out in the discussion of the time-dependent Equation [7], time durations of this order do not influence the onset of cavitation. Accordingly, the critical pressure for vaporous cavitation should be the same whether induced by ultrasonics or by a hydraulic flow.

Ultrasonics can also induce gaseous cavitation. However, ultrasonic gaseous cavitation is different from that associated with flow, so that the measured inception pressure for this form of ultrasonic cavitation has no significance for hydraulic cavitation.

The lower curve on Figure 4 shows how the sound pressure for the inception of cavitation increases as the water stands undisturbed for several days. The ordinate scale on the left is the measured sound pressure p_s, whereas the scale on the right is the critical pressure P_c calculated from $P_c = P_0 - p_s$. The gradual decrease in the critical pressure is believed to be associated with the gradual disappearance of the air nuclei as they rise to the surface. This is accompanied by a change from the gaseous to the vaporous form of cavitation.

Figure 5 shows the variation in the inception pressure with the air content of the water. The definite variation of inception pressure with air content indicates that the nuclei are not solid particles alone, but rather air cavities whose sizes depend in some way on the dissolved air content. The linear variation of inception pressure with air content, predicted by Equation [10], is verified by the data. The constant a_1, determined from the slope of the line, is approximately 4.

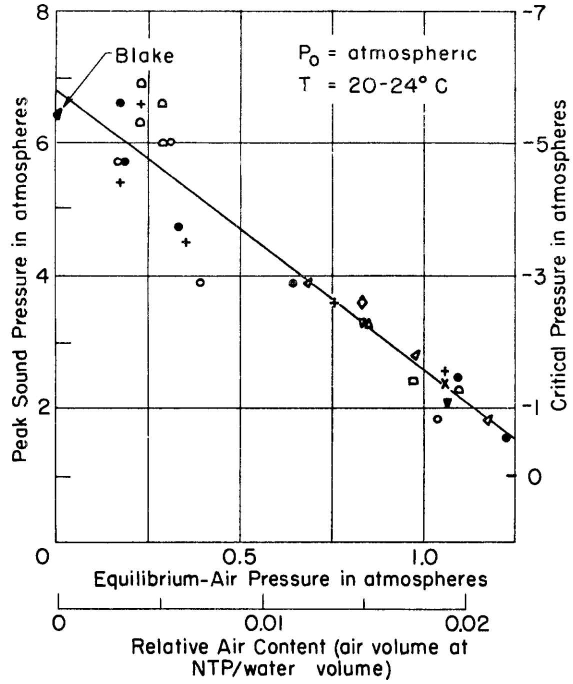


Figure 5 - The Effect of Air Content on the Inception Pressure for Ultrasonic Cavitation

Each plotted point represents the average of 10 to 20 measurements. Each symbol represents a different sample of water.

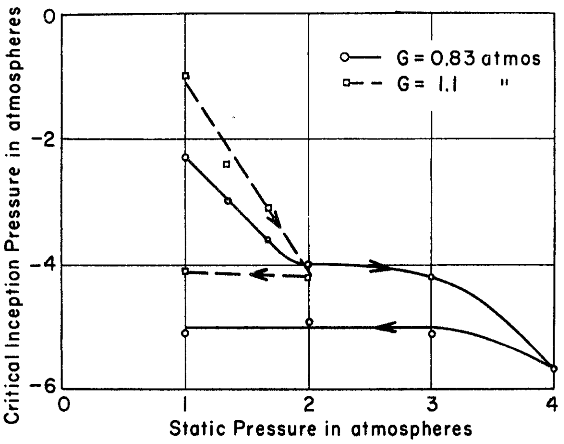


Figure 6 - The Variation of the Critical Inception Pressure with the Static Water Pressure

The arrows on the curves indicate the direction of the change in static pressure.

The variation of inception pressure with static pressure is shown in Figure 6 for several water samples. The arrows on the curves indicate the direction of the pressure change. The critical pressure becomes more negative as the static pressure is increased, but does not change appreciably when the pressure is reduced. Accordingly, the critical pressure depends only on the maximum static pressure to which the liquid has been subjected. This is the pressurizing effect predicted by Equation [10]. The constant a_2 has a value between 2 and 3.

These results indicate that the nuclei in undisturbed water seem to behave as predicted by the theory of stabilized air nuclei. Whether flowing water behaves in the same way is not yet known. To answer this question, it would be of interest to make these acoustical measurements in a stream of moving water.

For measurements in a stream of water, the spherical resonator could be replaced by a cylindrical resonator open at both ends. The water could then stream axially through the cylinder. The bubble detection and the onset of ultrasonic cavitation could be observed in the flowing water. Such a device might be useful for characterizing the water in a water tunnel.

CONCLUSIONS

It is now generally recognized that the onset of cavitation requires the presence of nuclei in the water. The nature and size of the nuclei determines the critical pressure for cavitation. Accordingly, certain scale effects in cavitation inception are associated with the nuclei.

Two fundamentally distinct forms of cavitation exist: gaseous cavitation involving the slow formation of permanent air bubbles by diffusion of dissolved air out of water, and vaporous cavitation involving the sudden and intermittent growth and collapse of cavities containing primarily water vapor. Vaporous cavitation is the more important type.

If the nuclei are simply free air bubbles, the critical pressure for either gaseous or vaporous cavitation can be calculated in straightforward fashion. For vaporous cavitation, the critical pressure is always below the vapor pressure of the water, and is negative for bubbles with radii smaller than about 10^{-3} cm. Accordingly, it would seem desirable that cavitation inception measurements be performed with water containing bubbles whose sizes range from 10^{-3} to 10^{-2} cm, in order to avoid negative inception pressures and associated scale effects.

If the water is undersaturated with air, or if the test is conducted in a water tunnel equipped with a resorber, free bubbles will dissolve and so cannot persist in the water. The nuclei in these cases are believed to be some form of stabilized air cavities. Two forms of stabilized cavities have been suggested: bubbles surrounded by mono-molecular skins of organic impurities, or air trapped in microscopic cracks on suspended solid particles. For either form of stabilized cavity, theory indicates that the inception pressure depends on both the dissolved-air content of the water and the maximum pressure to which the water is subjected. Accordingly, the maximum pressure in the resorber may be a significant parameter in cavitation tests.

Some cavitation inception measurements performed with ultrasonic apparatus seem to verify the theoretical predictions for the behavior of stabilized air nuclei. However, the measurements were made with undisturbed water, and it is not known if the nuclei in flowing water behave the same way. In fact, the behavior of nuclei is only partially understood, so that only tentative conclusions may be drawn at this time.

APPENDIX A

GROWTH BY GASEOUS DIFFUSION

If enough time is available, air-filled nuclei originally too small to burst into vaporous cavitation at the existing pressure may nevertheless grow by air diffusion until they become large enough. In this appendix, an approximate relation is obtained between the time available for growth by diffusion and the change in the critical pressure for vaporous cavitation resulting from the growth.

Consider a bubble initially of radius R_1 surrounded by water at a local pressure p. Assume that the pressure p is low enough to cause growth by gaseous diffusion, but not sufficiently negative to cause vaporous cavitation of the bubble. We ask the question: How much time is required for the bubble to grow from its original radius R_1 to the critical radius R_c for cavitation at the local pressure p?

First we note[14] that the critical radius R_c, at the water pressure p, for cavitation at this pressure is given by

$$R_c = -\frac{4\sigma}{3p} \tag{1}$$

Growth of a bubble by diffusion of gas can be approximated by the differential equation[17]

$$\frac{dR}{dt} = \frac{aD}{R} \cdot \frac{G - p - \frac{2\sigma}{R}}{p - \frac{4\sigma}{3R}} \tag{2}$$

where a is the solubility of the gas in the liquid, expressed as the ratio of the gas volume, measured at some pressure, to the volume of liquid saturated at the same pressure by that volume of gas,

D is the diffusivity of the gas in the liquid, and

G is the saturation pressure for the gas actually dissolved in the liquid.

For air in water at 25 deg C, $a = 0.017$ and $D = 2 \times 10^{-5}$ cm^2/sec. If the local water pressure p is assumed constant, Equation [2] can be integrated directly by separation of variables to give

$$t = \frac{16\sigma S}{27aDp^2}\left[(1-r)(1-r-2S) - 2S(1-S)\ln\left(\frac{1-S}{r-S}\right)\right] \tag{3}$$

where t is the time required for the bubble to grow by diffusion from initial radius R_1 to the critical radius R_c at the water pressure p, $r = R_1/R_c$, and $3/2S = 1 + (G/p)$.

A bubble of critical radius R_c will cavitate at the pressure p, whereas a smaller bubble, whose radius is R_1 at pressure p, will require a more negative pressure P_c to cavitate, where

$$P_c = -\left(\frac{2\sqrt{3}}{9}\right)\left(\frac{2\sigma}{R_1}\right)\left[1 - \left(\frac{pR_1}{2\sigma}\right)\right]^{-1/2} \tag{4}$$

which can be rewritten as

$$\frac{p}{P_c} = \sqrt{3r}\left[1 - \left(\frac{2r}{3}\right)\right]^{1/2} \qquad [5]$$

Equations [3] and [5] are simultaneous equations, with parameter r, giving the time required for a bubble, originally cavitating at pressure P_c, to grow to a size such that it will cavitate at the existing pressure p.

If the initial radius is not much smaller than the critical size, i.e., if $r \approx 1$, then the logarithm in Equation [3] can be replaced by the first two terms in its power-series expansion, and Equations [3] and [4] can be combined, leading to

$$t_p^2 \approx \frac{\left(\frac{8\sigma^2}{9aD}\right)}{\left(\frac{G}{-p}\right) - \frac{1}{2}} \left(1 - \frac{p}{P_c}\right) \qquad [6]$$

In several trial calculations, values of t calculated from this approximate expression were within 20 percent of the values given by Equations [3] and [4], provided $p/P_c > 0.8$. As a practical matter, there is probably little reason to use the more accurate expressions, since in a practical situation the bubble moves through a region of varying p during its growth.

For air bubbles in water at 25 deg C, the factor $8\sigma^2/9aD$ has the value 1.5×10^{-2} sec-atm^2.

Values calculated from Equation [3] are given in Table 1, page 10.

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The need for nuclei in the cavitation inception process is discussed. It is shown that the characteristics of the nuclei in the water determine the critical pressure for cavitation, and accordingly, that a variation in the nuclei content may introduce scale effects into tests of cavitation inception. Evidence is presented that the nuclei in water are cavities of undissolved air. The critical pressure for the onset of cavitation is given for several forms of air nuclei. It is shown that negative pressures are required for inception if the nuclei are small enough. Some

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2. Cavitation – Scale effects
3. Nuclei – Physical effects
4. Bubbles – Physical effects
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