CAVITATION AT THE SURFACE OF A SCREW PROPELLER*

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From the time that Rayleigh published his book on the hydraulic implosion that accompanies the collapse of a cavitation bubble it was assumed that the erosion of a solid in contact with a cavitating liquid is caused by this collapse of this cavitation bubble which had been brought to a region of elevated pressure from a region of reduced pressures, where these bubbles had, in fact, been formed (by the "boiling up" of the liquid).

In discussing the Kornfel'd report submitted to the Leningrad Physicotechnical Institute in January of 1940, the author of this paper criticized the standpoint (which Kornfel'd himself supported at that time) by contending that the erosion of solids result not from the collapse of bubbles passing nearby, but by the vibrations of the cavitating bubbles formed at the very surface of the solid material (the screw) and which remain attached to that material for a rather prolonged period of time.

The test performed in Kornfel'd's laboratory [1] in 1940 fully confirmed this concept. Further discussion of the problem of screw-propeller erosion and the appearance of cavitation leading to such erosion must therefore be based on the above-elaborated ideas. As will be demonstrated below, such an approach also offers new paths for an effective approach to the control of screw-propeller destruction.

The Appearance of Cavitation Bubbles in a Liquid Volume and at the Surface of Solid Materials in Contact with that Liquid. As is well known, in boiling water vapor bubbles are not produced uniformly throughout the entire volume, but – in practical terms – only at the bottom and at the side walls of the container vessel. Only on reaching a specific size do these vapor bubbles separate from the surface and enter directly into the volume of the liquid.

It goes without saying that the vapor bubbles can be generated directly within the liquid volume. This "volume" cavitation is, however, encountered only with some more or less substantial superheating of the liquid, in the case in which dust particles or some other solid colloidal particles are suspended within the liquid and then, under conditions which make "surface cavitation" difficult, i.e., the evolution of vapor bubbles at the walls of the container vessel. We will examine these conditions in detail below. At this point we would make mention only of the fact that the evolution of bubbles at the surface of finely fragmented particles suspended in a liquid essentially is a surface cavitation phenomenon in the above-indicated sense, rather than one of volume cavitation.

The absence of, or at least difficulty in achieving, purely volume cavitation in a liquid heated to the boiling point or superheated is usually explained by the fact that the pressure p of the saturated vapor in a tiny bubble of radius r is smaller than over the level surface of the liquid at the same temperature (p_∞). According to the familiar Thomson formula

$$\ln\frac{p}{p_\infty} = -\frac{2\alpha}{r}\frac{v}{kT},$$

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*The Frenkel' article on cavitation and its effect on the condition of screw-propeller surfaces (equally applicable to turbine buckets) has not been published before and was only recently discovered in the archives. The publication of this paper, not obsolete even today, and written in Frenkel's characteristic lively and "physics-oriented" manner, will serve not only as a sign of our respect for the memory of this remarkable Soviet scientist, but will serve also for further progress in the resolution of this particularly important problem in the field of engineering; in this article Frenkel' has proposed a possible approach toward the solution of this problem (The Editors).

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where α denotes the surface tension of the liquid, and v denotes the volume per 1 liquid particle. Thus, for the nucleation of a bubble within a pure liquid we need either substantial superheating, or (given a specified temperature) a substantial reduction in the outside pressure close to zero.*

However, these considerations by no means exhaust the problem. Moreover, they contradict the firmly established fact that liquids exhibit considerable strength, i.e., the capacity to resist omnilateral tensile forces or, in other words, the capacity to withstand negative pressures of great magnitude.

This fact is described in qualitatively correct fashion by the van der Waals theory according to which the liquid isotherms, given sufficiently low temperatures, contain segments of negative pressure (see Fig. 1). Furthermore, this fact is also confirmed by a number of experiments – first performed by Mueller in 1912 – on the tension of mercury enclosed in a sealed glass test tube.

As is well known, mercury exhibits a coefficient of thermal expansion that is substantially greater than that of glass. As the test tube together with the mercury was cooled, the latter should therefore have "boiled up" through the generation of cavitation bubbles (discontinuities) within its volume or at the wall; after the appearance of the gaseous phase, the liquid-mercury volume may change regardless of the change in the test-tube volume. This "boiling up" was actually found in Mueller's experiments, but not when the pressure within the test tube dropped to zero (because of the tension in the mercury filling the tube), but only when it reached a level of approximately minus 100 atm. The mercury underwent no volume discontinuity (volume cavitation) in this case, but separated from the glass wall at some point, and a mercury-vapor bubble was formed there instantaneously. This separation is accompanied by a clearly audible sound (a crack or a ring).

The phenomena described here were found only when the mercury had been repeatedly purified in advance through distillation to remove dust and all types of colloidal particles, and after the vessel walls had been repeatedly cleansed in hydrochloric acid and after the normal contaminating coatings had been removed. Under such conditions, the mercury exhibited its characteristic internal strength, exceeding 100 atm, and on reaching this level, it exhibited its characteristic bonding strength (adhesion) with the glass walls of the vessel in which it is contained.

Of course, these phenomena do not represent anything unique with regard to mercury or the glass with which it is in contact. These phenomena must be encountered in the case of any liquid in contact with any solid material when the above two conditions are satisfied: 1) removal of dust particles and other colloidal particles at whose surface the boiling up of the liquid is possible; and 2) thorough cleansing of the walls to remove adsorption layers which reduce the bonding strength between these walls and the liquid.

Thus we see that the boiling up of a liquid with a drop in pressure to zero and beyond, to negative values, is made difficult not only by the drop in the pressure of the saturated vapor in the bubbles being formed, as specified by the Thomson theory (a capillary drop in vapor pressure), but by the capability of the liquid to withstand substantial negative pressures without discontinuity (without "internal cavitation") and the ability to adhere strongly to the surfaces of solid materials. The generally held view to the effect that dust particles facilitate the boiling up of a liquid because they reduce the initial curvature of the bubbles forming on their surfaces and thus, according to the Thomson theory, raise the initial vapor pressure within these bubbles must be regarded as incorrect or, at the very least, as only partially correct. Indeed, from this standpoint vapor bubbles should be formed on the flat surfaces of the vessel walls without any superheating of the liquid or they should form as soon as the pressure drops to that of the saturated vapor (p_∞) over the flat surface. Indeed, as demonstrated by the Mueller experiment, bubbles need not form with a drop in pressure beyond zero, all the way to tens and perhaps even hundreds of atmospheres. The effect of the dust-particle surfaces on the boiling up of the liquid is consequently not governed by geometric factors, i.e., it is not governed by the initial curvature of the bubbles, but by physicochemical factors which determine the bonding strength between the liquid and the surface of the solid material, which is achieved without regard to the curvature of that surface.

We should take note of the fact that from a purely thermodynamic standpoint the state of the liquid under tension cannot be regarded as stable. It is not difficult to prove that as the liquid separates from the walls of the vessel subjecting the liquid to tensile forces and as the newly freed volume is filled with a

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*Its limit value can be calculated from the previous formula, if we assume there that $r \approx v^{1/3}$. In the case of water at room temperature ($T = 300$, $\alpha = 100$, $v^{1/3} = 2 \cdot 10^{-8}$) this yields $\ln(p/p_\infty) = 200 \cdot 4 \cdot 10^{-16}/10^{-14} = -4$, i.e., $p = p_\infty/100$. Further details in this connection can be found in the paper by Doring [2].

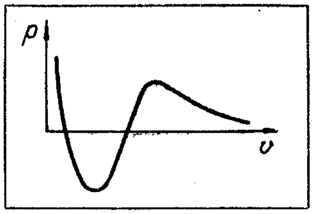

Fig. 1

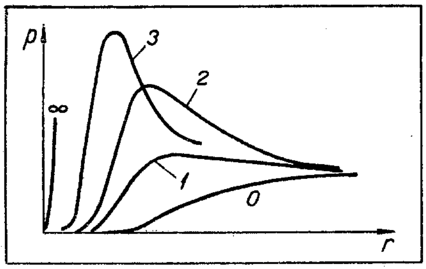

Fig. 2

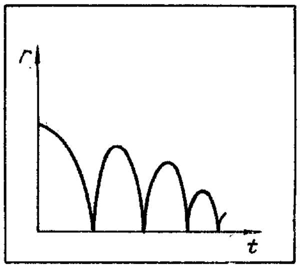

Fig. 3

Fig. 1. Low-temperature isotherm (p, v) for liquid.

Fig. 2. Pressure of incompressible fluid near vacuum bubble versus distance from it at various stages of bubble existence (from origin to break).

Fig. 3. Time-dependence of bubble radius.

saturated vapor exhibiting a certain positive pressure (depending on the temperature), the free energy of the entire system or, more accurately, its thermodynamic potential diminishes. However, this transition can be achieved only through certain intermediate states associated with a rise in the free energy, in which case the potential barrier separating the original state from the final state is so great that the original state is virtually stable ("metastable").

For simplicity, we propose that the vessel volume V remain constant as the liquid separates from its walls. We will denote by V_a the volume occupied by the liquid after its separation, while V_b will denote the volume occupied by the vapor that is formed, i.e., $V-V_a$. Furthermore, M and M_a will denote the mass of the liquid prior to and after separation; $M_b = M-M_a$ denotes the mass of the vapor. The thermodynamic potential of the liquid–vessel wall system prior to separation is equal to

$$\Phi_1 = M\varphi_a(p_1,\ T) + S_\alpha,$$

where S denotes the inside surface of the vessel; α denotes the surface tension of the boundary separating the inside surface from the liquid; and $\varphi_a(p_1,\ T)$ is the specific thermodynamic potential (i.e., referred to unit mass) of the liquid at the initial (negative) pressure p_1. After separation, the potential of the liquid–vapor–vessel wall system (given the same temperature T) is equal to

$$\Phi_2 = M_a\varphi_a(p_2,\ T) + M_b\varphi_b(p_2,\ T) + S_a\alpha + S_b\beta + s\gamma,$$

where φ_b denotes the specific potential of the vapor; S_a, S_b, and s are, respectively, the contact surfaces between the liquid and the wall, between the vapor and the wall, and between the vapor and the liquid, while α, β, and γ are the corresponding surface tensions.

Since the specific potentials of the vapor and the liquid must be equal when these materials are in equilibrium, we have

$$M_a\varphi_a(p_2,\ T) + M_b\varphi_b(p_2,\ T) = M\varphi_a(p_2,\ T).$$

The change in the potential of the entire system on separation of the liquid from the vessel walls is consequently equal to

$$\Phi_1 - \Phi_2 = M[\varphi_a(p_1,\ T) - \varphi_a(p_2,\ T)] - S_b(\beta - \alpha) - s\gamma.$$

Denoting the difference $p_2 - p_1$ by Δp (when the saturated vapor pressure p_2 is small, this quantity is virtually equal to the absolute value of the initial negative pressure) and if we assume that quantity not to be too great, we have approximately

$$\varphi_a(p_1,\ T) - \varphi_b(p,\ T) = -\left.\frac{\partial\varphi_a}{\partial p}\right|_{p_2}\Delta p + \frac{1}{2}\left.\frac{\partial^2\varphi_a}{\partial p^2}\right|_{p_2}(\Delta p)^2.$$

The derivative $\partial\varphi_a/\partial p$ is equal to the specific liquid volume v_a, while $\partial^2\varphi_a/\partial p^2 = \partial v_a/\partial p$ is equal to the product of the latter by the compressibility factor $\varkappa$.

Thus,

$$\Phi_1 - \Phi_2 = -V|\Delta p| + \frac{V}{2}\varkappa|\Delta p|^2 - S_b(\beta - \alpha) - s\gamma.$$

Since the overall volume of the system remains unchanged, it is advisable, in the place of the thermodynamic potential, to consider the free energy $F = \Phi - pV$. The change in this quantity in this case turns out to be equal to

$$F_1 - F_2 = \frac{1}{2}\varkappa V(\Delta p)^2 - S_b(\beta - \alpha) - s\gamma. \qquad (1)$$

The first term in the right-hand member is the elastic energy of the liquid under tension. The last two terms determine the change in the free energy of the wall on exposure of the surface portion S_b earlier covered with the liquid, and they also determine the free energy of the newly formed liquid–vapor surface. These are obviously small in comparison with the first term, provided the vessel volume is not too small. The change in the potential Φ consequently reduces to the virtual liquidation of the energy of the elastically stretched liquid, as was to be anticipated.

We can now turn to an examination of the conditions which govern the bonding energy between the liquid and the solid walls. This problem is of decisive importance for the clarification of the factors affecting the appearance of surface cavitation, and for determining means of combating the erosion of solid materials, where this erosion is a result of cavitation.

This bonding energy can be measured either by the force (per unit area) needed for the separation of the liquid from the surface of the solid material, i.e., by the maximum negative pressure needed for the destruction of this bond (Δp_{max}), or by the work which must be expended in this case, i.e., by the increase in the free energy per unit surface.

With removal of the liquid from the surface of the solid material through a distance δ on the order of the radius of the sphere of molecular action, the increase in the free energy per unit surface is equal to

$$\sigma = \gamma + \beta - \alpha. \qquad (2)$$

This quantity can be equated to the product of the force Δp_{max} by the distance δ. We thus obtain the following formula for the approximate evaluation of Δp_{max}:

$$\Delta p_{max} = \frac{\sigma}{\delta}. \qquad (3)$$

We note that in entirely analogous fashion we can evaluate the force (the negative pressure) which must be applied to cause the actual separation of the liquid; here we need only treat σ as the quantity 2γ, i.e., the doubled surface tension of the liquid. For water in contact with some solid material, assuming $\sigma \approx 100$ erg/cm^2 and $\delta \approx 3 \cdot 10^{-8}$ cm, we have

$$\Delta p_{max} = 3 \cdot 10^9 \text{ dyn/cm}^2 = 3000 \text{ kg/cm}^2,$$

i.e., about 3 thousand atm. This theoretical value for the force of liquid (water) adhesion with the solid wall is markedly exaggerated (by a factor of approximately 100) relative to the values which can be found experimentally, at least under standard conditions. This contradiction between theory and experiment is quite analogous to the contradiction found by Ioffe in 1924 in comparing the theoretical strengths of solids relative to the breaking force (on the order of several hundred kg/mm^2) with the comparatively low strengths found in actual practice. This latter contradiction is explained, as is well known, by the existence of inhomogeneities and, particularly, by surface cracks at whose edges stress concentration is found – a concentration which approaches the theoretical ultimate strength and leads to the breaking up of the material through the gradual development (enlarging) of cracks.

A similar mechanism may be used to explain the comparatively low bonding strength between the liquid and the solid material. However, here the role of the cracks must be taken by the places characterized by particularly low values for the theoretical strength, i.e., "the adhesion energy" σ. Beginning at one such "weak" point, the separation of the liquid from the solid material must rapidly expand as a result of the boiling up of the liquid, i.e., the formation of a cavitation vapor bubble. If the latter does not separate from the surface during the initial stage of its development, this development will lead to the separation of the liquid over the entire surface of contact with the solid material or, in any case, over a macroscopic portion of the surface.

The problem of strengthening the bond between the liquid and the solid and the problem of eliminating or, at least, reducing the surface cavitation thus reduces to the elimination of these "weak spots," characterized by particularly low values for the adhesion energy.

Precisely what are these weak spots? It is natural to assume that when metals come into contact with water such spots are those segments of the solid surface that are covered with adsorption layers* of hydrophobic substances. Such substances include, as we know, the various organic materials containing the hydrocarbon groups, in particular, for example, certain surface-active substances (adsorbent on the free surface of the water, serving to reduce its surface tension). The molecules of such substances are generally made up of the hydrophobic group ("residues") and from the active group (carboxyl COOH, hydroxyl OH, etc.), which exhibit a strong affinity for water and becomes immersed in the water, whereas the hydrophobic "residue" stays on the surface (in the form of a float).

On introducing such substances onto the surface of separation between the water and the metal we find that, as a rule, such surface-active substances should weaken the bond between the water and the metal surface, since hydrophobic molecular skeletons are situated between the metal surface and that of the water, whereas the active ends attach themselves to the metal surface (to which they are attracted even more strongly than to the water).

However, it is possible to select substances whose molecules exhibit a hydrophobic stem and two active ends, one of which exhibits strong affinity for water, while the other exhibits a strong affinity for the metal. When a substance of this type is introduced into an aqueous solution it must be adsorbed at the boundary of separation between the water and the metal in the form of a monolayer capable of strengthening the bond between them.

Talmud [3] proved the existence of a large number of substances capable of functioning as a "molecular solder" between two solid materials such as, for example, metal and paraffin; he demonstrated that this "solder" is achieved in the form of a monolayer situated between the surfaces of the two solids and bonds one to the other. In the Talmud experiment the substance forming the solder between the paraffin and the metal was introduced into molten paraffin from which it was adsorbed at the surface of contact with the metal, and here it remained in the form of a monomolecular layer (monolayer) during the hardening of the paraffin. A discontinuity formed within the paraffin when an attempt was made to tear away the latter from the metal, and the strength of the paraffin was thus reduced relative to the strength with which it was bonded to the metal surface.

It was also found that certain soaps can function as a "molecular solder" between water and solid materials (glass, metals).

Thus we see that while a number of organic substances weakly soluble in water – in particular, fatty acids and other surface-active substances – in the case of adsorption at metal surfaces weaken the strength of the bond between the metal and water (thus facilitating the appearance of surface cavitation), a number of other organic substances whose molecules exhibit two active ends can, conversely, be used to strengthen this bond.

Hence it follows that to reduce surface cavitation in water we must remove organic contaminants of the first kind from the metal surfaces and, where possible, to replace them with substances of the second kind, capable of functioning as a molecular solder.

As demonstrated by the Frumkin experiments [4], organic contaminants can be removed from the surface of a metal in contact with an electrolyte solution by the introduction between these of a potential difference on the order of 0.5-1 V (of any sign). Since sea water is a rather concentrated electrolyte solution, it is clear that a possible means of combating erosion in screw propellers – since it is governed by surface cavitation – is a low-voltage (on the order of half a volt) alternating current and a rather high frequency from the screw propeller or its most vulnerable surface portion to the water.†

It goes without saying that the use of this method involves substantial structural difficulties associated with the need to insulate the appropriate portions of the propeller from the shaft and hull of the vessel.

If this method is impractical or insufficiently efficient, we must attempt another method – the coating of the propeller surface with substances of the second kind (to raise the bonding strength) provided that they are capable of expelling the substances of the first kind (lowering the bonding strength) and that they remain rather strongly bound to the propeller surface.

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*In particular, with layers only one molecule in thickness.

†With direct current the propeller surface, or the water, would undergo electrolysis.

The practical solution of these problems is, of course, impossible exclusively on the level of theoretical considerations. It requires fundamental research that is purely experimental in nature.

We now have to turn to an examination of the problem relating to the appearance of surface cavitation bubbles and to the mechanism of their destructive (erosive) effect.

As regards the formation of bubbles, this may be governed by two diverse factors: 1) the streamlining of a solid by a flow of a liquid under conditions in which a reduced pressure is developed, and in particular, a negative pressure; and 2) by vibrations of the solid and liquid surfaces.

In the first case, the problem of zones of bubble formation is solved by application of the Bernoulli equation

$$\frac{p}{\rho} + \frac{1}{2} u^2 = \text{const} \tag{3a}$$

to the liquid flow streamlining the solid surface (p is the pressure; ρ is the liquid density; u is the velocity of the liquid with respect to the solid). Equation (3a) should be applied in this case to the boundary layer of the liquid, without making any provision for the viscosity of the latter and the existence of a Prandtl wall layer in which the velocity drops from the above-indicated value to zero, since this drop is not reflected in the magnitude of the pressure in the direction normal to the surface.

In the second case, we must proceed from the following expression for the pressure amplitude:

$$\Delta p = \rho c \Delta u, \tag{4}$$

where Δu denotes the amplitude of the velocity of the liquid or the solid at the surface; ρ is the liquid density; and c is the speed of sound within the liquid. Denoting the amplitude of the oscillatory displacement of this surface by a, and the oscillation frequency by ν, we have

$$\Delta u = 2\pi \nu a$$

and consequently,

$$\Delta p = 2\pi \nu c \rho a.$$

When $\nu = 10^4$ sec^{-1}, c = 10^5 cm/sec, $\rho = 1$ g/cm^3, and $a = 10^{-3}$ cm this formula yields

$$\Delta p = 6 \cdot 10^4 \cdot 10^5 \cdot 10^{-3} = 6 \cdot 10^6 \text{ dyn/cm}^2 = 6 \text{ atm.}$$

Thus in the case of a "nonseparation" vibration of the liquid, it should experience negative pressure up to 6 atm. It is natural that under normal conditions, i.e., with existence of points of reduced bonding strength between the liquid and the solid surface, such nonseparation vibrations of the liquid could not take place and the vibration of the solid would necessarily lead to the formation of cavitation bubbles, if not over the entire surface, then at least over some portion of it.

For purposes of comparison, we note that when p = 0 in the case of u = 0 the Bernoulli equation (3) would lead to the establishment of a negative pressure of 6 atm for those surface segments in which the velocity of the liquid flow were to attain values of

$$(2 \cdot 6 \cdot 10^6)^{1/2} \approx 3 \cdot 10^3 \text{ cm/sec} = 30 \text{ m/sec.}$$

We see from this comparison that the vibration of the solid and, in particular, the vibration of a propeller blade, is an extremely significant factor in the development of surface cavitation, and in any event it is no less significant than streamlining at velocities on the order of tens of meters per second. However, while streamlining can compete with vibration as a factor governing the appearance of surface cavitation bubbles, it is totally ineffective with regard to the vibration of these bubbles, which, as was shown above, is a factor directly responsible for the erosion of the solid surface. The vibration of the surface bubbles is possible only when both the solid and its streamlining liquid experience vibrations.

Hence it follows that the surface cavitation of water, on rotation of a screw propeller, would be entirely harmless if the rotation of the propeller could be accomplished without any vibration whatever.

Unfortunately, it is hardly likely that this condition can be satisfied. In conjunction with the hull of the vessel and the water, the propeller makes up a self-oscillatory system whose vibration – particularly at high speeds of propeller rotation and vessel motion – cannot be entirely eliminated.

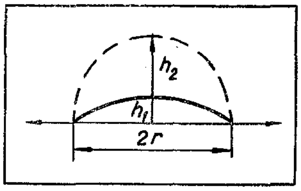

Fig.4

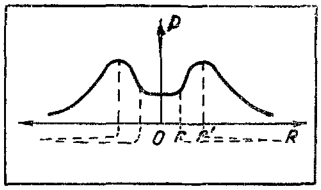

Fig. 5

Fig.4. Bubble oscillation at solid surface body (dashed line, expansion phase; solid line, compression phase).

Fig.5. Schematic dependence of pressure at solid body surface on distance from center of bubble at the surface at the instant of maximum bubble compression.

Nevertheless, these considerations show that even partial reduction in propeller vibrations (for example, by eliminating particularly dangerous resonance frequencies) should reduce the erosion associated with cavitation, if it cannot weaken the latter.

We can now turn to an examination of the erosion mechanism generated by the vibrations of surface cavitation bubbles. These vibrations must be generated in approximately the same manner as those of the volume cavitation bubbles situated at some distance from the boundaries of the liquid. In the case of low-amplitude vibrations for which the pressure in the liquid remains positive the entire time, as is the case in a gas (or vapor) filling these bubbles, the vibrations of the latter are purely linear (harmonic) in nature, a fact which is expressed by the reduction in pressure with a maximum expansion of the bubble that is equal to the increase in pressure with maximum compression of the bubble.

With an increase in the amplitude of liquid vibrations, the bubble vibrations become increasingly asymmetric, and they distort the vibrations of the surrounding liquid ever more intensively. When the amplitude of the pressure oscillations in the liquid becomes so substantial at great distances from the bubble that in the half-period of liquid stretching the pressure within the liquid attains negative values, the bubble within which the pressure must remain positive throughout the entire period of time expands much more markedly than it is compressed in the second half-period. On compression of the bubble the liquid tends toward its center and, decelerating sharply, develops pressures near and within the bubble that are many hundreds and even thousands of times greater than the average maximum pressure at points in the liquid distant from the bubble. Fixing a bubble to the surface of a solid exerts no significant effect on the nature of its vibrations, only slightly weakening the intensity of the hydraulic implosions experienced by the metal surface in the bubble zone and its immediate surroundings.

In the case of a vacuum bubble of an incompressible liquid, examined by Rayleigh, the pressure distribution near the bubble on compression of the latter can be represented by the following series of curves (where 0 corresponds to the initial state and ∞ corresponds to the instant of bubble collapse).

The formation of a pressure maximum near the bubble (in whose cavity the pressure remains equal to zero) is associated with pronounced deceleration of the liquid, caused by the reduction in the volume which it seeks to fill. At the instant of bubble collapse this pressure maximum concentrates at the center and reaches infinity.

If the liquid were in fact incompressible (and inviscid), the matter would not end here. Because of the law of conservation of energy and the principle of reversibility of motion, the velocity for all points of the liquid at the instant of bubble contraction to zero should change, its centripetal flow should be replaced by centrifugal flow, and the compression of the bubble should be replaced by its expansion, with exact reproduction of the above pattern of pressure distribution, but in reverse sequence. This result can be illustrated by the dropping of a solid sphere onto a solid horizontal surface from which it should bounce to the same height from which it fell, if a portion of the energy – on impact – did not convert into the energy of elastic vibrations of both materials (i.e., into sound and heat). In considering the elasticity (compressibility) and thermal conductivity of the liquid, we find that a portion of the kinetic energy picked up by the liquid as it compresses the bubble is dissipated in the form of heat and sound waves. Therefore, following the collapse of the bubble, it no longer expands to its original dimensions, and its vibrations are gradually attenuated. The approximate variation in bubble radius with time is shown in Fig. 3, from which we see that the vibration period is constantly reduced together with the amplitudes of these vibrations. As the bubble contracts to zero, the pressure maxima should remain permanently infinite. Indeed, a bubble filled with a gas dissolved in the water and with water vapors does not contract to zero, but to some finite magnitude. This corresponds to a finite value for the pressure peaks, gradually diminishing as the bubble vibrations are attenuated. It was demonstrated above that the thermal effects associated with these vibrations should lead to extremely rapid attentuation of the vibrations and may even entirely eliminate the oscillatory process (an aperiodic regime). This is the reason that in the absence of external forces capable of maintaining the bubble vibrations these "free" or "natural" vibrations cannot yield a significant mechanical effect, even if the bubble is in the immediate vicinity of a solid surface or sit directly on that surface.

An entirely different picture is found in the case of forced bubble vibrations caused by or supported by periodic oscillations of pressure in the surrounding liquid – by oscillations which in turn are associated with the vibrations of the solid material. Of particular significance in this case is the resonance condition, i.e., the coincidence of the vibration period with the periods of the free bubble vibrations (or one of its harmonics). In this case the vibration amplitude of the bubble may attain a very high magnitude and the pressure peaks both at the surface of contact between the bubble and the solid material and, in particular, near such a surface, may prove to be sufficiently high to result in the destruction of the surface layer (of even the solid material itself) within a very brief period of time (as a consequence of "fatigue").

It should be noted that in the case of rapid vibrations the circumference about which the bubble is in contact with the solid material may be regarded as constant, so that the bubble vibrations can be reduced to the swelling and compression of the surface in contact with the water that is resting on that circumference (Fig. 4) (the solid line corresponds to compression, and the dashed line corresponds to the expansion of the bubble; the circumference radius r remains constant).

The constancy of this circumference follows from the familiar phenomenon of wetting hysteresis, or of the boundary corner, whose equilibrium value can be established only comparatively slowly. With constant r the pressure peaks at the instant of greatest bubble compression (i.e., minimum value for bubble "height," $h = h_{min}$) should be somewhat weaker in comparison with the case in which the bubble experiences omnilateral compression, since the deceleration of the liquid associated with the constriction of the flow near the bubble in the case of omnilateral compression is more pronounced than in the case under consideration, where the compression passes at the limit to a unilateral form, and the deceleration is governed exclusively by the compression of the gas in the bubble. However, even in this case this pressure may be quite high, especially because the compression of the bubble is initially omnilateral in nature (given its substantial convexity).

The pressure distribution at the surface of a solid material at the instant of the maximum, i.e., the greatest bubble compression, is shown schematically in Fig. 5.

The pressure maximum, in practical terms, should not be found within the bubble itself, but at some distance from its edge, just as in the case of the omnilateral compression examined by Rayleigh. In the negative phase, i.e., at the instant of greatest bubble expansion, the pressure within the bubble should drop virtually to zero, whereas the pressure in the surrounding liquid and, in particular, at the surface of bubble contact with the metal, it may assume negative values. It is possible that during the negative phase the edges of the bubble will be able to shift apart somewhat, returning to their original position on completion of the positive phase.

Earlier we considered the condition for the appearance of surface bubbles and the nature of their vibrations, but we failed entirely to touch on the problem of the duration of their existence (which for the specified amplitude governs their destructive effect, nor did we consider the factors involved in bubble breakup).

Surface bubbles should originate as a mass at the weak spots of a vibrating (or streamlined) surface. Here they attain certain averge dimensions which are governed by the vibration amplitude (or speed of flow), as well as by the vapor pressure and the amount of gases dissolved in the water. The problem of the relationship between bubble dimensions and the above-enumerated factors requires special investigation, which we have not yet undertaken.

The Kornfel'd experiments show that individual bubbles can move away from the surface and merge with each other. If the vibration period of the largest bubbles formed in this manner is randomly close to the vibration period of the solid material and that of the surrounding liquid, the bubbles will undergo particularly intensive vibrations which will lead to erosion effects. The bubbles, in this case, may break apart again or separate from the surface. Such separation may also be experienced by weakly vibrating nonresonance bubbles, provided the dimensions of these bubbles are sufficient for their lift force to overcome the force with which they are held to the surface.

All of this requires thorough study.

Of significant interest with regard to this problem is the question of the various kinds of secondary effects which occur within cavitation bubbles, as well as in the immediate vicinity of the bubbles (at the boundary between the solid material and the liquid).

One of the most interesting side effects associated with cavitation in water is the formation of free oxygen or the hydroxyl, which leads to various oxidation reactions. The existence of such reactions on passage of ultrasonic oscillations through the water (for example, the luminescence of phenobarbital dissolved in water, the reduction in the viscosity of polymer solutions because of their depolymerization under the influence of oxygen, and many others) has been established by a number of researchers, in particular [5]. The fact that the reactions are not the direct result of the ultrasonic oscillations, but brought about only indirectly by the cavitation bubbles which arise under the influence of these oscillations is proved, by the fact that the chemical effects cease when the average liquid pressure is raised to two or more atmospheres (depending on the intensity of the oscillations). As regards the mechanism involved in the chemical reactions under the action of cavitation, the author in [6] indicated that this mechanism reduces to electrical discharges which pass through the cavitation bubbles at the instant that they are formed. These discharges may result in the dissociation of molecular oxygen, the formation of hydrogen peroxide, etc., either directly, or through a photochemical procedure, since these discharges must be accompanied by the emission of ultraviolet rays.

It was assumed in [6] that the cavitation bubbles in which electrical microdischarges take place are formed within the liquid volume in the form of gradually expanding lenses. However, it is presently regarded as more probable that these bubbles are formed at the surfaces of solid materials and that the subject effect, roughly speaking, conventional electrification as a result of contact, friction, or the separation of various materials.

As is well known, a double electric layer exists between a metal and an electrolyte, such as that formed by ordinary fresh water and, in particular, by sea water, with a portion of that layer in direct contact with the solid material (the Helmholtz double layer), and the other portion a diffusion layer. This last layer is formed, on the one hand, by the surface of the metal charged with electricity of some sign (usually negative), and on the other hand, by a rather thick liquid layer in which charges of the opposite sign prevail. The thickness of this layer (Stern or Debye) is the smaller, the greater the average concentration of ions of either sign in the water (i.e., the greater the electrical conductivity of the latter), and it can be calculated from the formula

$$\delta = \sqrt{\frac{\varepsilon kT}{8\pi e^2 n}},$$

where ε is the dielectric constant of the water; ±e is the ion charge; n is the average ion concentration at a great distance from the metal. Assuming that $n \approx 10^{16}$ cm^{-3}, which corresponds approximately to fresh water (for salt water $n \approx 10^{18}$–10^{19}), and ε = 80, we have

$$\delta = \frac{9}{5\cdot 10^{-8}}\sqrt{\frac{4\cdot 10^{-14}}{10^{6}}} = 4\cdot 10^{-7}\ \text{cm}.$$

The potential jump between the metal and the electrolyte usually amounts to 0.1–1 V. Taking the lower limit, for the average value of the electric-field strength in the diffusion double layer we have

$$E = \frac{0.1}{4\cdot 10^{-7}} \approx 2\cdot 10^{5}\ \text{V/cm}.$$

This field is retained in the cavitation space when the water separates from the metal, corresponding to the surface density η of the charge on the metal (according to the formula $E = 4\pi\eta$), and this density should obviously not change as the water separates from the surface, since it is offset by an opposite charge in the surface layer of the water. When the cavitation space (initially in the shape of a lens) is filled with water vapor and with gases dissolved in the water, an electric spark should jump across this space, provided the thickness h of the cavitation lens is at least several times greater than the mean free path of the electrons in the gas filling the space. Thus, for example, in the case of water vapor at room temperature (a pressure of 50 mm Hg) this path is approximately equal to 10^{-5}–10^{-4} cm. The electric breakdown of the cavitation lens will consequently occur as soon as its thickness reaches 10^{-4}-10^{-3} cm. This value is completely commensurate with the experimental data on bubble dimensions for bubbles which are formed on surface cavitation. The lateral dimensions (diameter) for these bubbles are even greater in magnitude – on the order of 10^{-2} cm.

We should take note of the fact that for the passage of the electric discharge through the gas filling the bubble the latter must grow with sufficient speed, since otherwise the discharge will pass within the liquid surrounding the bubble (the potential of various points in the liquid on separation from the metal will grow in direct proportion to the distance of these points from the surface of the metal).

The time required for this "liquid" discharge is determined by the time of liquid relaxation

$$\tau = \frac{\varepsilon}{4\pi\sigma},$$

where σ is the electrical conductivity of the liquid. In the case of fresh water with the above-indicated ion concentration, in order of magnitude, this time is 10^{-10} sec. The rate of surface-bubble formation, i.e., the velocity with which the liquid surrounding the bubble moves away from the solid surface, must thus be on the order of $10^{-4}/10^{-10} = 10^{6}$ cm/sec, i.e., on the order of the speed of sound propagation in a liquid.

For the question of interest to us in connection with the erosion of screw propellers the microdischarges which occur in surface cavitation are extremely significant, since the active (atomic) oxygen formed as a result of these discharges must be responsible for the corrosion of the metal surface and this will facilitate its further destruction under the effect of pressure oscillations within the bubbles themselves. To reduce this effect, the metal surface must be coated with anticorrosion films; however, we must bear in mind that here it is necessary to strengthen the bond between the water and the film covering the metal so as to reduce the overall cavitation effect.

The reduction in the sparking associated with surface cavitation can also be achieved through an artificial increase in the electrical conductivity of the water flushing the metal, and this is done through the introduction of an additional potential difference (on the order of 0.1-1 V) to offset the natural potential jump between the water and the metal or, finally, through the reduction of this jump by means of some special coating.

The chemical effects experienced by the metal surface (the screw) as a result of the sparking associated with surface cavitation cannot result in the destruction of the metal, but they do facilitate this destruction under the action of mechanical forces (pressure peaks). To some extent, they thus determine the "induction," i.e., the time during which the metal is not subject to the destructive action of a mechanical agent (pressure oscillations).

With regard to the effect of this agent, it is not limited to simple action on the metal surface, leading to destruction as a result of fatigue. Penetrating into the cracks formed at the surface as a result of separation of coordinated layers, the water exerts a "wedge-like" effect which, as was demonstrated in [7], catastrophically accelerates the process of destruction.

Summarizing all of the above, we see that the effort to combat the erosion of screw propellers must proceed along the following lines:

1. To increase, as much as possible, the adhesion of the water to the surface of the propeller: a) by coating it with appropriate "adhesives;" b) by removing all contaminants which normally reduce the adhesion of the water, e.g., with the aid of a (variable) voltage on the order of 1 V between the propeller and the water.

2. To reduce sparking in surface cavitation: a) by increasing the conductivity of the water near the propeller or b) by liquidating the natural contact potential jump between the water and the metal.

3. To reduce propeller vibrations, since only in the presence of such vibrations can surface cavitation lead to erosion. As regards the methods of combating vibrations, to find these we first have to study the factors leading to vibration. This problem is presently most significant and urgent in the effort to overcome the erosion of screw propellers.

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