HYD 12

CAVITATION AND SURFACE TENSION

A Translation of

Cavitation et Tension Superficielle

By F. K. Th. Van Iterson

from

Proceedings of the Royal Academy of Science Amsterdam

Vol. 39, 1936, pp. 138-148 and 330-339.

Translated by

Edward F. Wilsey

U.S.Bureau of Reclamation

Nov. 1936.

CAVITATION AND SURFACE TENSION.

1. Generalities and Present State of the Problem of Cavitation.

A study of the centrifugal pumps at the stations for unwatering of the Wieringemeer basin which is a part of the Zuiderzee reclamation, has provoked several series of model tests with the aim not only of obtaining an increased capacity of the pumps, but also to eliminate their rapid deterioration by cavitation. These experiments have resulted in the elimination of several types of impellers among them those with three vanes, which although their capacity was excellent they were subject to the beginning of cavitation (accompanied by a slight noise) depending on the suction height imposed by the basin.

We have studied the cause of the phenomenon of cavitation for certain types of impellers.

Great was the disappointment when an intense cavitation was disclosed at the pumping stations, Lely and Leemans. This occurred not only while the basin was being drained but also, a circumstance more grave, when the pumps operated under a normal suction height and head.

The profiles of the vanes of pump impellers are often analogous in shape to those of aerofoils, which have already been thoroughly studied.

We now proceed to a study of the causes of cavitation.

The concept generally adopted is that cavitation in a hydraulic machine takes place at any point where the absolute pressure of the water falls below the vapor pressure, for example, below 1/100 of an atmosphere for the mean winter temperature.

In quantitative calculations, we can neglect this small absolute pressure, and assume that the water commences to boil when the pressure approaches absolute zero.

The abrupt condensation of the globules of water vapor in the zone where the absolute pressure of the fluid vein rises again to a value greater than the vapor tension causes noise, vibration, deterioration, and the rupture of salient machine parts. These constitute the symptoms of cavitation.

Theoretical Investigation

In order to better understand the behavior of the more important centrifugal pumps used in Holland which will serve as object studies for future pumping stations, the Superintendent of the Zuiderzee charged Burgers and Van Der Hagge Zijnen with the determination of the characteristics of the flow through the pump impellers by the method of conformal transformation.

The scientific world should admire the manner in which these savants have accomplished this task. This work will remain one of the important contributions to hydrodynamics.[1]

[1] Berekening van het verloop van de stroomsnelheid van den druk langs een doorsnede van een schoep van een wasier met 5 schoepen van een der centrifugaalpumpen te Medemblik.
(Calculation of the Loss of Velocity and Pressure along a Profile of One of the Vanes of the Five-vaned Impellers of the Centrifugal Pumps at Medemblik, by J. M. Burders and B. G. Van der Hegge Zijnen; Two volumes, 1933, (in the technical library in Holland).

We reproduce two figures from this paper. Figure 4 shows several stream lines (in relative movement); figure 5 gives the calculated theoretical distribution of the relative velocity and the pressure around a profile of a single vane.

This theoretical calculation indicates that the maximum vacuum is equivalent to a column of water 9.34 meters (30.64 feet) high; consequently at this point on the profile the absolute pressure is less than one-tenth atmosphere.

But a slight modification of the angle of incidence resulting, for example, in a slight change in the smooth entrance conditions or farther along the vane, small imperfections in its fabrication causing roughness, should create local velocities greater than the calculated values.

It is therefore certain that a sufficient margin of safety against cavitation resulting from water vapor bubbles does not exist in this pump.

The Different Kinds of Cavitation and their Consequences

We can separate the phenomenon of cavitation into the following categories, some of which overlap:

1. Superficial cavitation: Small globules of air or vapor appear on the walls.

They are held by the metallic surfaces and disappear as if absorbed by them.

This type of cavitation results in a slight decrease in the pump capacity and an increase in the suction; this increase in the suction has been duplicated in venturi tubes.

This type of cavitation erodes the materials of construction at that place where the globules of air disappear.

2. More accentuated cavitation: The track of the water vapor consists of a foam formed by the small globules that are detached from the walls. These move freely in the water, and except for some are reabsorbed in the water current downstream from the place of

their formation. This type of cavitation affects the capacity considerably and modifies the characteristics of the machine.

3. Cavitation with localized corrosion of the vanes: Pockets of air and water vapor oscillate but are unstable on the metallic surface, although they accompany the vanes in their rotation. The flow characteristics are therefore strongly affected.

4. Very accentuated cavitation with intense boiling along the walls and between them: The largest globules of vapor are entrained by and condense in the liquid with a characteristic noise and violent vibration which can become dangerous.

In that which follows we shall study only cavitation of the first category.

If an increase in the capacity of hydraulic machines of high specific speed is linked to the choice of profiles for the vanes or, in other words, to sections comparable to aerofoils such as have been tested in the laboratory, this gain is acquired at the expense of the destruction of important parts of the machine. This destruction may be likened to a contagious disease.

Engineers and physicists having been searching for some means to combat it.

Laboratories for the investigation of cavitation phenomena are being installed at great expense in many countries [2]

[2] Experiments on cavitation using small models of the pumps at Wieringermeer have been performed in the Hydraulic Laboratory at Delft (in a closed circuit which can be put under pressure). The description of three laboratories for investigating cavitation in hydraulic turbines are found in the following: A. Tenot; Turbines Hydrauliques (Hydraulic Turbines), vol. II, 1932, Librairie d' E. T. Paris, Tenot has described his interesting laboratory for experiments on cavitation at l'Ecole d'Arts et Metiers at Chalons sur Marne; by means of a stroboscope with neon lamps, he can watch what is happening under the vanes of a propeller revolving at a speed of about 3,000 r.p.m., and is therefore able to follow the different phases of cavitation. Another of the many institutes has conducted experiments on cavitation of ship screws. The labor tory of the greatest repute is that of the Kavitation Anlage der Hamburgischen Shiffbua-Versuchsanstalt G.m.B.H.

It is necessary to recognize that the gravity of the problem justifies the expense and the assiduous work of a numerous personnel.

Too often machines are out of service in large hydro-electric plants. A large number of technicians are occupied in repairing metal parts eroded by cavitation.

Worse still are the difficulties experience by merchant ships and ships of war in consequence of the cavitation of the screws. The vibration of steamships is often due to this scour e.

The S.S. "Normandie" suffered so acutely from the effects of cavitation that the eroded screws had to be repaired after two or three voyages. This involved a serious economic loss.

Rapid destruction of the propellers is the rule for steamships holding the blue ribbon. For cruisers and torpedo boats many examples can be cited in which screws have been destroyed in hours.

In the present state of the art of naval construction the difficulties occasioned by the cavitation of propellers. has rendered an increase in the power of ships impossible.

Experimental Contribution to the Study of Cavitation; Influence of the Quality of the Water on the Separation of the Air Dissolved in the Liquid.

Physicists and engineers have been searching for a better explanation of this hydrodynamic phenomenon in order to explain the erosion which it provokes.

The author now presents his small contribution to the explanation of the effect of cavitation of the first category.

M. G. Driessen, chief of the mechanical research service of the Dutch State Mines, has performed some experiments which throw some light on the phenomenon.

The pumping station of Haarlemmermeer has experienced a large number of difficulties due to cavitation which are accentuated in autumn.

Among the reasons which can be the cause of the disagreement between the results obtained by experiments on small models and the experience with industrial pumps in service at Wieringermeer, a difference in the quality of the water has been thought of.

Our experiments were performed at Delft using the pure water provided by the distribution system of the city.

In contrast to this, the water at Wieringermeer was agitated, and muddied during the excavation f the canal. The first question to be investigated is whether the impurities in the water play an essential role in the production of cavitation.

Figure 6 shows one of the glass Venturi tubes used in the experiment.

The results shown in figure 7 are surprising.

Cavitation in pure water saturated with air at atmospheric pressure begins at a vacuum equivalent to five meters (16.4 feet) of water, that is to say, at an absolute pressure of 0.5 atmosphere. (Minus 50%).

For water to which 0.5 gram of powdered coal per liter (1/2 ounce per quart) has been added, cavitation commences at a vacuum of one meter (3.28 feet) of water, that is to say, at an absolute pressure of 0.9 atmosphere. (Minus 10%).

The vapor tension of water at different temperatures is also shown in figure 7. It is seen to be well below this absolute pressure given above for all ordinary temperatures.

Therefore it is not the boiling of the water which produces cavitation of the first category, but as Dijxhoorn remarks in referring to our experiments. "The separation of the air dissolved in the water when the pressure is decreased is the primary cause of this phenomenon".

For winter temperatures, when cavitation is often most marked the vapor tension of the water can be neglected and the separation of the air considered alone.

The beginning and ending of cavitation are disclosed by an increase and a sudden decrease, respectively, in the suction, and better still, by the characteristic noise of cavitation of the first category, This resembles the sound produced when air is being liberated during the heating of water.

Experiments Concerned with Explaining the Erosion of Solid Walls by Cavitation: Influence of Surface Tension.

We believe that the erosion caused by cavitation is due to a force generally neglected in hydrodynamics because of its small value - 72 dynes per centimeter, or 0.075 gram per centimeter - namely, the surface tension of the air bubbles.

Figure 8 shows the pressure in an air bubble and the pressure in the surrounding water which is saturated with air at atmospheric pressure.

If the air in the bubble is not at atmospheric pressure it will either be quickly absorbed by the water or air will separate from the water until this pressure is established. According to the law of De Henri, the air pressure inside a bubble has a tendency to put itself in equilibrium with the pressure of saturation. In all cases, even with large globules of vapor, at the precise instant of their collapse, they necessarily contain some residual air at a pressure of at least one atmosphere.

When equilibrium exists between the interior pressure of the globule, the exterior pressure in the liquid and the surface tension we have:[3]

$$\Delta p = \frac{2\gamma}{r}$$

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[3]The equation of equilibrium of a hemisphere gives us:

$$2 A r \gamma = A r^2 \Delta p$$

$$\Delta p = \frac{2\gamma}{r} \quad and \quad r = \frac{2\gamma}{\Delta p}$$

Where γ = surface tension in grams per centimeter Δp = the difference in pressure between the air in the globule and the pressure in the liquid, and r = radius.

When $r=0$, $\Delta p = \infty$

The origin of a globule implies, therefore, an infinite pressure.

Certainly this mathematical result is not physically true. The surface tension, γ , cannot be considered constant for globules with a radius smaller than 10^{-6} centimeters. It commences to diminish at first slowly, then more rapidly in order to approach zero when the radius, r, approaches zero.

The conclusions, however, are not influenced by the lowering of γ for very small globules.

Pure water can neither boil nor cavitate. Air in solution cannot be liberated by lowering the pressure below that at which it has been dissolved.

Meyer has demonstrated that pure water containing dissolved air in a clean container can withstand a tension of more than one hundred atmospheres.[4]

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[4]Muller-Pouillets. Lehrbuch der Physik (Textbook of Physics). Ed.II, 1926, vol. 3, first half of Thermodynamik, p. 301, labile Zustand (negative pressure).

The boiling of water can be retarded by the absence of impurities; it can even be superheated.

According to a law of Kirchoff[5], the negative pressure in

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[5]G.Kirchoff. Vorlesungen uber Mechanik (Lectures on Mechanics) 1876, p.186. J.Ackeret, Experimentale und theoretische Untersuchungen uber Hohlraumbildung im Wasser, (Experimental and Theoretical Investiation of Cavitation in Water), 1930, p. 8.

a liquid is maximum along the walls which guide its flow.

According to this law, globules of air are created on the walls, or better, on surfaces of solid particles in suspension in the liquid. These surfaces serve to separate the air exactly as catalyzers promote chemical reactions. It is easy to verify experimentally that surfaces clean of all impurities are not capable of freeing air or gas dissolved in excess in the water; it is necessary to consider unclean surfaces in the light of a fourth determining factor called a "collector" in the technique of treating minerals by flotation; in general, this fourth factor can be any substance containing sixteen atoms of carbon or more.

It seems reasonable to us that the air bubbles are formed wherever the three determinate factors, solid wall, collector and liquid exists together.

An instructive experiment consists in boiling distilled water in a vessel whose bottom has been greased a little, then afterwards in another very clean vessel to which has been added a little caustic soda in order to dissolve all traces of grease found in the air and in the water. In the first vessel, water will boil regularly at 100° C. while in the other the water can be superheated and boils only with explosive violence.

Air bubbles in a closed region cannot exist below a certain diameter for a given pressure in the liquid.

What is the diameter of these newly created globules?

We have:

$$r = \frac{2\gamma}{\Delta P} = \frac{2\gamma}{P_i - P_e} \quad \begin{cases} P_i = \text{internal pressure} \\ P_e = \text{external} \quad " \end{cases}$$

In our experiments, pure water began to cavitate at

$$P_i - P_e = 0.5 \text{ atm.} = 500 \text{ gr./cm}^2 \quad \text{Hence: } r = \frac{2 \times 0.075}{500} = 0.0003 \text{ cm.}$$

Therefore, globules of a diameter smaller than six microns cannot exist in pure water. They grow rapidly as the negative pressure increases absorbing air, but in cavitation of the first category they remain small. According to a law in physics, large bubbles ought to grow at the expense of the small ones; when bubbles approach and come in contact with each other they ought to combine.

But when water is impure, that is contaminated by particles of oil or organic matter, there is a tendency to form a foam containing numerous small globules.

Experiments show that many globules remain small and isolated, particularly if they are in a closed space.

Water moistens the pores in the metal and forms a quasi-chemical combination. The velocity of the water in contact with the metal is zero.

Globules of a fraction of a millimeter in diameter are slowly carried away through the closed laminar space. while the larger ones which thrive in a turbulent region are either carried away or divided.

For a better understanding of the phenomena of cavitation, let us consider a single microscopic bubble moving along a wall in a constricted region as in, for example, the converging, diverging tube or venturi tube shown in figure 10.

The water has been saturated with air at atmospheric pressure; bubbles are created in the constricted region at that place where the vacuum reaches a value of at least one-half an atmosphere in the case of pure water. At their inception they have a diameter of say 0.6 micron.

The vacuum increases as the neck of the tube is approached. If a single small bubble is moving slowly in the constricted region and is always surrounded by water saturated with air at atmospheric pressures, the following formula holds:

$$r = \frac{2\sigma}{\Delta P}$$

where ΔP is the vacuum.

The formula shows that the neck where ΔP is a maximum the globule ought to be smaller than at its inception. and when the neck is passed ΔP decreases, and r increases approaching ∞ when $\Delta P = 0$. Then when the pressure of the water becomes greater than atmospheric pressure, the radius, r, ought to approach $-\infty$ in the limit. The law of equilibrium demands, therefore, that for an infinitesimal vacuum, the radius of the globules ought to be infinitely large, and that for a positive pressure the globules ought to be reabsorbed.

Naturally, the phenomenon does not take place in this way. Water is saturated with air only to two percent of its volume. When the pressure diminishes until it provokes the spontaneous creation of bubbles, they appear in numbers proportional to the amount of air separated from the water. Therefore these globules cannot increase indefinitely as the vacuum decreases. This can be the case only for a small bubble in water always saturated with air.

In reality, they form a kind of foam in the constricted region and the air is not supplied.[6]

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[6]In relieving the pressure in the water containing air at a greater pressure, one can conceive how the bubbles are generated, and tell why at their inception they have equal diameters. But in a short time a dispersion in the size of the bubbles is produced. Some bubbles grow at the expense of others. These by breaking up reduce to bubbles with a diameter of the order of microns.

It is not possible for us to pursue mathematically the change in diameter of the globules of air moving in the constricted region which diminish, then grow in size at the expense of the air diffused throughout the water.

We, therefore, pass over this period of very limited change in the diameter of the globule in order to consider the problem equally as interesting as the formation of the globule which dominates the destruction of metallic walls, that of the quasi-spontaneous disappearance of the globules at the moment when

$$P_e \geqq 1 - \frac{2\sigma}{r}$$

We now calculate the speed of contraction of a globule and the time required for its disappearance from the instant when its equilibrium is upset.

We shall neglect the initial speed of contraction which is then very small.

We also assume that the air presents no resistance to reabsorption.

This hypothesis appears admissible because at the last moment of its existence when the pressure is almost infinite the remaining residue of the air globule should be absorbed instantaneously. Furthermore, the volume of water surrounding the globule is very large compared to that of the globule itself.

If S is the unit weight of the liquid, g the acceleration of gravity, and considering the notation of figure 11, the kinetic energy of the whole mass of water contracting around the globule is:

$$A = \int_{r_1 = r}^{r_1 = \infty} \frac{4\pi r_1^2 S}{2g} \left(V \frac{r^2}{r_1^2} \right)^2 dr = \frac{2\pi S}{g} V^2 r^3$$

In this equation we have used the relation: $dA = \frac{1}{2}\, dm$

and the equation of continuity: $4\pi r^2 V = 4\pi r_1^2 V_1$

Let r be the radius of the globule at the instant when the sudden contraction commences and suppose that the acceleration is entirely due to the contraction resulting from the surface tension.

In fact there is a superposed phenomenon which acts in the same sense and which will be discussed later. However it is of small importance from the point of view of the difference of pressure.

We can then write that the change in kinetic energy is equal to the change in potential energy liberated by the contraction of the surface (change in capillary energy):

$$4\pi (r_o^2 - r^2)\gamma = \frac{2\pi s}{g} v^2 r^3$$

$$v^2 = \frac{2g\gamma}{s}\left(\frac{r_o^2 - r^2}{r^3}\right)$$

It is seen that the speed of contraction becomes infinitely large when the radius of the globule approaches zero because:

$$v = \infty \text{ , when } r = 0$$

In order to determine the time required for the globule to contract from the radius, r, to the radius, r = 0, we have:

$$v = \frac{dr}{dt} = \sqrt{\frac{2g\gamma}{s}\left(\frac{r_o^2 - r^2}{r^3}\right)} \qquad \frac{d\left(\frac{r}{r_o}\right)}{dt} = \sqrt{\frac{2g\gamma}{s r_o^3}\left[\frac{1-\left(\frac{r}{r_o}\right)^2}{\left(\frac{r}{r_o}\right)^3}\right]}$$

Putting $r/r_o = \sin \phi$, we have

$$t = \sqrt{\frac{r_o^3 s}{2g\gamma}} \int_{\phi=\frac{\pi}{2}}^{\phi=0} \sin\phi \sqrt{\sin\phi}\, d\phi = 0.873 \sqrt{\frac{r_o^3 s}{2g\gamma}}$$

The potential energy liberated, transformed into kinetic energy and finally absorbed in impact is:

$$A = 4\pi r_o^2 \gamma \quad \text{gram-cm.}$$

For the following radii of the globules: r = 0.005. r = 0.001. r = 0.0005, r = 0.0003 cm., the times required for the contraction are:

$$t = \frac{2.54}{10^5} \qquad t = \frac{2.28}{10^6} \qquad t = \frac{0.803}{10^6} \qquad t = \frac{0.3}{10^6}$$

seconds, respectively.

A globule which, at the critical moment, has a diameter of 10 microns, disappears in $8/10^7$ seconds. Entrained in a current whose velocity is 12.5 m/sec., it travels, therefore, 1/100 mm.

VI

The Influence of Oil on the Variation of the Adhesion of the Globules of Air to Water or to Metal: Oil, a Catalytic Agent of Cavitation.

Recently, the following problem was submitted to us: Four large bronze centrifugal pumps were tested in Holland and indicated a high efficiency. At Curacao where they were used to pump sea water for an oil refinery they incurred extreme cavitation.

We attributed this to the fact that the water was contaminated with oil. Some laboratory experiments demonstrated that with traces of Diesel oil the vacuum in the venturi tube is increased and the cavitation more pronounced due to this so-called catalyzer of cavitation.

What then is the role of the oil? In the first place, all of the experiments showed that the surface tension of the water was much diminished when contaminated with oil.

Furthermore, it is believed that air bubbles do not attach themselves to glass surfaces or damp metallic surfaces if they are absolutely clean; the result is that the bubbles cannot form as the experiment on boiling water in a clean container demonstrated.

In other words, the presence of the oil in water and on wet walls has a double effect. First, it diminishes the surface tension of the contaminated water, and, second, it increases the cohesion of air bubbles to the greasy surfaces. These two effects lead to the same results because they both increase the affinity of air bubbles for solid surfaces as opposed to water.

According to the tables of Landolt and Bornstein, the angle of capillarity between oil and brass (in the presence of water) is from four to six degrees; this is small but it is sufficient to fix microscopic globules of air to the walls of the constricted region.

Air bubbles do not attach themselves to damp leather which is a material resistant to cavitation.

For this reason moist leather washers are utilized in household faucets.

It is possible that damp metals which are absolutely pure do not have a large enough angle of capillarity with air bubbles for the latter to attach themselves.

Figure 12* shows a photo-micrograph of an air bubble one-half millimeter in diameter adhering to a polished steel surface cleaned with alcohol. The angle of capillarity is 22-1/2 degrees.

This phenomenon should be different when the medal is greased. Water discharged from hydraulic turbines and pumps and water in the wake of ships is always contaminated by traces of oil for which metallic walls have a large affinity and to which the globules of air adhere tenaciously. Figure 13* is a photograph of a globule of air 1/2 millimeter in diameter adhering to a polished steel surface greased with a little vaseline. The angle of capillarity is now 90 degrees and the globule is a hemisphere. The globules in the constricted region can be so conceived.

It is necessary to add for the sake of being complete that the angle of capillarity is larger when the globules are contracting than when they are expanding. The globules represented in the figures are expanding.

VII

Large Local Pressures Subsequent to the Sudden Contraction of Air Bubbles: Their Effect on the Erosion of the Walls.

All of the globules are created within the constricted region. Many of them are carried along by the current in which they collapse. Others which remain fixed to the walls destroy material as will now be shown.

What are these forces which destroy material?

In the limiting case when the angle of contact is zero degrees, that is to say, when the globule is in contact with the surface at apoint, the force of the impact is directed against the wall and the capillary energy, $A = 4\pi r_0^2 \gamma$. is expended at the point of contact.

Let us assume that in reality the globules are hemispherical in shape as represented in figure 13 and let us study further the distribution of pressure at the moment of collapse of a globule.

First, imagine that the globules do not contract to a point, but that the surface possesses hemispherical cavities which contain weightless, elastic, incompressible spheres such as shown in figure 15.

Because of symmetry and equilibrium the distribution of pressure ought to be that indicated in the figure.

* For photographs, see the original paper.

However, in this study it is not a question of a static force but of the impact of water on metal, in other words. of a collision between two elastic bodies.

We commence by calculating the pressure of contact between two bars of infinite length and of unit cross section. whose ends collide with a relative velocity v. Let μ and E be the unit weight and the modulus of elasticity, respectively of the bars and u the velocity of sound in the bar. Consider the instant when the pressure, p, reaches a maximum, and let w be the velocity of the separation at this instant. Consider one of the bars and the front of the sound wave at rest, the bar moving in the opposite direction to the velocity of the sound.

It is known that due to the effect of the collision a part of the bar is compressed at a uniform pressure, p, the front of the sound wave (in the region between the compressed part and the part which is not influenced by the collision) moving with the velocity of sound.

It is easily shown that:

$$\left(\frac{1}{2} v - w\right) = \frac{p}{E_1} u_1$$

$$\left(\frac{1}{2} v + w\right) = \frac{p}{E_2} u_2$$

$$v = p\left(\frac{u_1}{E_1} + \frac{u_2}{E_2}\right), \quad p = \frac{E_1 E_2}{u_1 E_2 + u_2 E_1} \quad \text{But} \quad u = \sqrt{\frac{E}{\mu}}$$

Therefore

$$p = \frac{u_1 \mu_1 \; u_2 \mu_2}{u_1 \mu_1 + u_2 \mu_2} \quad \text{or} \quad p = v \frac{\sqrt{\mu_1 E_1} \; \sqrt{\mu_2 E_2}}{\sqrt{\mu_1 E_1} + \sqrt{\mu_2 E_2}}$$

The same formulas are obtained for the force transmitted by an incompressible body without mass, interposed between the two bars; and these formulas are also valid for the case represented in figure 15. The last two formulas give, therefore, the unit pressure for the case when the globule is contracting strikes the incompressible interposed sphere, v, being calculated from the formula on page 10.

When no such sphere is interposed. when the hemispherical globule can contract to a point, v beomes infinite and the two formulas for the pressure when $v = \infty$ reduce to $p = \infty$.

No material can resist a collapse which creates an infinitely large pressure.

VIII

Phenomenon of the Beginning of Contraction of the Bubbles and the Zone of Erosion.

How do the bubbles begin to contract? Let us return to the case of the venturi tube.

Figure 17 illustrates a case of cavitation of the first category potent enough to destroy materials by erosion. At some place on the walls the globules collapse.[7]

[7] Ackeret, J. Experimentale und Theoretische Untersuchungen uber Hohlraumbildung im Wasser, p. 32. Stossvorgang in einen Kanal. (Experimental and Theoretical Investigation of Cavitation in Water. Impact in a Tube).

Because of the space occupied by the globules up to the boundary where they disappear, certainly the velocity of the water in this region is considerably augmented.

When this limit has been passed the effective cross section of the water becomes normal again and the liquid undergoes a sudden retardation.

The average increase of the abrupt change of pressure due to this retardation from v_1 to v_2 can be calculated from the following equation:[8]

$$P_2 - P_1 = V_2 \, S \left(\frac{V_1 - V_2}{g} \right)$$

[8] Andre Tenot: See footnote 2.

in which s = the unit weight of the liquid.

This phenomenon (Borde-Bellanger) which is similar to that produced on the surface of the blades of turbines, pumps and propellers is accompanied by a dissipation of energy: $\frac{(V_1 - V_2)^2}{2g}$ per unit weight of water; that is one of the causes of the decrease in the capacity when the cavitation is present but it does not explain the localized difference of pressure capable of eroding the walls.

This sudden retardation of the liquid, a veritable earthquake, compresses the globules until the state of equilibrium between the interior and exterior pressure differential and the surface tension is destroyed.

The increase of pressure due to the retardation is so large that it facilitates the reabsorption of the air. thus the hypothesis which we have made in our analysis of neglecting the resistance to the reabsorption of the air is justified.

We should state again why the zone of cavitation is not bounded by a well defined frontier.

The flow in hydraulic machines is ordinarily unstable because of the large amount of turbulence always existing in the flow and also because of the variation in the pressure in turbines and pumps. The frontier of the globules moves back and forth because of the turbulence produced in the constricted region. which has been studied by Burgers and v. Karman. These globules do not exist individually.

As to why destructive cavitation manifests itself, it is necessary to imagine a region in the constriction through which the foam moves and which contains enough energy due to the surface tension that the sudden release of this potential energy becomes dangerous.

Then crevices commence to form and the destruction of the wall follows rapidly. The foam enters the fissures. As a result of this back and forth movement the line a-a passes over these fissures, the air bubbles there are compressed because of the sudden retardation of the water and then their capillary energy is released.

We have remarked that the beginning of cavitation is characterized by an increase in the capacity of hydraulic machines.

With the development of laboratories and the general adoption of model testing, there is a tendency to regard slight cavitation with insufficient knowledge.

For high Reynold's numbers, that is to say, in the execution of large scale projects, the growth of the constricted region is proportional to the linear dimensions of the mechanical parts. The dimensions of the globules, the time of their disappearance, and the path traversed after the critical instant are independent of the scale. It follows that for a unit of surface of the mechanical parts, the excess energy liberated increases with the linear dimensions and for large hydraulic machines as well as for the propellers of ships the effects of cavitation can be important while they are imperceptible in small models.

TABLES FOR CONVERTING UNITS USED IN FIGURE 7

Temperature °C	Temperature °F	Vapor Tension Abs. Ft. of Water
0	32.0	0.20
1	33.8	0.22
2	35.6	0.24
3	37.4	0.25
4	39.2	0.27
5	41.0	0.29
6	42.8	0.31
7	44.6	0.33
8	46.4	0.36
9	48.2	0.38
10	50.0	0.41
11	51.8	0.44
12	53.6	0.47
13	55.4	0.50
14	57.2	0.53
15	59.0	0.57
16	60.8	0.61
17	62.6	0.65
18	64.4	0.69
19	66.2	0.73
20	68.0	0.78
21	69.8	0.83
22	71.6	0.88
23	73.4	0.94
24	75.2	1.00
25	77.0	1.06
26	78.8	1.12
27	80.6	1.19
28	82.4	1.26
29	84.2	1.34
30	86.0	1.41
31	87.8	1.50
32	89.6	1.59
33	91.4	1.68
34	93.2	1.77
35	95.0	1.87
36	96.8	1.98
37	98.6	2.09
38	100.4	2.21
39	102.2	2.33
40	104.0	2.46

Absolute Pressure			
Cm. of Water	Ft. of Water	Cm. of Water	Ft. of Water
350	11.48	710	23.29
360	11.81	720	23.62
370	12.14	730	23.95
380	12.47	740	24.28
390	12.80	750	24.61
400	13.12	760	24.93
410	13.45	770	25.26
420	13.78	780	25.59
430	14.11	790	25.92
440	14.44	800	26.25
450	14.74	810	26.58
460	15.09	820	26.90
470	15.42	830	27.23
480	15.75	840	27.56
490	16.08	850	27.89
500	16.40	860	28.22
510	16.73	870	28.54
520	17.06	880	28.87
530	17.39	890	29.20
540	17.72	900	29.53
550	18.05	910	29.86
560	18.37	920	30.18
570	18.70	930	30.51
580	19.03	940	30.84
590	19.36	950	31.17
600	19.68	960	31.50
610	20.01	970	31.82
620	20.34	980	32.15
630	20.69	990	32.48
640	21.00	1000	32.81
650	21.32	1010	33.14
660	21.65	1020	33.46
670	21.98	1030	33.79
680	22.31		
690	22.64		
700	22.97		

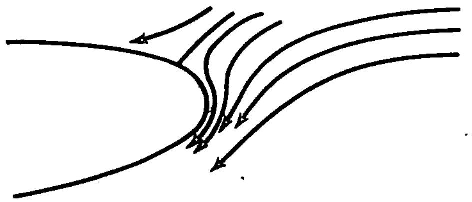

FIGURE 4 - SOME STREAM LINES RELATIVE TO THE VANE ABOUT TO ATTACK AN IMPELLER OF ONE OF THE CENTRIFUGAL PUMPS AT MEDEMBLIK ACCORDING TO BURGERS AND VAN DER HEGGE ZIJNEN

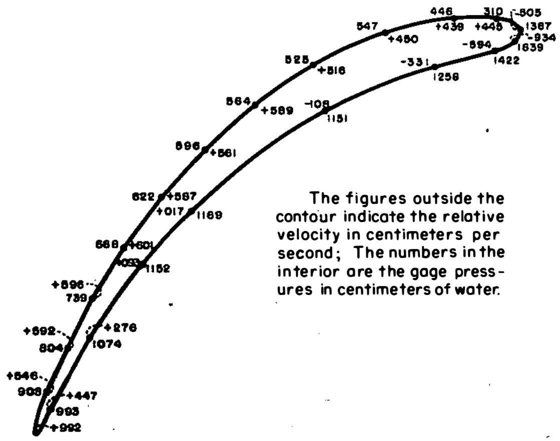

FIGURE 5 - DISTRIBUTION OF VELOCITY AND PRESSURE AROUND A VANE OF AN IMPELLER OF ONE OF THE CENTRIFUGAL PUMPS AT THE "LELY" STATION AT MEDEMBLIK

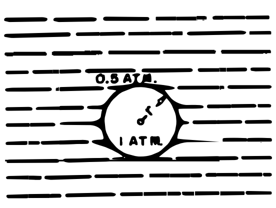

FIGURE 8 - THE AIR PRESSURE WITHIN THE BUBBLE FLOATING IN WATER SATURATED WITH AIR AT ATMOSPHERIC PRESSURE ACQUIRES EQUILIBRIUM WITH THE WATER PRESSURE AND SURFACE TENSION

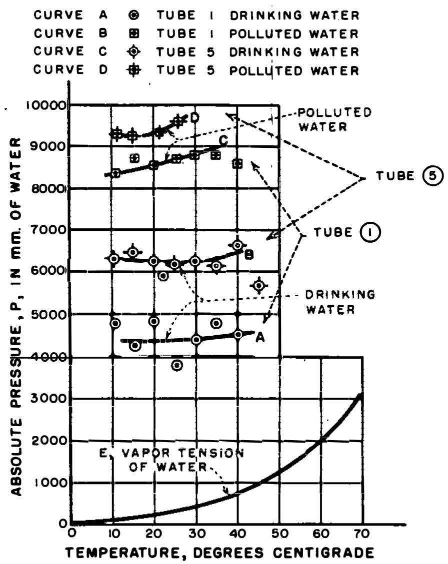

FIGURE 7 - ABSOLUTE PRESSURE AT THE INCEPTION OF CAVITATION FOR BOTH PURE AND POLLUTED WATER AS A FUNCTION OF THE TEMPERATURE

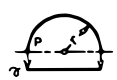

FIGURE 9 - EQUILIBRIUM OF OF A SURFACE EXTENDED BY INTERIOR PRESSURE

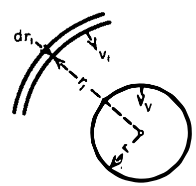

FIGURE 11 - BUBBLE CONTRACTING CONCENTRICALLY

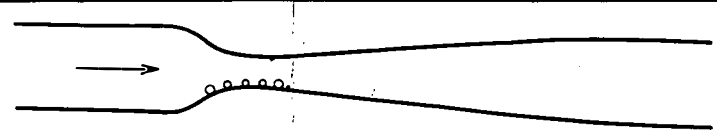

FIGURE 10 - AIR BUBBLES ADVANCING ALONG THE THROAT OF A VENTURI TUBE. THE POINT TO THE RIGHT INDICATES WHERE THEY SUDDENLY DISAPPEAR

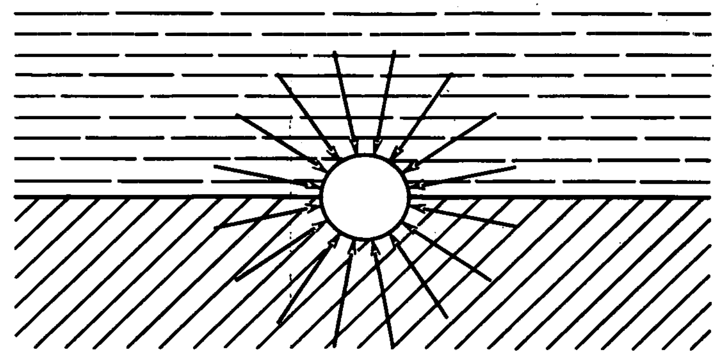

FIGURE 15 - IMPACT OF A HEMI-SPHERICAL BUBBLE CONTRACTING ON AN INCOMPRESSIBLE, WEIGHTLESS SPHERE RESTING IN A SURFACE CAVITY

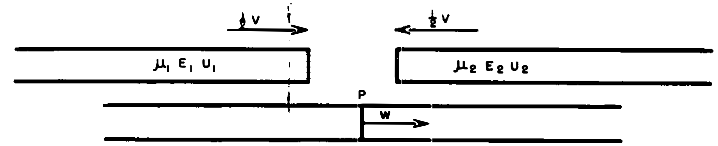

FIGURE 16 - AXIAL IMPACT BETWEEN TWO BARS OF DIFFERENT MATERIALS

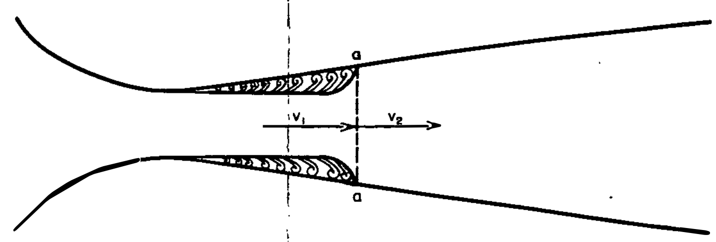

FIGURE 17 — CAVATATION OF THE FIRST CATEGORY CHARACTERIZED BY THE SPONTANEOUS DISAPPEARANCE OF AIR BUBBLES AT THE FRONTIER, a-a, WHICH OSCILLATES BACK AND FORTH