UNITED STATES
EXPERIMENTAL MODEL BASIN

NAVY YARD, WASHINGTON, D.C.

CAVITATION

BY J. ACKERET

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CAVITATION

by J. Ackeret

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Translated by M. C. Roemer

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INTRODUCTION

Cavitation in flowing liquids occurs when the static pressure at any point in the stream drops to the vapor pressure corresponding to the temperature of the liquid. The liquid then boils and, through the formation of bubbles, is converted into a heterogeneous mixture of liquid and gaseous phases. It is understandable that a considerable disturbance will be created in the flow, and this phenomenon has caused much trouble in the design of rotating machines.

In spite of this fact, cavitation, as this formation of hollow spaces is known technically, though comparatively easy to reproduce in the laboratory, has until now been given practically no attention in physics. Thus for the last twenty years the engineering profession has been forced to study the problem. Loss in efficiency and power output of hydraulic machines may follow as a result of the disturbance in flow, but in addition, experience shows that, particularly for high velocities, the appearance of cavitation gives rise to extensive corrosion, i.e., destruction of the surface over which the flow has taken place, the surface taking on a spongy appearance. Many theories have been formulated in order to explain the often contradictory experimental results, but we are still far from a satisfactory understanding of the corrosion phenomena.

Technical knowledge of cavitation and corrosion is scattered and unsystematic. In factories, shipyards, and power stations there is to be found a great mass of data which for the most part has not been worked over. It will not have much value until more light has been shed on the principal problems through systematic laboratory research under controlled conditions.

Cavitation is not a purely hydrodynamic phenomenon. Since vaporization is dependent on heat conduction, capillarity, etc., thermodynamics must be brought in, and theoretical treatment becomes unavoidably complicated. Fortunately for engineering, only the avoidance of cavitation and seldom the peculiarities of developed cavitation is commonly of importance, so that for practical use simple rules for the inception of cavitation are provisionally sufficient. The physicist, however, will be interested in the developed cavitation itself, as a means of attacking the problem of corrosion.

The experimental investigation of cavitation is still in its elementary stages. Very little systematic work has been done. For industrial purposes there exist today a large number of cavitation laboratories, the function of which is to determine quantitatively the point at which cavitation begins with hydraulic models in order to avoid unfavorable conditions in the full-scale structures. With the rapidly growing importance of cavitation in the improvement of hydraulic machines, and with increased activity, experimental and theoretical, in the laboratory, we may anticipate that the present unsatisfactory condition of our knowledge will soon be improved.

CHAPTER I

GENERAL CONSIDERATIONS ON THE SUBJECT OF CAVITATION

1. BEHAVIOR OF FLUIDS AT VERY LOW PRESSURES

The curve representing Van der Waal's equation gives us a good insight into the behavior which is to be expected from a fluid when (at constant temperature T_1) the pressure is continuously decreased. In the p – v curve (Fig. 1) the isotherm is labeled A–B–C–D–E–F–G. Let A be the starting point. If we decrease the pressure we move in the direction of the arrow, toward B, where the pressure is that at which vaporization takes place normally; this pressure is constant as we go from B through D to F, which points correspond to the gaseous condition. B is the point representing the state where we must first expect the appearance of cavitation.

With water, the pressure p_B for various temperatures is:

t =	0	5	10	15	20	25	30	50	70	100° C
p_B =	0.0063	0.0089	0.0125	0.0173	0.0236	0.0320	0.0429	0.125	0.317	1.033 kg/cm²

If the investigation is to be made with special care, the liquid used must first be completely freed of gas, placed in carefully cleaned glass vessels, and protected from shocks of all sorts; in this way we may succeed in bringing B down toward C. If the temperature of the liquid is low, (for example, $T = T_2$ = room temperature for water or mercury) the isotherm will cut the line of zero pressure, which is to say that negative pressures, or tensile stresses will be set up in the liquid.

J. Meyer found maximum tensile stresses of 34 atmospheres for distilled water, 39.5 atmospheres for ethyl alcohol, and 72 atmospheres ethyl ether. However, the rupture strength was not reproducible, and appeared to be dependent on many chance conditions. For water, the point C is very much lower, of an order of magnitude of –1000 atmospheres. Whether tensile stresses may also be set up in industrial liquids, which are always more or less impure, is as yet uncertain, but certainly conceivable. In many cases an individual liquid element will be in the region of low pressure for but an instant, which will be too short a time for vaporization, that is, for supplying sufficient heat.

Aside from this, a certain amount of gas separation naturally takes place when such gas is present in solution in excessive amounts, and the solution is subjected to low pressure for some time. It is entirely inadmissible to speak of cavitation in flow, since a gas can give any pressure drop desired through expansion.

It is not without interest, however, to note that in spite of this there exist many analogies between cavitation phenomena and flow processes at the velocity of sound.

2. PRESSURE DISTRIBUTION IN FLOWING LIQUIDS

Where a flowing liquid is free of vortices (in the hydrodynamic sense), which is true in many cases of practical importance, the pressure equation is:

$$p = \text{const} - \varrho g z - \frac{\varrho}{2} c^2 - \varrho \frac{\partial \Phi}{\partial t} \tag{1}$$

where p is pressure, ϱ density (constant), c velocity, Φ velocity potential, z the height of the reference point, and g the acceleration of gravity.(11)* The term $\varrho \frac{\partial \Phi}{\partial t}$ disappears for steady flow, in which case Eq. (1) is transformed into the well-known Bernoulli equation,

$$p = \text{const} - \varrho g z - \frac{\varrho}{2} c^2$$

in which the constant applies for the whole region of flow. Cavitation may first be expected where $\left(\varrho g z + \frac{\varrho}{2} c^2\right)$ is a maximum. If we disregard the influence of gravity, which procedure is permissible in many cases, cavitation will appear where the absolute value of the velocity is a maximum.

According to an important principle of Kirchhoff(10)(11), the greatest velocities, in frictionless and vortex-free flow, are found not within the body of the liquid, but always at the boundary walls. Despite the fact that we may not ignore fluid friction at the surface, the Kirchhoff rule is very often realized in practice. The frictional effects extend, in these cases, only to a thin boundary layer, while potential flow prevails outside, and the pressure distribution is almost undisturbed.

Figure 2 shows some examples; the small circle indicates the region of lowest pressure.

For full bodies the boundary layer is easily removed; a strongly turbulent body of dead water arises, and in some cases larger discrete vortices (Kármán vortices) are formed. An especially low pressure prevails then in the vortex cores, and investigations often discover the first indications of vaporization here. The Kirchhoff principle is then, naturally, not applicable. (Not vortex-free)

Strong single vortices with central cavities filled with water vapor sometimes arise from water propellers, turbines, etc. Fig. 3 gives a photograph of such a tube which moreover possesses very uniform constrictions. Flamm(5) has made a large number of stereo-photographs of propeller vortices.

The variable term $\varrho \frac{\partial \Phi}{\partial t}$ figures in the case of reciprocating water pumps, for example, where the velocity of the approaching water is always changing, and also in water power pipe lines.

* Numbered references will be found in bibliography.

CHAPTER II

EXPERIMENTAL INVESTIGATION OF CAVITATION

Due to the lack of systematic research, we can only concern ourselves with typical or technically important cases.

1. FLOW THROUGH CHANNELS AND TUBES

Convergent-divergent tubes (nozzles) are very suitable for producing and investigating cavitation. O. Reynolds[18] described the following research a long time ago: Water flows out from a water pipe after passing through a convergent-divergent glass tube, Fig. 4. At the constricted point the pressure is lowest, as given by Bernoulli's equation, and cavitation is accordingly to be expected there. Down stream of the constriction there is formed a bubble layer of variable extent. "Water at ordinary temperatures boils in an open vessel", he said, in order to bring out the paradoxical character of the phenomenon. If the barometric pressure is B, cavitation is possible at the narrowest cross-section when the influx pressure p_1 is greater than B/η_s, where η_s is the degree of conversion, or efficiency of the diffusor connected at the narrowest cross section.

Practically, η_s is about 0.6 - 0.7, therefore a pressure $p_1 = 10/0.6 = 16.7$ meter head of water, absolute, is necessary. Domestic water lines are therefore satisfactory for the investigation. Smoluchowski[19] initiated similar researches.

Fliegner[6], Hochschild[9], and Ackeret[1a][1b] repeated these investigations with better apparatus and measured the pressure. In these last experiments, the rate of flow was maintained constant, (accordingly, at constant Reynolds' number) but the absolute pressure in the measuring region was varied by throttling the nozzle.

If the throttling is quite strong we have the pressure distribution shown in Fig. 5. The pressure drops from p_1, at the entrance A to the vapor pressure of cold water, and remains constant until the throttling station is reached (curve ABCD). If now it is throttled, the pressure at the entrance varies but that at the beginning of the diverging part of the nozzle does not. The vapor bubbles, however, draw back toward the narrowest cross section. The pressure mounts rapidly at the point (C) where they disappear. (Curve ABCE) By throttling more strongly, the pressure curve is shifted to the position ABF as a result of which the bubbles at the narrowest cross section B will disappear. Until then the rate of flow is unaltered. It is not until the resistance is further increased that, with p_1 still constant, the rate of flow falls off. This behavior is very similar to the processes in the Laval vapor nozzle, where the rate of flow does not vary with increased resistance as long as the resistance is not so high that the critical pressure is exceeded in the narrowest cross section. There, also, we find in the diverging section a rapid increase in pressure. As Stodola has shown, we are dealing, in the Laval nozzle, with a Riemann condensation stratum*. A condensation stratum is also possible in the case of cavitation.[1a] It occurs where the bubbles disappear, therefore at C in Fig. 5.

The following consideration gives an idea of the magnitude of the pressure jump: Let a mixture of pure water and vapor bubbles flow through a tube. Let A–A of Fig. 6 be the plane of the pressure jump. Equations of continuity and the momentum law now give, in the stationary condition

$$\varrho_1 u_1 = \varrho_2 u_2 \qquad \text{(equation of continuity)}$$
$$\varrho_1 u_1 (u_1 - u_2) = p_2 - p_1 \qquad \text{(momentum law)}$$

After the jump the bubbles are small or else they are condensed. ϱ_2 is then equal to ϱ_0, the density of the pure water. For ϱ_1 we can write

$$\varrho_1 = \varrho_0 (1 - \chi),$$

where χ represents the bubble content, by volume, before condensation. Then

$$p_2 - p_1 = \frac{\varrho_0 u_1^2}{2} 2 (1 - \chi) \chi.$$

The jump becomes a maximum for

$$\chi = \frac{1}{2},$$

that is,

$$p_2 - p_1 = \frac{\varrho_0 u_1^2}{2} \cdot \frac{1}{2}.$$

For the densest packing of spheres, χ would be

$$\chi = \frac{\pi\sqrt{2}}{6} = 0{,}74;$$

In practice, however, the concentration of bubbles is not so great. In the nozzle experiment the stratum is not uniform, but in principle it proceeds smoothly. Detailed study of the mechanism of the condensation processes have been made by Ackeret.[1b] The significance of condensation in corrosion phenomena will be given in the third chapter.

Figures 7 and 8 give two shadow photographs of bubble formation in the divergent part of the nozzle. The picture of the bubbles is taken against a white band. Fig. 7 corresponds to a lesser throttling, Fig. 8 to a greater throttling. The point at which the white band stops is the seat of the pressure jump.

2. INVESTIGATION WITH AIRFOILS

The blades of ship propellers and the blades of low pressure water turbines and pumps show a broadly analogous behavior with respect to the cavitation phenomena. Investigations on wing sections were carried out by Ackeret[1b] and Mueller[13] at the K. W. Institut für Strömungsforschung at Göttingen. The test arrangement is shown

* See article by Busemann, "Gasdynamik" p. 394 et seq.

in Fig. 9. The water, driven by a rotary pump, flows through pipes in a closed circulating system. The function of the reservoir is to equalize the pressure variations, and above all to remove the air bubbles which arise in the pump. The air space above the water surface in the reservoir is connected to a vacuum pump or a compressor, as the case may be. In this way it is possible to give the absolute water pressure any value desired within certain limits, while keeping the velocity in the pipes absolutely constant and therby keeping the Reynolds' number fixed. The measuring chamber consists of a rectangular channel, in which the section to be investigated is installed. The bubble formation can be observed through glass windows. Fig. 10 shows a foil in place; Figs. 11, 12, and 13 show a thick wing section investigated by Ackeret, Figs. 14 and 15 a crescent section, such as is often used for ship propellers. On lowering the pressure the first bubbles appear at the points of lowest pressure. From here they stretch out behind and disappear at a distance which depends, in an almost completely reproducible manner, on the external pressure, Fig. 11. Pressure measurements show, here also, a pressure increase at the end of the band of bubbles. As the pressure drops further, (velocity remining constant) condensation moves toward the rear edge and even extends out beyond this edge. At a definite external pressure the bubbles will finally disappear, and a space is formed which contains no liquid water, but is filled with water vapor at the saturation pressure. We then have two free flow-boundaries in the Kirchhoff-Helmholtz sense. Fig. 13 (shadow photograph). With thin sections bubble formation is present at the leading edge almost as soon as the foil forms any angle with respect to the flow. Here also the bubble area extends backward when the pressure is lowered, Figs. 14 and 15.

Let us consider a definite condition of cavitation, for example that in which the whole blade surface is covered with bubbles. At a distance from the foil such that the flow may be considered as undisturbed, the pressure will be p, velocity c, and dynamic pressure $\frac{\varrho}{2} c^2 = q$. In the bubble region, the vapor pressure p_d will prevail, and velocity c_d. Then according to Bernoulli's equation

$$p - p_d = \frac{\varrho}{2}(c_d^2 - c^2) = q\left(\left(\frac{c_d}{c}\right)^2 - 1\right).$$

Proceeding from this to obtain the same condition of cavitation, that is, the same flow pattern, we may not choose p and q at will, since c_d/c is then a fixed ratio, but we must have

$$p = p_d + \lambda q,$$

Therefore there is a linear relationship between p and q. Fig. 16 gives the experimental confirmation of this relationship for the blade section of Fig. 11, with an angle of attack of +2 degrees, (angle between under side of section and direction of flow). In fact, as typical cases, investigations were made of the inception of cavitation, the covering of the whole upper surface of the wing, and the complete separation, with formation of free flow-boundaries. Further values are given by Ackeret[1b].

Mueller*, was able to trace the bubble formation at the hydrofoil more closely with the aid of Thun's slow-motion outfit, a moving-picture arrangement which, with the help of slotted discs gives rapid short-time exposures of as many as five thousand per second.

Figure 17 shows a section of the film. At the left we see, at time intervals of 1/1200 of a second, the shadow picture of the bubbles, and at the right, at time intervals of 1/5000 second, a view of the bubbles from above. Fig. 18 gives a section of the right-hand film which contains ten single exposures and which shows very clearly the bubbles and how they first arise and then disappear while moving in the direction of flow.

3. INVESTIGATION OF OTHER BODIES

Spheres were investigated with respect to cavitation by Ramsauer(15) and Ackeret(1b). Here is a case where the bubble formation does not take place on the upper surface of the body, as would be predicted from the Kirchhoff law, but begins in the large vortices behind the body. It is only at low pressures or high velocities that the bubbles approach the sphere and finally fill the region behind the equator, which is designated as the dead-water zone. Here also the disappearance of the bubbles shows itself by a pressure jump. For very low pressure a cavity filled with water vapor is then formed very much as for the hydrofoil, Fig. 20.

Bauer(2a) and Ramsauer(15) shot steel spheres through water at high velocities (up to 600 m/sec). Ramsauer was able to confirm the cavity behind the sphere, but unlike Fig. 20, it formed a cone with a wide-angled apex. Bauer has treated this type of cavitation theoretically.

4. CAVITATION OF SHIP PROPELLERS

The phenomena observed on the blades of ship propellers are, in the main, similar to those observed for the single airfoil. Besides the bubble formation on the surfaces, however, separation takes place in the very intensive individual vortices which detach themselves from the individual blade tips and from the boss. At high velocities, free flow-boundaries are formed (corresponding to Fig. 13) which lower the propeller thrust considerably. The constructors of the first torpedo boat of the English navy to be propelled by steam turbines contended with this phenomenon for ten years (1890-1900) and the name "cavitation", which was first coined by Barnaby, dates back to this era. The solution of the difficulty, which was soon found, was first, to make the specific thrust, that is, the thrust per unit of blade surface, as small as possible, and second, not to choose too high an RPM. To be sure, the latter could at first be achieved without loss of turbine efficiency, as cog wheel or liquid

* loc. cit.

reduction gears were successfully built in 1912. The propellers of high speed steamers are, in the first respect, characteristically different from air propellers, Fig. 21, since in the latter cavitation takes no part at all, and the surface must be made as small as possible in order to decrease the resistance.

The water depth (H in Fig. 22) in which the propeller turns is naturally of great significance in the occurrence of cavitation. Submarine propellers turn without cavitation at great depths, and only begin to show cavitation on rising.

5. CAVITATION IN WATER TURBINES AND PUMPS*

With further increase of the power transmitted, and of the head or gradient used, the problem of cavitation in circulating machines has gradually become of paramount significance. Unlike propellers, in the case of turbines and pumps there usually exists the further difficulty that the impeller, which is generally endangered, is above the level of the tail water, and therefore works by suction head (Fig. 23, which represents a suction arrangement). Between impeller and tail water is a static head H_s (suction head). H_s should not, of course, amount to more than the barometric pressure, B, and therefore at sea level it should be equal to approximately ten meters of water. Actually this pressure is out of the question, for the lowest pressure on the blades, which is determinative for the development of cavitation, as a result of the dynamic pressure drop, is very much lower than $B - H_s$. Since dynamic pressures are all proportional in a rotating machine, the transmitted head H and the dynamic suction are all proportional to the dynamic pressures, and we can simply set these proportional to the fluid heads. For dynamic decrease the maximum which is available is $B - H_s$. The ratio

$$\frac{B - H_s}{H} = \sigma$$

gives this reserve in dimensionless form, and it is considered as a cavitation coefficient of D. Thoma[21a]. As σ grows smaller the reserve grows smaller, and greater cavitation phenomena are to be expected. Turbine manufacturers have recently been experimentally investigating the cavitation in turbo-machines. A model of the turbine or pump in question is usually tested at constant total head H, but with variable suction head H_s and pressure head H_d. If there were no cavitation, the work N, the efficiency η, and the weight of water passing through Q, would remain constant for all values of σ. For small values of σ, however, cavitation manifests itself in many ways. Fig. 24 shows schematically such a test arrangement. The water circuit is not completely sealed, so that the suction water level can be set at various heights, and the suction head thereby varied. The weight of the water is measured in this case with a

* References (1c), (3), (7c), (17), (20), (21a), and (21b). It is remarkable that L. Euler in 1754 had already considered cavitation in his Turbine Theory.[4]

calibrated nozzle, (Venturi meter). The level of the tail water is varied by means of the slide valve D. The turbine shown schematically in Fig. 23 possesses an impeller in the form of a propeller. Fig. 25 shows the flow of water, the efficiency, and work for constant total head, and for variable σ, for a five-bladed wheel, a so-called Kaplan turbine. For $\sigma = 0.45$ a considerable disturbance is set up, in which work and efficiency drop off rapidly as σ is decreased, and the water passing through increases. This abrupt change is a result of the formation of a free flow-boundary (as in Fig. 13) in the outer parts of the wheel. Bubble formation on the suction side of the blade was observed for values of σ as low as 0.6. With the help of such research, it is possible so to direct the installation of great power station turbines that cavitation with its harmful results can be avoided. While increasing the size of the blade surface in order to escape cavitation is possible for ship propellers, the unlimited increase in the size of the blades is prevented by the attendant rapidly increasing frictional forces. Frictional losses and danger of cavitation are today the Scylla and Charybdis of rotating machines for liquids.

CHAPTER III

CORROSION ATTENDANT UPON CAVITATION*

It has been known for a long time that there was a relation between cavitation and the severe corrosion of material which often took place. At large relative velocities between the water and the body surfaces, this corrosion can occur to an extraordinary degree. Cases have been known where turbine impellers and ship screws were badly damaged after but a few days of use. Since physical and chemical properties of the materials no doubt play a considerable part, it is conceivable that our knowledge of the causative conditions is particularly scanty here.

Surfaces which have been corroded by cavitation are characterized by their fissured, sugary, porous appearance, in contrast to the smoothly polished surfaces produced by the erosion (scouring by sand) which occurs so frequently in turbines.

Ordinary cast iron is a material which is particularly susceptible to attack by corrosion. Where cast iron impellers are in service for some time, they are often badly damaged. Figs. 26 and 27 show a piece of a cast iron blade of a large turbine impeller, Fig. 26 the surface and Fig. 27 the section of the corroded blade. At several points the blade, which was about 40 mm thick, was completely broken through. As might have been expected, the pressure side of the impeller blade was not attacked. Figs. 28 and 29 show the corrosion of the cast iron impeller of a turbine for higher pressure heads. Considerable corrosion is present at the entrance to the sharply

* References (1a), (3), (7b), (7c), (14), (20), and (21).

curved blade (Fig. 28) as well as at the exit (Fig. 29), where the lowest pressure prevailed.

Cast steel is superior to cast iron, and bronze is better still; more precise investigations, which would be of great importance, are lacking as yet.

Ship propellers often show corrosion at those points where the very powerful vortices mentioned on P. 7 attach themselves to the propeller blades.

Besides metals, according to Föttinger(7c), glass is also corroded when velocities are sufficiently high, and in addition, agate and the like seem to be attacked. Experiments on the protection of turbine blades through enameling have, as far as is known, proved fruitless.

The theoretical insight into the phenomenon of corrosion is still very meagre. While the talk at first was of purely chemical forces, with mention of nascent oxygen in the bubbles and emphasis on the relatively greater solubility of oxygen in water as compared to nitrogen, today we are inclined to believe that the processes involved are essentially mechanical. C. A. Parsons(14), Föttinger(7), and Ackeret(1b) have thoroughly identified themselves with this view. If we consider the results of recent research, the mechanical theory may be represented as follows:

A vapor bubble which travels in the direction of the current flow comes, finally, into the zone of sharp pressure increase, into the condensation stratum. The pressure increase in the stratum amounts in normal cases to several atmospheres, and is therefore not capable of achieving any noteworthy mechanical effects. When the bubble floats through the stratum, however, it is compressed to the rear of the stratum by the greater external pressure, p_a. Fig. 30. Its originally large radius 1 is diminished. The equilibrium position 2, which corresponds to the external pressure p_a, is exceeded, however, as a result of the inertia of the water flowing in the direction of the arrows, and the compression continues up to position 3. It is easily shown that the small radius 3, corresponds to very large pressures which are very quickly reached. Assuming isothermal compression of the gas content, for the sake of simplicity, although the heat transfer required for this condition to be true would certainly not be sufficiently rapid, the energy law would give us, through equating of the work done outside by p_a with the compressive work done on the bubble, approximately

$$\frac{p_3}{p_1} = e^{\frac{p_a}{p_1}}$$

from which, since p_a/p_1 readily assumes values of the order of magnitude of ten, extraordinary pressures may result. Thorough calculations give values of hundreds to thousands of atmospheres. From the order of magnitude, this mechanism would be sufficiently effective; a further argument in its favor is the observation that the damage is greatest where our present knowledge would have us predict the condensation stratum.

In general, the evidence is against purely mechanical erosion; it is more likely that the rapidly varying mechanical strains to which the external surface is subjected intensify the chemical action, which is always present even though evident only at the surface. We are not certain, however, so that much experimental work is still to be done in the satisfactory solution of this extremely important practical problem of corrosion.

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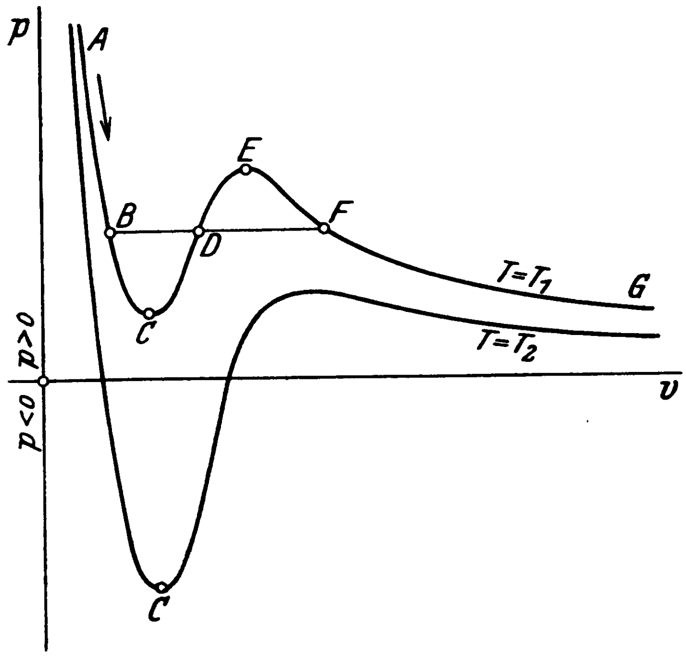

Fig. 1. Van der Waal's Chart.
Possibility of occurrence of tensile stresses in liquids.

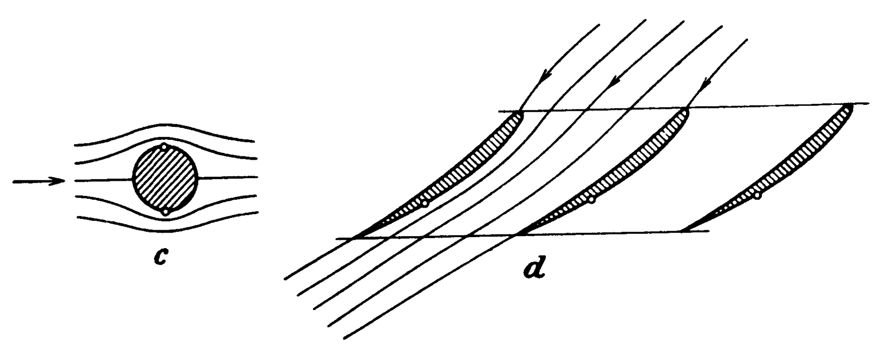

Fig. 2. Points of lowest pressure of flow.
a: convergent-divergent nozzle; b: hydrofoil; c: cylinder; d: foil grid (turbine impeller)

Fig.3. Hollow vortex tube below a turbine wheel, formed by cavitation. Steady waves are visible. View through a port in the suction tube.

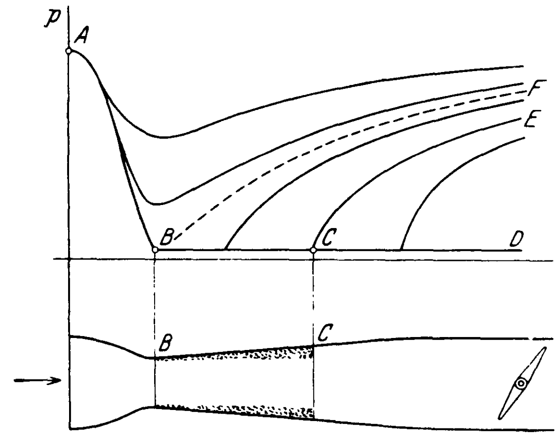

Fig. 5. Pressure curves in a nozzle under various conditions of cavitation caused by varying contraction of the outlet.

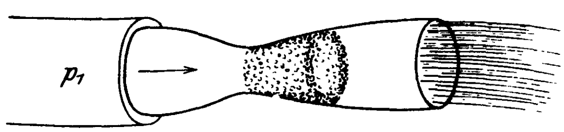

Fig. 4. O. Reynolds' basic test. Cavitation in a glass nozzle. Bubble formation from the smallest cross section extending downstream.

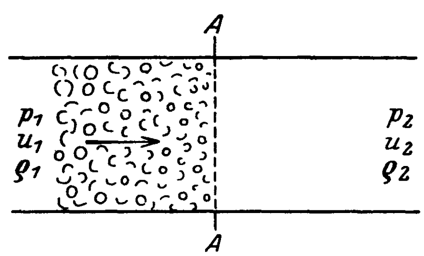

Fig. 6. On the theory of condensation strata in cavitation.

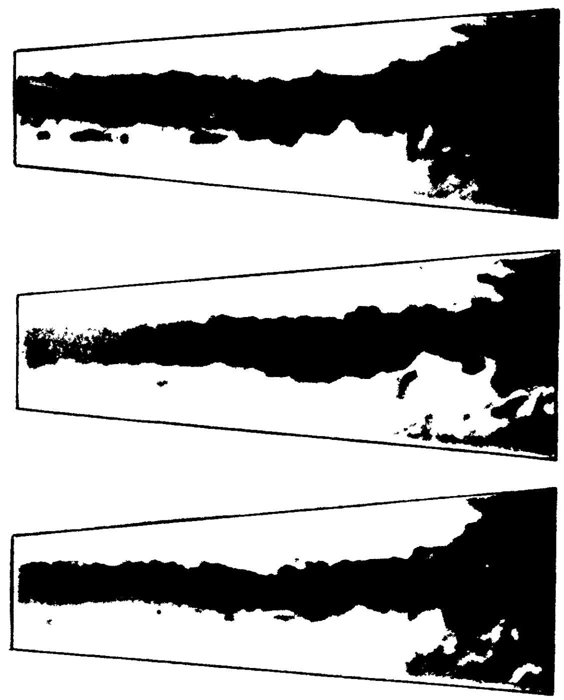

Fig. 7. Silhouettes of bubble bands in the divergent part of the nozzle. Time between exposures 1/100 sec. Slight choke.

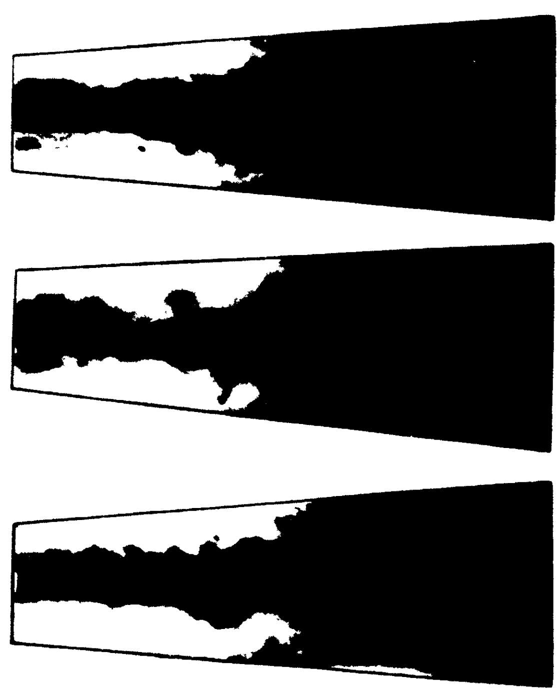

Fig. 8. Bands of bubbles with greater choke.

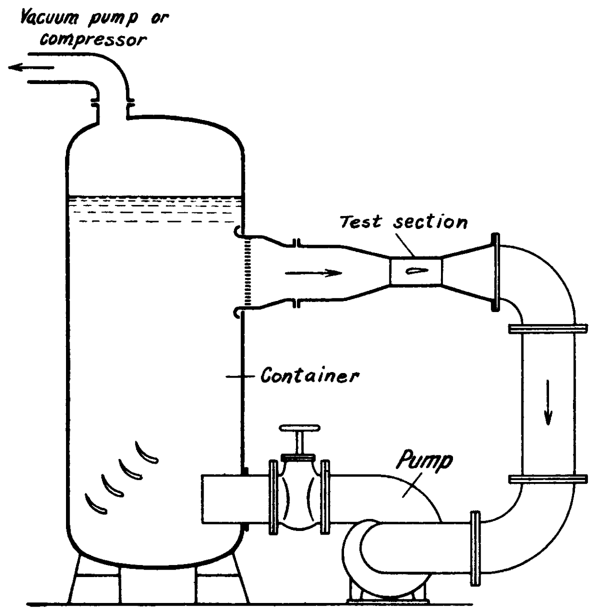

Fig. 9. Cavitation tank of the K.W. Institut für Strömungsforschung at Göttingen. Complete circuit of water the absolute pressure of which can be altered at will by evacuation or compression of the air space in the container.

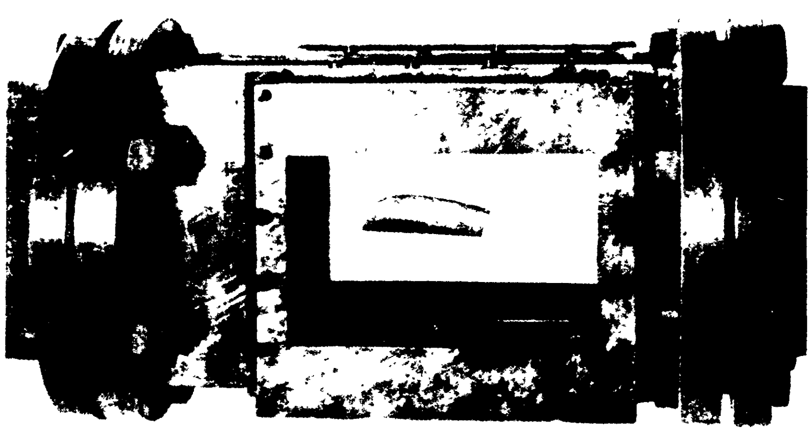

Fig. 10. View of the measuring section for hydrofoil tests.

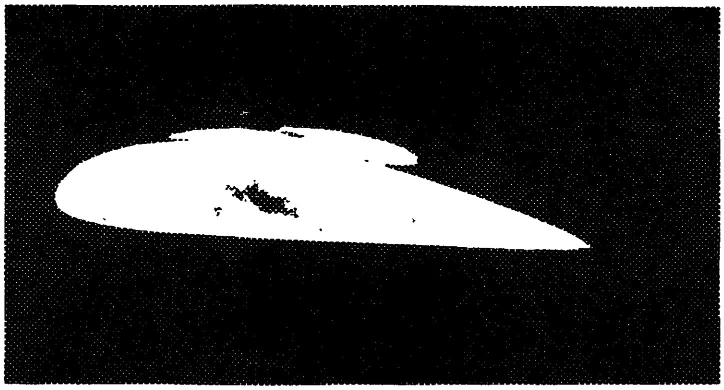

Fig. 11. Cavitation on a thick foil section. Beginning of bubble formation on the suction side.

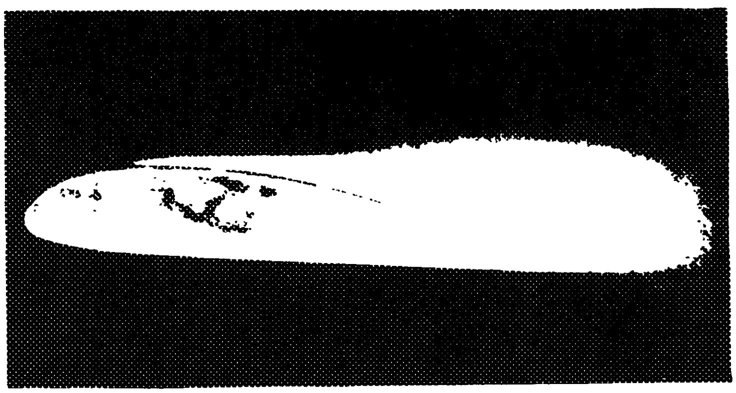

Fig. 12. Advanced stage of cavitation. Bubbles extend over trailing edge of foil.

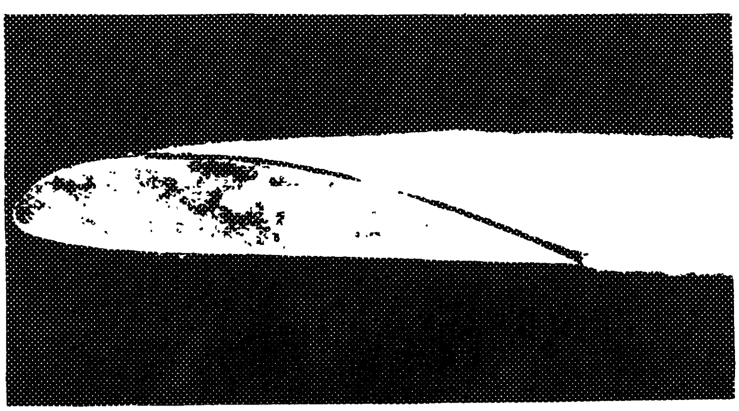

Fig. 13. Formation of free flow on the section. To the rear of the foil is a cavity filled with water vapor.

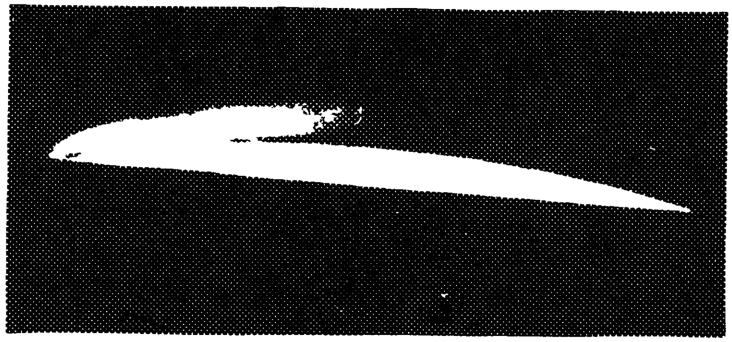

Fig. 14. Beginning of cavitation on a crescent-shaped section of a marine propeller blade.

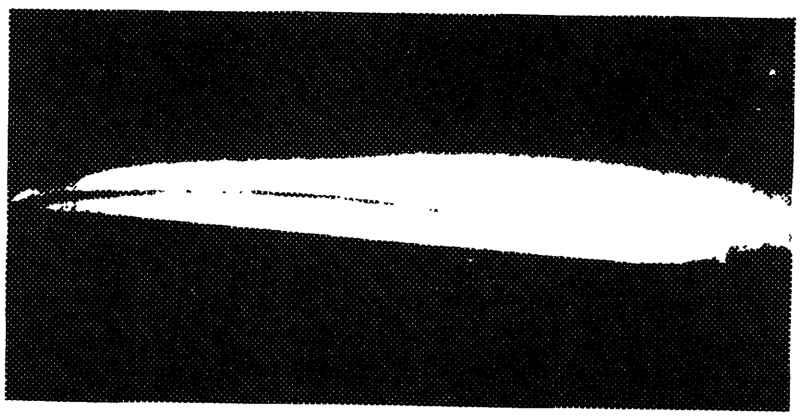

Fig. 15. Cavitation in advanced stage on the crescent-shaped section.

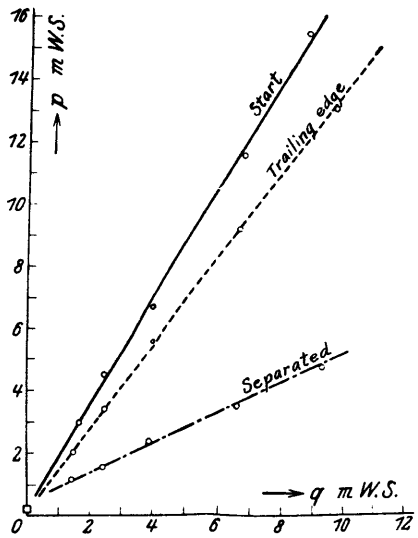

Fig. 16. Linear dependence between external pressure p and dynamic pressure q for a thick section. "Beginning", "trailing edge" and "separated" designate three cavitation conditions as shown approximately in Fig. 11, 12, and 13, respectively. The rectangle designates the saturation vapor pressure p_d.

Fig. 18. Enlarged portion of the film at right in Fig. 17. Growth of the bubbles is plainly visible.

Direction of flow

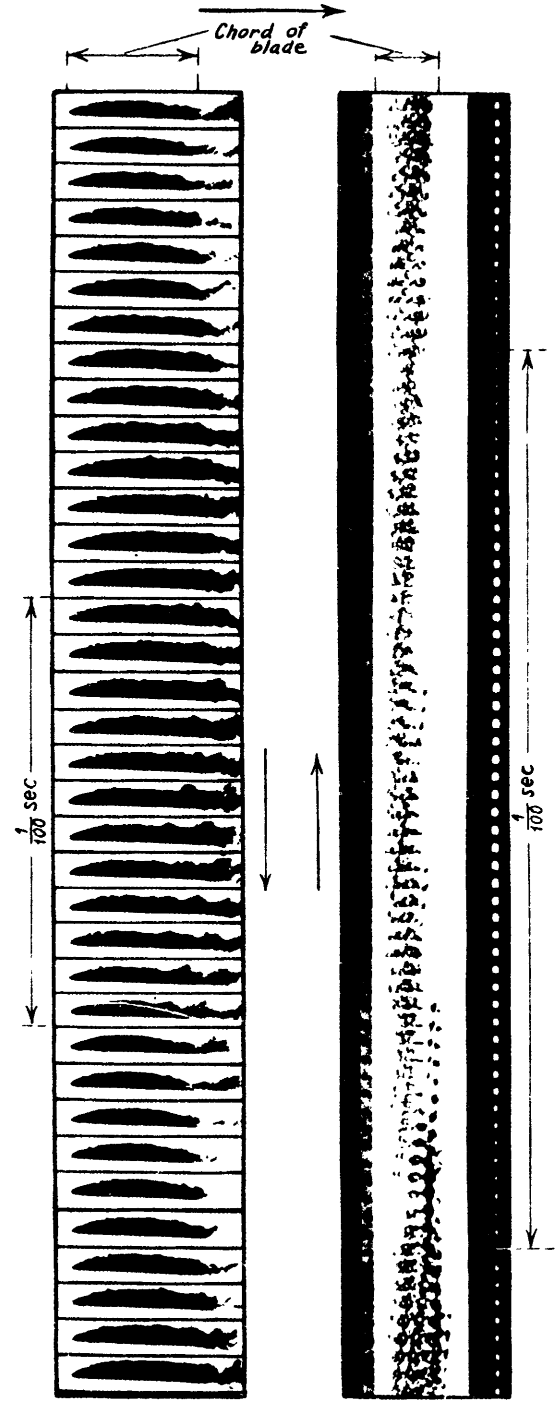

Fig. 17. Photograph by Mueller-Thun method. Bubble formation on top side of a foil. Left, silhouette. Right, view of bubbles from above.

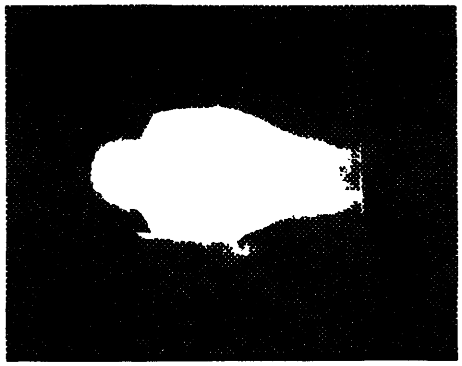

Fig. 19. Bubble formation to rear of a sphere in a flow coming from the right. The bubbles vanish when pressure jumps.

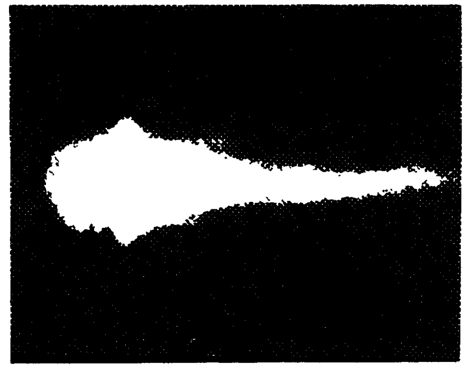

Fig. 20. Hollow space to rear of the sphere.

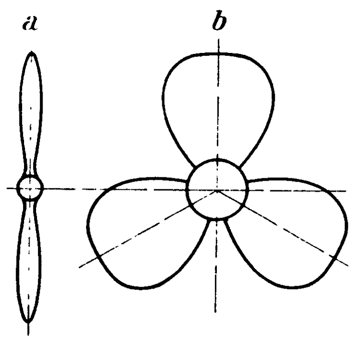

Fig. 21. Air and water propellers. Cavitation renders considerably greater blade areas necessary for the water propeller.

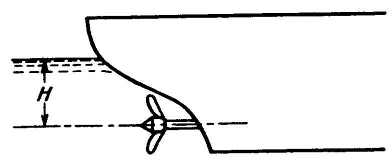

Fig. 22. Depth of immersion of marine propellers.

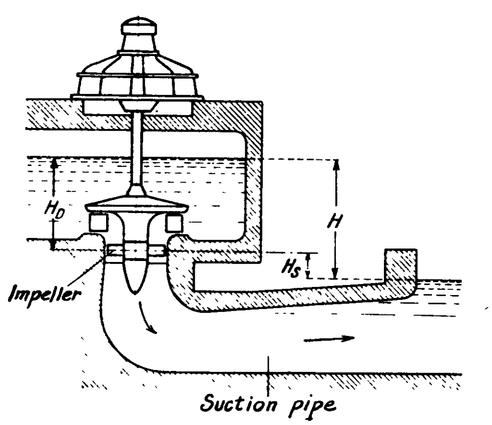

Fig. 23. Low pressure turbine plant. H = total head, H_s = suction head, H_d = pressure head.

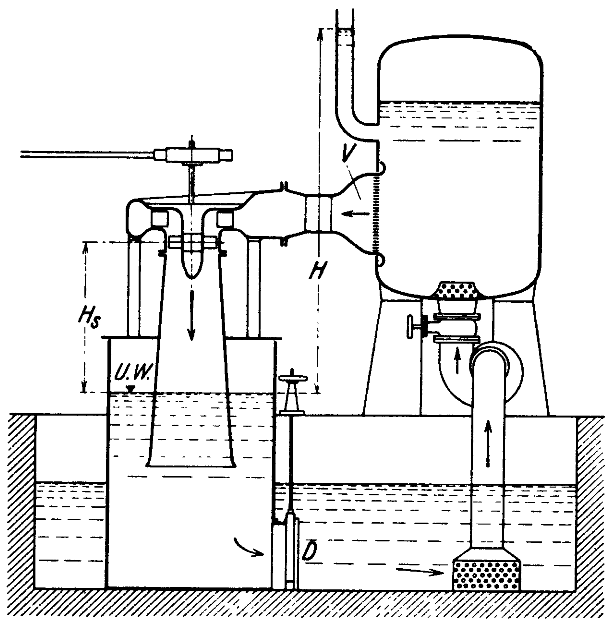

Fig. 24. Cavitation tunnel for hydro-turbines. Nearly closed circuit. Adjustable lower water level UW. Volume of water measured by Venturi nozzle meter.

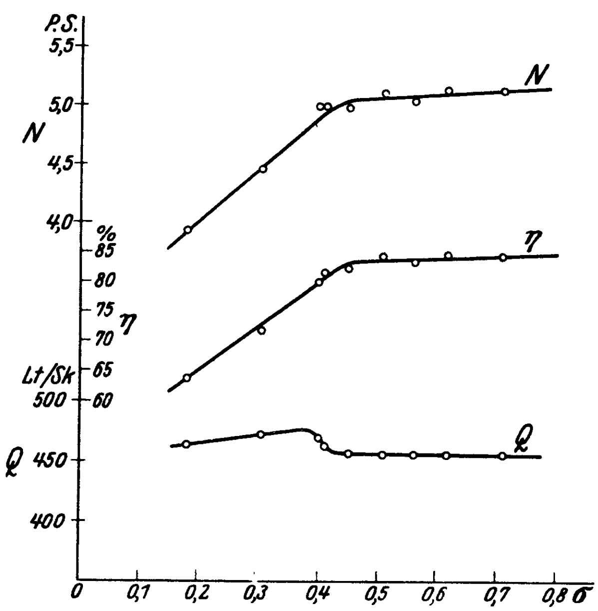

Fig. 25. Behavior of a Kaplan impeller under various suction conditions (indicated by σ) and otherwise constant conditions. Effect of high suction head (small σ) on output N, performance N , and flow of water Q. Large drop when free jet begins to form.

Fig.26. Corrosion of cast iron caused by cavitation. View of corroded surface.

Fig. 27. Section through corroded piece in Fig.26.

Fig.28. Highly corroded cast impeller wheel of a Francis turbine. Leading edges of vanes, suction side.

Fig.29. Trailing edges in turbine Fig.28.
Typical corrosion of cast iron.

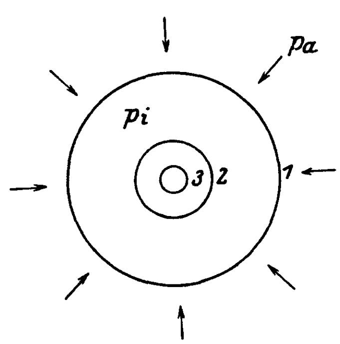

Fig.30. On the mechanical
theory of corrosion.