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Cavitation in hydraulic machinery

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Abstract

The phenomenon of cavitation can be revealed, among others, in technics by decreased efficiency of machinery and installations, in medicine by negative action on heart and circulatory system, in biology by disintegration of erythrocytes and bacteria. Cavitation penetrates each year deeper and deeper to many regions of technics, chemistry, biology and medicine. Cavitation as the process of formation of fluid discontinuity under negative pressures is a very complex phenomenon and depends on fluid parameters and its motion.

For the time being no consistent theory of the cavitation phenomenon was produced that would include all fluid properties. Several simple cases were only analyzed. The results of that analysis give a flavour of cavitation phenomenon, sufficient enough to make preliminary considerations of the influence of basic factors (pressure, temperature, velocity) on the course of that phenomenon. The change of the motion character, caused by cavitation, results in the change in pressure distribution of the whole flow area and in such away affects the phenomenon itself. In this paper individual phases of that phenomenon are examined: a) initial phase of cavitation formation; b) phase of developing cavitation, and c) phase of fully developed cavitation.

Keywords: Cavitation; Hydraulic machinery

The phenomenon of cavitation was for the first time described by O. Reynolds in 1873 in the context of problems connected with propulsion in British navy ships. Today, cavitation is a well recognised phenomenon occurring in a wide range of problems connected with motion of liquids, to begin with the problems of flow of blood in blood vessels, effects on structural changes in bacteria and yeasts, chemical processes, problems of flow past stationary bodies, motion of bodies in stationary liquids, operation of fluid-flow machinery, hydraulic machinery and hydro engineering equipment [4, 19].

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In engineering practice, cavitation leads to a considerable decrease in efficiency of the operating machinery, for example decrease of force acting on the ship propeller blades, unfavourable changes in operational characteristics of turbines, pumps and many other types of fluid-flow machinery. Cavitation also leads to destruction of machinery by a harmful effect of cavitational erosion and causes devastation of hydro engineering equipment and decay of population of fish.

According to US statistics, cavitation erosion alone, without corrosion, gives rise to an annual devastation of 20 million dollars. The progress in engineering, including increasing of the speed of rotating machinery, and also increasing pace of life, lead to increasing occurrence of the phenomenon of cavitation and increasing hazard. Therefore, theoretical and experimental investigations of this phenomenon are nowadays conducted worldwide [13, 26].

Cavitation [1] is a phenomenon occurring in the region of flowing liquid during a decrease of pressure below some critical value close to the evaporation pressure. Cavitation is pronounced in generation of gas/vapour bubbles in the region of the lowest pressure and their implosion in the region of higher pressures. The presence of gas dissolved in the liquid is conducive to occurrence of cavitation. Theoretically, the liquid begins to boil, when the pressure in some regions drops below that of the saturation pressure. In real situation, the pressure of the onset of cavitation depends on the physical state of the liquid. For a larger amount of dissolved gas, the decrease of pressure leads to separation of gas from the liquid and formation of gas regions called cavitation caverns where the pressure is higher than the saturation pressure. At the presence of microscopic bubbles in the liquid, the onset of cavitation can take place when the liquid pressure is above the saturation pressure.

It follows from the kinetic theory of liquids [3] that pure liquids (ideally pure) undergo disruption under tension of a few thousand N/cm^2. In reality, liquids are disrupted relatively easily at pressures equal, or near, the saturation pressure. The responsibility for this fact can be devoted to the presence of admixtures dissolved or not dissolved in the liquid, which deteriorate the ability of the liquid to resist tensile stress. Not wetted particles or undissolved gases are among admixtures that have the greatest effect on deterioration of liquid resistance to tensile stress. These admixtures promote the loss of liquid flow continuity and the onset of cavitation. It is assumed that they have a role of centres of cavitation, with the absence of which it is difficult to realise the onset of cavitation [25].

The main cavitation centres are undissolved gas bubbles called cavitation nuclei. Thus cavitation centres (in the form of vapour, gas or vapour-gas bubbles, suspended solids, hydrogen or hydroxide ions, etc.) are cavitation nuclei submerged in the liquid in the region of local pressure drop below the boiling pressure.

Explaining the phenomenon of cavitation [5], the presence of microscopic vapour-gas bubbles (cavitation nuclei) of radius of the order of 10-3 mm is assumed. They remain present in the liquid as a result of decreased surface tension due to several factors, including organic admixtures adsorbed in the form of a monomolecular layer at the surface of the microbubble, or adsorbed interacting hydrogen and free ions.

A hypothesis, which places the cavitation nuclei in slits of the solid surface is also well established [21].

The state of incipient cavitation is a state where the nucleus assumes dimensions that enable it to overcome the surface tension and allow its growth. In the flowing liquid, the phase of incipient cavitation is accompanied by conspicuous opacity of the liquid called the cavitation cloud. This cloud, being the mixture of the liquid and bubbles, is most visible during the phase of incipient cavitation.

During its motion in the liquid, a single cavitation bubble changes its volume [5], beginning with the instant of reaching the critical radius, until its implosion near the solid wall, or at its surface. During the bubble implosionshock waves and cumulation streams occur, which lead to destruction of the material, and are a cause of other undesirable phenomena like noise, vibration of the machinery, transient pressure field and energy losses. Each cavitation bubble is formed from a nucleus, grows to critical dimensions, and finally decays, that is implodes. This entire process of living of the cavitation bubble takes a few millisecond.

Analysing the bubble equilibrium [10, 11, 24], the liquid inertia and gas diffusion are usually not taken into account. However, these phenomena play an important role in the development of the bubble growth. Bubble growth can occur not only due to the loss of stability at a constant mass of the gas, but also as a result of diffusion of gas from outside.

The process of bubble growth due to diffusion of gas from the surrounding liquid is sometimes called a gaseous cavitation, as contrary to vapour cavitation, when the bubble growth takes place as a result of departure from static equilibrium. Gaseous cavitation can be induced by exciting gas bubbles to intensive linear oscillations. Gaseous cavitation can occur at arbitrary amplitudes of acoustic pressure, whereas vapour cavitation occurs only after reaching some critical pressure whose value depends on the cavitation centres submerged in the liquid. As a result of that, cavitation can occur at various absolute pressures. Increasing the critical pressure can be achieved by increasing the hydrostatic pressure, degasification and cooling of the liquid [4].

In real situations vapour cavitation is always accompanied by gaseous cavitation. As the cavitation bubbles are mostly filled with the saturated vapour of the corresponding liquid, the processes of diffusion take place at a relatively slow pace. In most cases it is assumed that the disruption of the liquid continuity is due to vapour cavitation.

At the instant of implosion of the cavitation bubble, high pressure and temperature occur inside it. It was found experimentally [8] that the temperature in the material near the imploding cavitation bubble reaches between 773 K (500° C) and 1073 K (800° C).

Imploding of cavitation bubbles in milliseconds or microseconds generates shock waves and increase of the pressure in the surrounding liquid up to 40000 N/cm^2 [12].

In some cases the destructive effect of cavitation of the bubble can occur during its growth. If the rate of growth of the bubble is large enough, the cavitation bubble plays a role of generator of a shock wave which can cause deformations in the material. Among causes of deformation are also rapid motion of the bubbles, of the order of a few dozens of meters per second, or their pulsations and division. Instantaneous peaks of concentration of bubbles can occur during rupture of the cavitation cloud or jet impingement [25].

In the flowing liquid, at places of the highest velocity where the pressure is the lowest, cavitation regions filled with bubbles appear. Moving towards zones of lower velocities and higher pressures, the bubbles implode causing destruction of the material. Thus, in cavitating flow, simultaneous processes of generation, growth and implosion of cavitation bubbles take place.

A non-dimensional parameter, called the cavitation number, is assumed to describe the phenomenon of cavitation:

$$\sigma = \frac{p_\infty - p_{cr}}{0.5\rho\nu^2},$$

where p_{cr} is the critical pressure giving rise to cavitation. This pressure is usually taken equal to the saturation pressure, although as already mentioned, cavitation can also take place at a pressure different from the saturation pressure.

Unsteadiness of the pressure field in the boundary layer, and the effects of content of cavitation centres, body geometry and scale imply that σ is not a constant value and changes according to these effects.

Due to the presence of cavitation centres in the liquid flow, cavitation begins as a process of separation of gas from the liquid at a pressure higher that the saturation pressure. Therefore, the emerging cavitation cavern can be partly filled by gas of pressure higher than the saturation pressure. This means that cavitation forms at the cavitation number σ higher that that corresponding to the saturation pressure. In this case the inception of cavitation depends on the content of gas in the liquid. This effect is very clear during the flow past submerged bodies (e.g. underwater foils) [20, 23].

The time during which the particle remains in the region of low pressure depends on the flow velocity and body dimensions. Therefore, for low velocities, that is when the particle remains longer in the region of low pressure that for larger velocities, the probability of occurrence of cavitation is considerably higher. The cavitation bubbles have more time to complete their growth. This is particularly clear during the flow past submerged bodies. This effect is known as the scale effect. The effect is not always clear with change of body dimensions. It follows from a majority of experimental evidence, [19], that the cavitation number, for motionless bodies flown over, increases with the increasing body dimensions. However, investigations of fluid-flow machinery provide the opposing evidence – here, the cavitation number decreases with the increasing dimensions of the machinery [15].

Implosion of cavitation bubbles is accompanied by shock waves, giving rise to noise. This noise extends on a wide range of frequencies spanning over 1 MHz. Small bubbles are responsible for high frequency noise, whereas low frequency noise is attributed to implosion of larger bubbles.

During investigations of physics of cavitation, the phenomenon is induced by means of ultrasonic waves. In practice ultrasonic waves of frequency between 10 kHz to 10 MHz, which give rise to formation of relatively small bubbles, are used. During propagation of acoustic waves a transient pressure field is formed and the process of growth and implosion of cavitation bubbles proceeds in a cycle [27].

Particularly harmful is the effect of cavitation on living organisms, especially on their blood circulation systems. The flow of blood in blood vessels (vanes and arteries), as a flow in a close system of elastic conduits exposed to deformation, is particularly prone to cavitation. As a result of local pressure changes that take place in blood vessels, the phenomenon of cavitation can occur, which is the main cause of damage of cardiac valves. They can also cause thickening of blood vessel walls, accelerating the process of *artheriosclerosis*, as well as lead to degeneration of red cells.

Artificially induced cavitation is applied in many technological processes, for example in chemical processes to accelerate the reactions, in purification and degasification of liquids, or emulsification. The resonating bubbles accelerate the process of mixing, increasing the contact surface between two liquids, or a liquid and another surrounding liquid. In this way, processes of purification and emulsification of weakly-mixing liquids take place.

Cavitation is accompanied by a destructive process called cavitation erosion. This is one of the main concerns in fluid-flow machinery. Shock waves emerging during implosion of cavitation bubbles and cumulation streams give rise to deformations and micro-cracks followed by changes in geometrical structure of the surface, increased surface roughness, peeling of solid particles from the material. Proceeding changes in the outer layer of the material cause deepening and widening of cavitation pitholes and loss of the material mass. The way the cavitation erosion develops depends on a number of parameters describing physical and chemical properties of the liquid and solid, as well as on the form and structure of hydrodynamic phenomena related to cavitation [4], including

- parameters characterising the flow, that is quantities describing the channel geometry (shape and dimensions), distribution of pressure (frequency and amplitude of pulsations), as well as distribution of velocity (absolute and relative),
- parameters characterising the flowing liquid, that is its chemical composition, temperature, gas content, pH agent, viscosity, electric conductivity, etc.
- parameters characterising the material , its structure, mechanical properties (strength and yield point, fatigue strength, hardness, etc.), energy state, resistance to corrosion, state of the surface, etc.

One reason for a difficulty in quantitative and qualitative description of cavitation is lack of a profound, inclusive, and at the same time, synthetic theory of cavitation, which could emerge from a variety of opinions on the essence of cavitation, and which, including various its aspects, could blend them into one concept.

Another source of shortages and discrepancies in our view on the essence and development of cavitation is imperfection of measuring equipment for investigation of the cavitation process itself and cavitation erosion. This, especially at the early stage of investigations, made it difficult to find a correlation between results of investigations carried out using different methods. It was only recently when the experimental methods and equipment for investigations of the phenomenon of cavitation and cavitation erosion have been normalised. The number of international institutions dealing in recent years with cavitation and cavitation erosion confirm the fact that investigation of these phenomena became a matter of great significance.

The conception of producing a bubble of vapour and gas with the aid of a focused giant pulse of a laser seems to be very advantageous from the viewpoint of similarity to the natural cavitation bubble [14-16]. The relatively low energy of about 1 J which is fed into water, the absence or only small contribution of other phenomena accompanying the bubble formation, and finally, the possibility of producing single bubbles at fixed location seem to promise that this might be a method, which would make possible detailed investigations of the nature of the vapour-gas bubble and its development cycle [6-8]. This is likely to lead to formulation of the physical model and, equally important the technical model of the cavitation phenomenon, which would be considerably more adequate than the models currently used for the description of the natural phenomena.

For generation and recording of vapour-gas bubbles a set-up as shown diagrammatically in the figure was used. A giant pulse of a ruby laser was focused in a cell filled with distilled water.

A xenon flash-lamp triggered simultaneously with the laser illuminated for about 1 ms the neighbourhood of the optical focus. The visual effects were recorded on a film placed in a high-speed camera with rotating mirror [5].

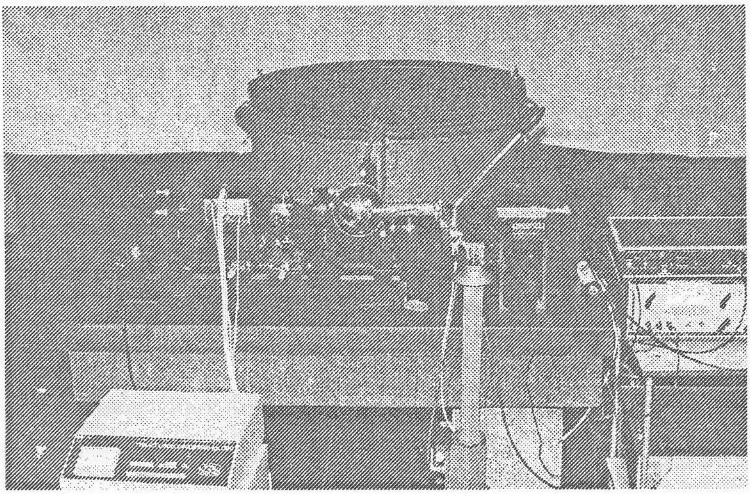

Figure 1. General arrangement of the facility.

We present below one of films showing the development and decay of a vapour-gas bubble generated by a focused giant pulse of a laser. It follows from this record that during the bubble life-time the growth and implosion occur several times till complete vanishing of the bubble. In the second phase of the bubble development its geometry changes. A characteristic whirlpool forms and then a cumulative jet punctures the bubble. Particles in the vicinity of the bubble gain during its implosion radial velocities of the order of 50 m/s. Simultaneously, rotation of the liquid around the bubble is observed. Pulsations of the bubble diameter result in the pressure changes around it. Implosion of the bubble and presence of the cumulative jet are accompanied by generation of an acoustic wave. The front of the cumulative jet develops a velocity reaching 150 m/s. This jet seems to be the main cause of cavitation damage. Also pressure changes in the vicinity of the bubble and acoustic noise were recorded [8].

The hypothesis of phenomena occurring in the course of development and decay of a vapour gas bubble generated with a laser pulse, has been based on the assumption of rotation of the vapour-gas bubble, slow in the first phase of

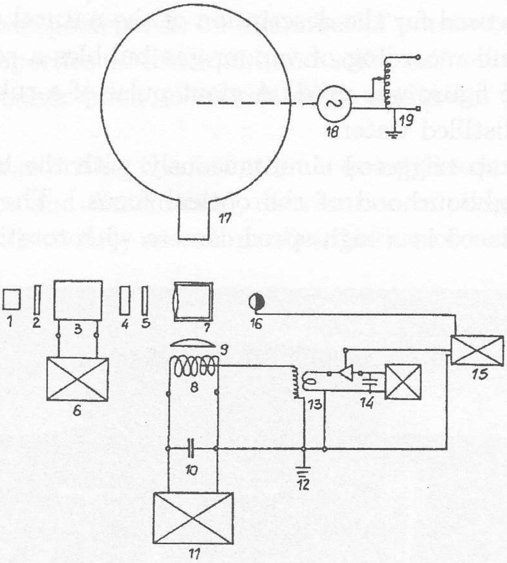

Figure 2. General view of the test facility (light pulse parameters: energy – about 0.8 J, duration-30 ns, beam diameter before focusing – 8 mm); 1 – rotating prism, 2 – 50% mirror, 3 – rubin laser head, 4 – dye commutator of the resonator quality factor, 5 – 50% mirror, 6 – laser feeder, 7 – cuvette with a focusing unit built-in, 8 – illuminating xenon flash-lamp, 9 – xenon lamp focusing unit, 10 – battery of the xenon lamp feeding capacitors, 11 – H. T. feeder, 12 – low-reactant ground, 13 – releasing pulse-transformer, 14 – 500 fast pulser, 15 – double pulse generator, 16 – fast photodiode, 17 – 320 000 frames per second camera with rotating mirror, 18 – rotating mirror driving motor, 19 – mirror rotation control autotransformer.

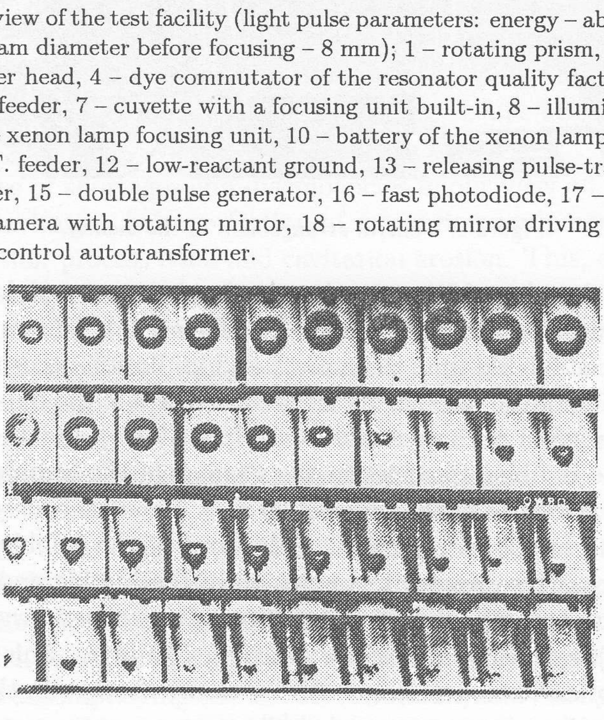

Figure 3. Vapour-gas bubble inception and decay. Camera speed: 50 000 frames per second. Registration start delay: about 60 μs. Maximum bubble diameter about 5 mm. Width of the film 16 mm of 27 DIN.

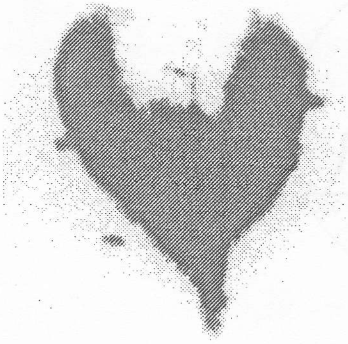

Figure 4. Vapour-gas bubble in the second stage of collapse.

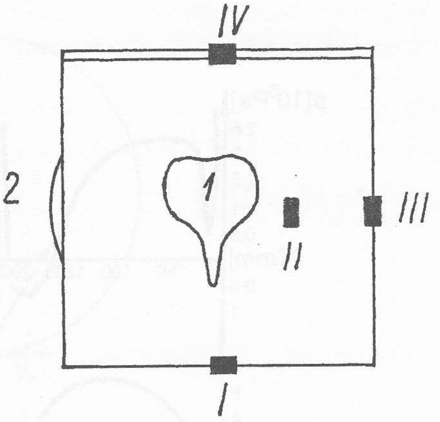

Figure 5. Various locations of piezoelectric sensors in the vicinity of the bubble; I – lens system focus – bubble centre, 2 – focusing lens system I – sensor in the bottom of the container, II – sensor placed 5 mm from the centre, III – sensor mounted in the side wall of the container, IV – sensor placed 1 mm beneath the free surface of water.

its existence and extremely intensive in the subsequent phases, especially in the second phase. The films as well as pressure and acoustic noise records seem to suggest unequivocally the mechanism as described below [9].

The focused laser pulse places in a relatively small volume of water, a large amount of heat, of 0.6 to 0.8 J, in about 30 ns, which corresponds to an average power of about 2.5 MW. Rapid evaporation of water results in a considerable pressure pulse giving the particles of water in the vicinity of the bubble a kinetic energy. The bubble grows at first very rapidly, to slowdown and stop growing in about 100 μs since the bubble formation beginning. The high pressure in the bubble occurring in the first phase of its development changes gradually to partial vacuum. At the same time water round the bubble, behaving as a compressible liquid, gains a potential energy in the vicinity of it. The bubble begins to shrink and particles of water near the bubble surface become accelerated in the radial direction toward the centre.

The remaining phenomena may be explained easily if it is assumed that simultaneously slight rotation in a plane parallel to the cell bottom occurs. At least partly elastic collision of particles in the time implosion leads to the growth of the bubble, which in this, second period of its life, rotates very quickly. The pressure below atmospheric observed between the bubble and the cell bottom(the nearest wall) causes first a rapid shift of the bubble towards that wall and then, together with quick rotation, development of a whirlpool, which is seen extremely clearly

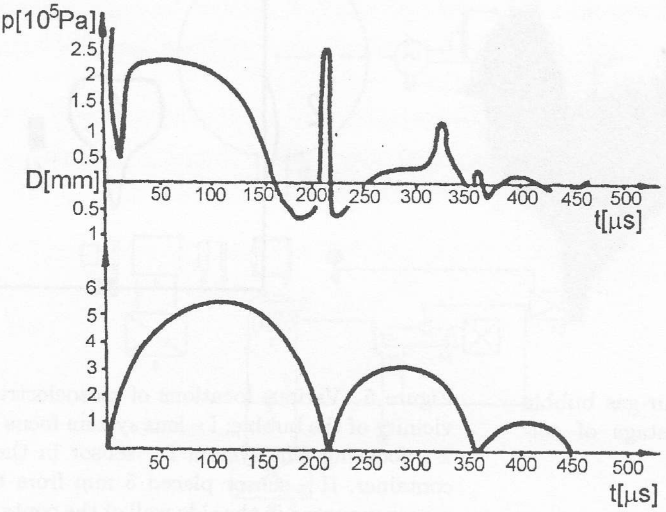

Figure 6. Distribution of pressure p with respect to time at the bottom wall of the cuvette versus variations of the bubble diameter D.

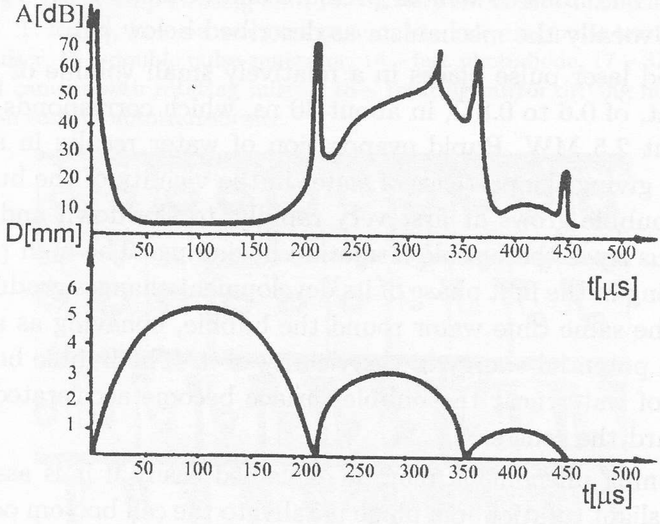

Figure 7. Distribution of intensity A of the acoustic wave generated by the bubble with respect to time versus variations of the bubble diameter D.

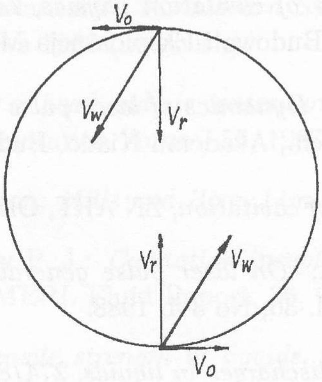

Figure 8. Velocity vectors of the molecules at the bubble wall.

on the high-speed camera film. The rotation of particles on the bubble surface spreads farther but the rotational speed decreases. The gases and vapour inside the bubble rotate too but this motion is braked less intensely. As the bubble surface 'stretches' elastically the pressure inside decreases.

Due to rotation the pressure distribution is not uniform. A considerable pressure drop occurs along the whirlpool axis. This lower pressure and the low value of the centrifugal force acting on the water particles on the bubble surface near the whirlpool axis cause development of a marked hollow in the upper part of the bubble, seen clearly on the film. With the surface tension forces overcome a thin jet of water is injected into the bubble along its axis and accelerated in the vapour-gas region owing to both the gravity forces and the partial vacuum. The water jet, called the cumulative jet, develops in the gaseous medium inside the bubble and whirlpool attaining high velocities. If the whirlpool reaches at that time the wall the jet will energetically impinge on it. Thus, two kinds of erosive action of the cavitation bubble seem to occur, namely high frequency oscillations generated by rotating water braked on the wall and, beside that, impingement of the water (cumulative) jet.

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