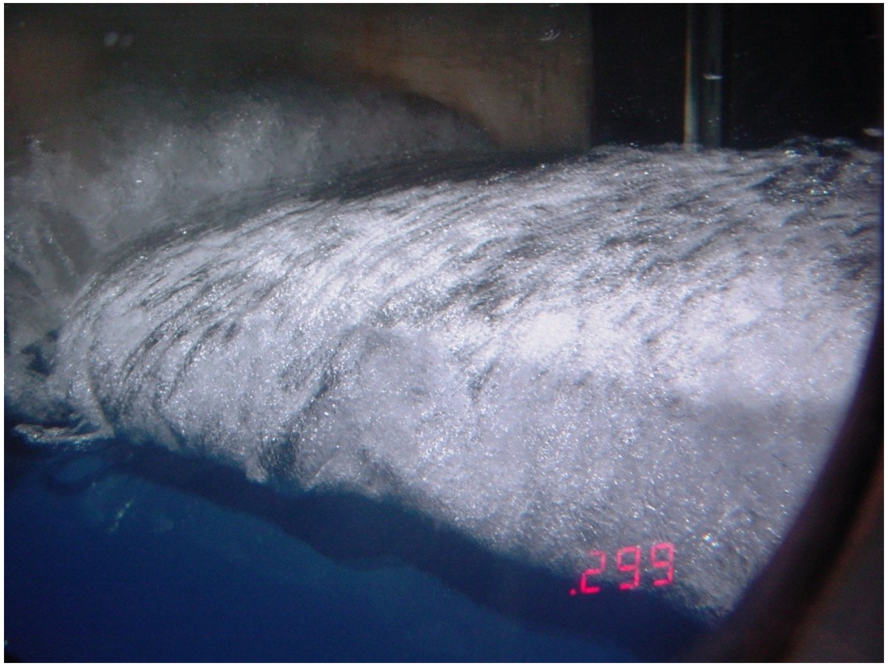
J. Szantyr – Lecture No. 7 – Basic Theory of Cavitation

Definition of cavitation

Cavitation is a phenomenon of generation, development and desinence of vapour/gas bubbles in liquids, caused by local changes of pressure at (almost) constant temperature.

Cavitation is influenced by:

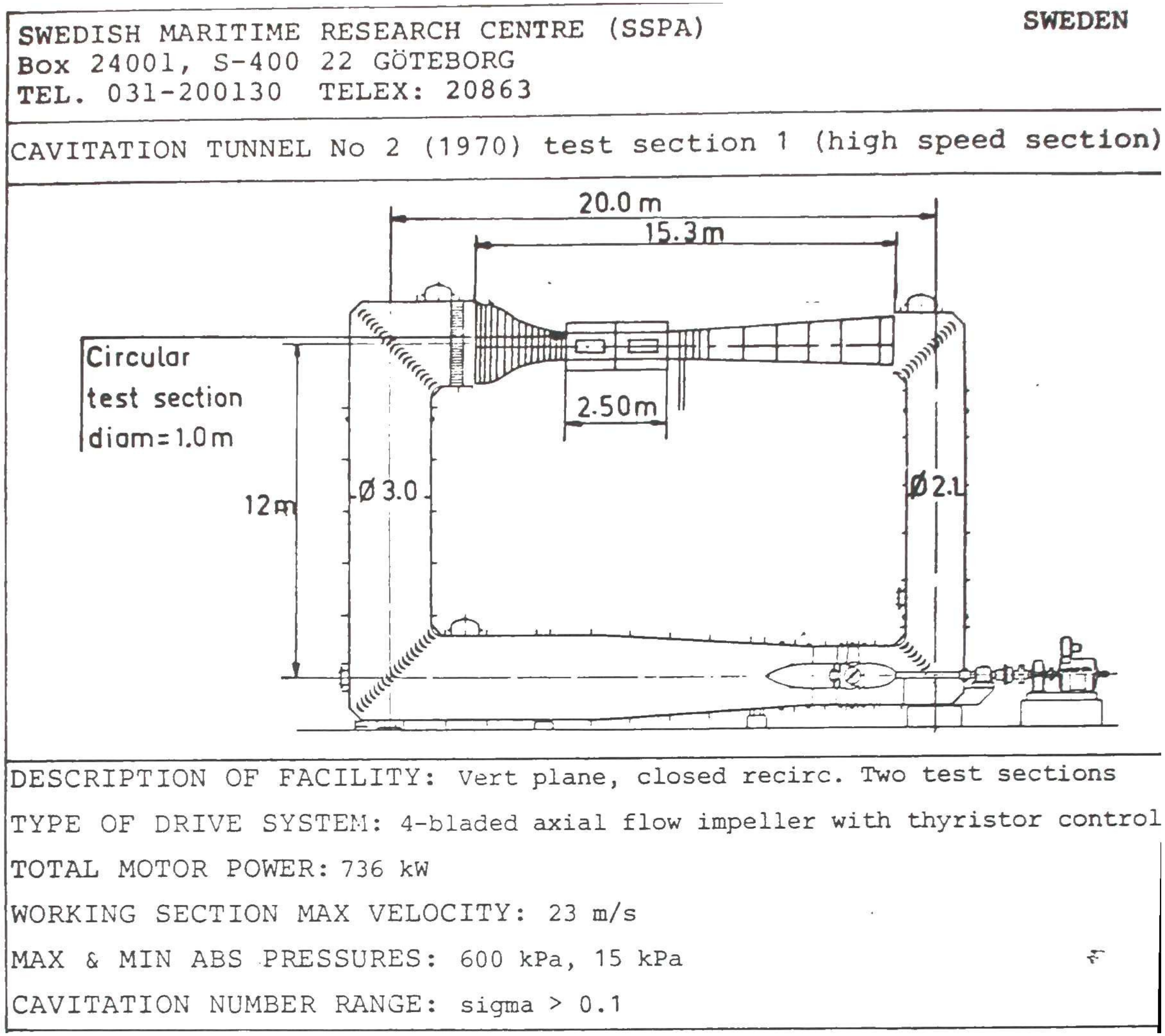
- diffusion/degassing
- vaporization/condensation
- inertia of liquid
- surface tension
- adhesion
- viscosity of liquid



Cavitation may occur in:

- **liquid gases – rocket fuel,**
- **liquid metals – coolant in some nuclear reactors,**
- **natural liquids – media in fluid flow machinery (e.g fuel in diesel engines),**
- **blood – in flow through an artificial heart valve.**

Experimental research of cavitation is performed in cavitation tunnels. These are closed circuit water channels, in which high speed water flows may be generated and static pressure may be reduced and controlled using vacuum pumps. In the test section of the tunnel various objects and measuring systems may be installed.



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CAVITATION TUNNEL No 2 (1970) test section 1 (high speed section)

DESCRIPTION OF FACILITY: Vert plane, closed recirc. Two test sections

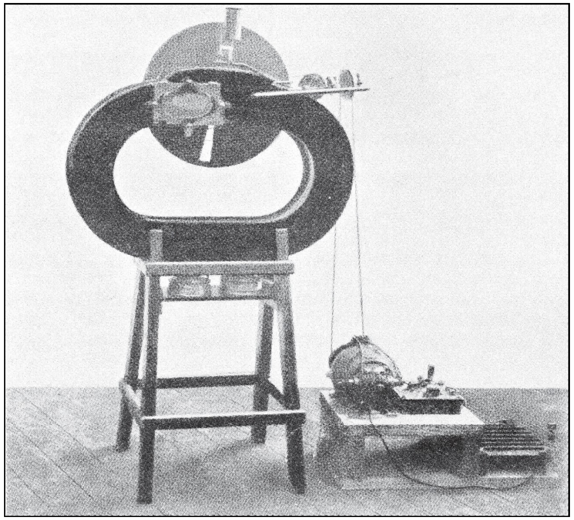
TYPE OF DRIVE SYSTEM: 4-bladed axial flow impeller with thyristor control

TOTAL MOTOR POWER: 736 kW

WORKING SECTION MAX VELOCITY: 23 m/s

MAX & MIN ABS PRESSURES: 600 kPa, 15 kPa

CAVITATION NUMBER RANGE: sigma > 0.1



The first cavitation tunnel constructed by Parsons in 1895

Charles Parsons
1854 - 1931

Similarity parameter for cavitation is called the cavitation number (or index) σ

$$\sigma = \frac{p - p_v}{{}^1\!/_2\,\rho U^2}$$

where: p – pressure at the given point

p_v - critical vapour pressure, about 2000 [Pa] for water

U – flow velocity

ρ – density of liquid

Lower cavitation number means higher danger of cavitation and more intensive cavitation phenomena

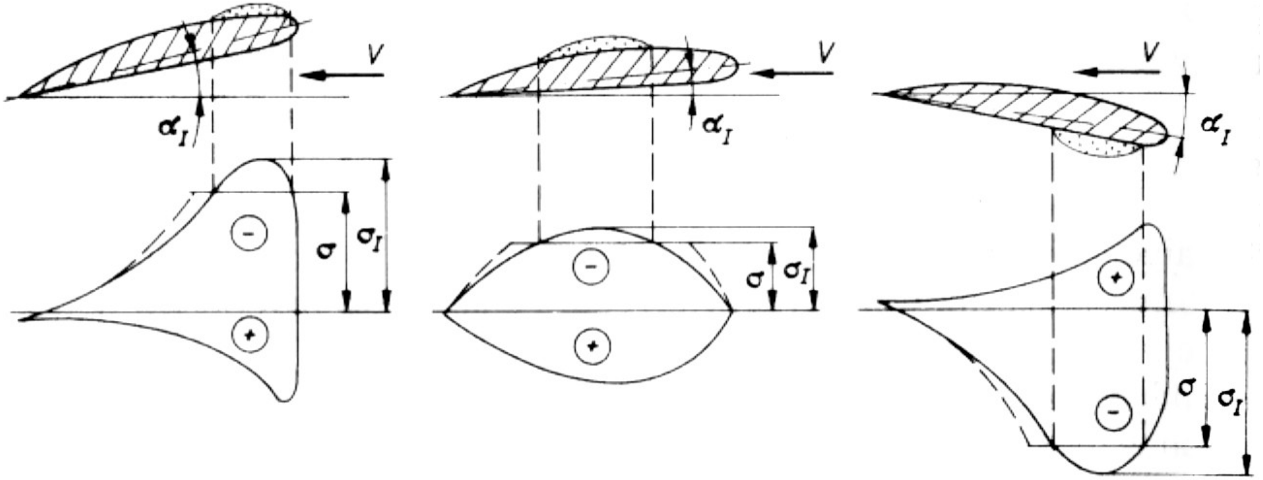
Simplified condition for inception of cavitation has the form**:**

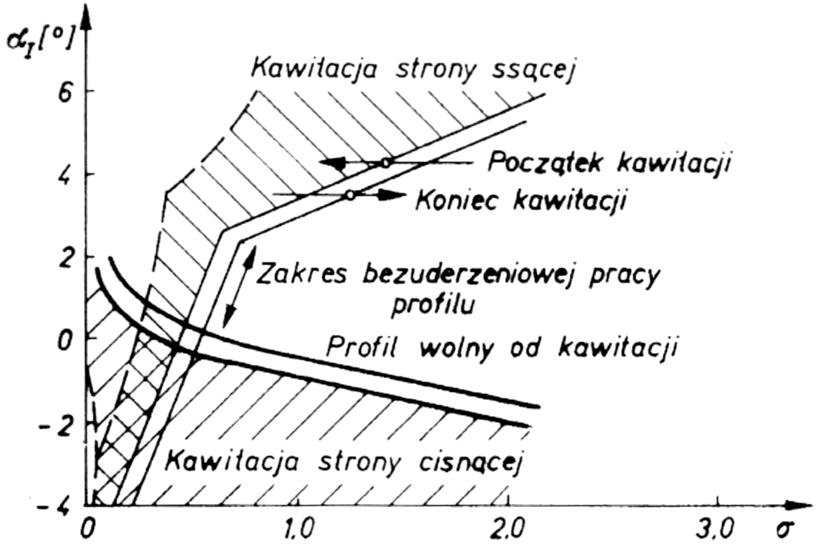
$$C_p = \frac{p_\infty - p}{{}^1\!/_2\,\rho U^2} \geq \sigma = \frac{p_\infty - p_v}{{}^1\!/_2\,\rho U^2} \qquad \text{or:} \qquad p \leq p_v$$

where: p_∞ - pressure „far in front” of the analyzed object

p – pressure in given point at the object

Approximate assessment of cavitation inception and estimation of its extent at different operating conditions of the profile





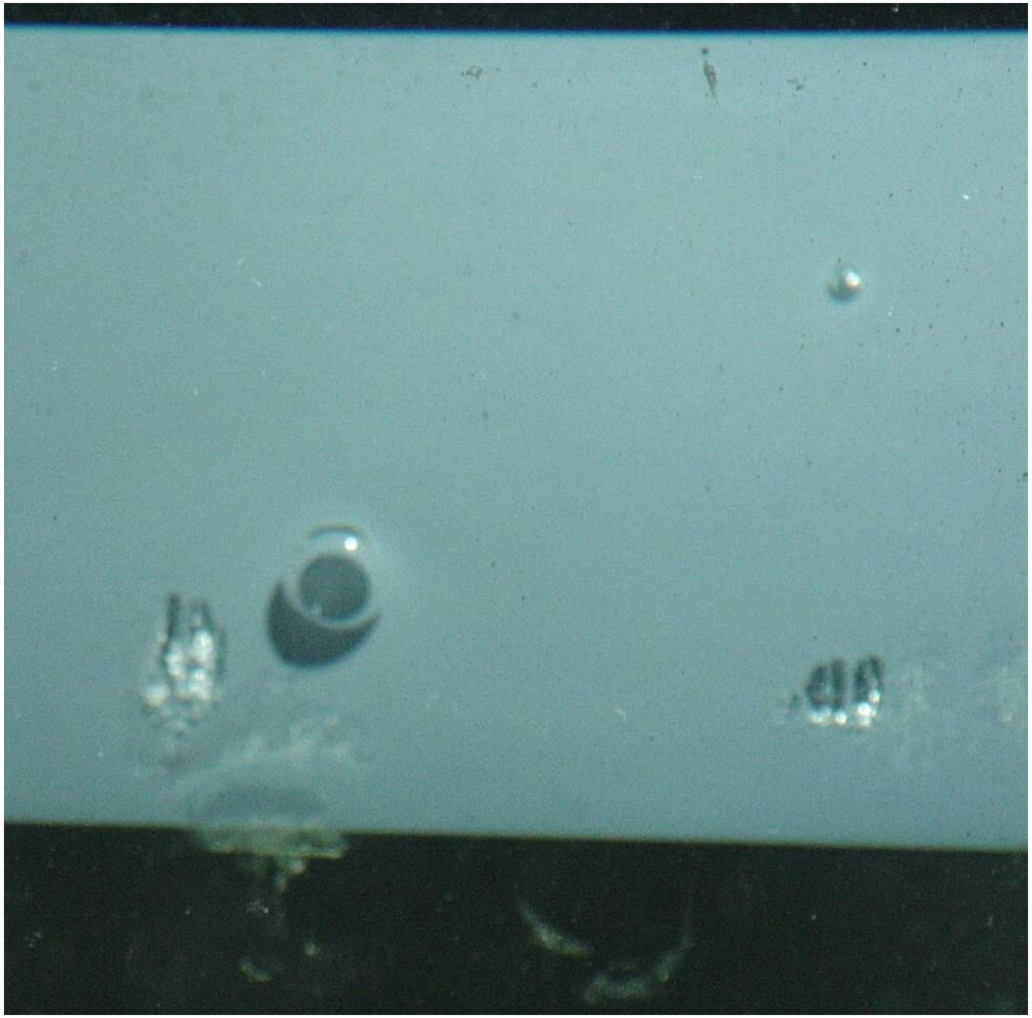
Cavitation diagram for a profile

Development of cavitation on a vertical hydrofoil

Development of cavitation on a horizontal hydrofoil

Cavitation inception

Cavitation inception results from destabilisation of gas nuclei naturally present in the liquid

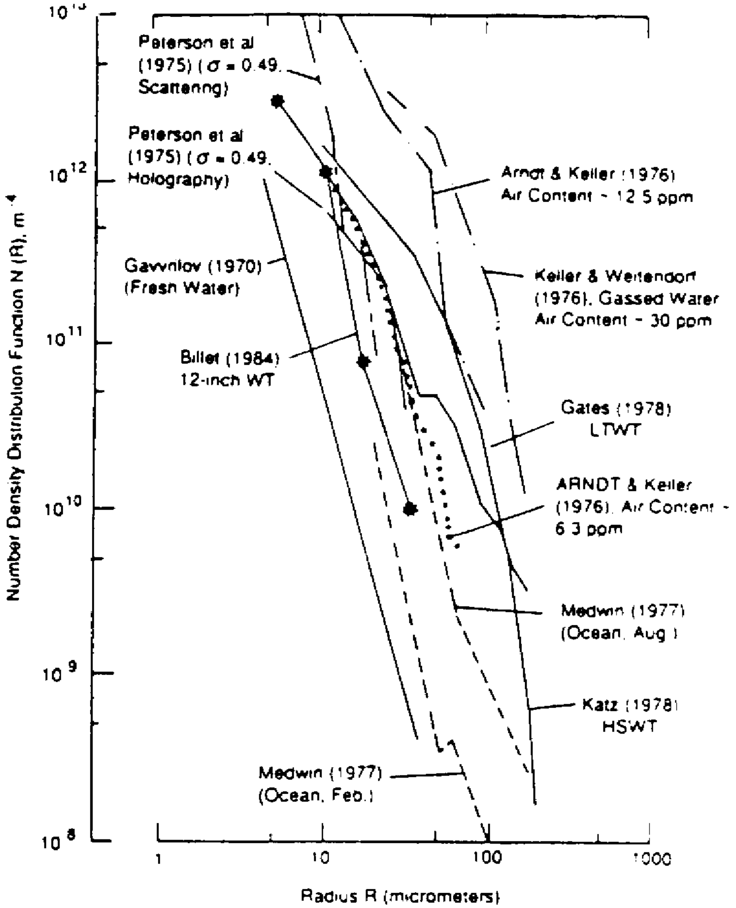


Equilibrium condition:

$$p_e = p_v + p_g - \frac{2A}{R}$$

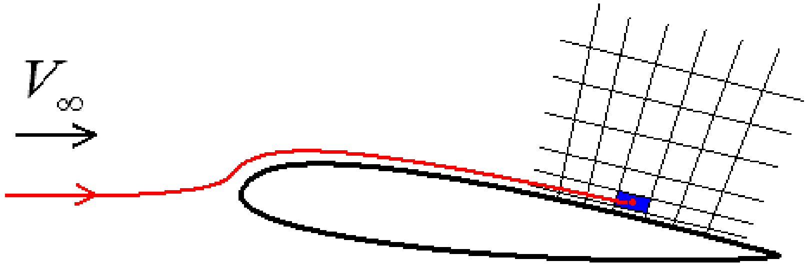
A – surface tension

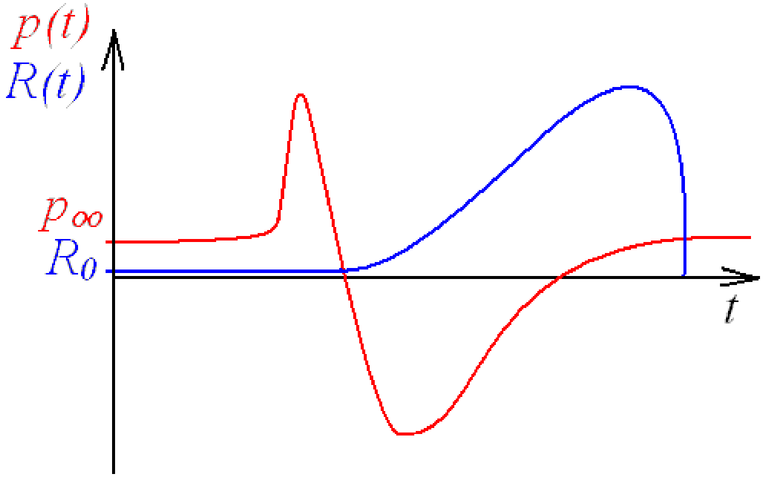
Distribution of gas nuclei in water



If natural liquids had been ideally homogenous, i.e. if they had not contained gas microbubbles and small solid particles, then cavitation would have not appear at all in fluid flow machinery because of high resistance of homegenous liquids to tensile stresses

History of development and desinence of a cavitation bubble





Rayleigh-Plesset equation:

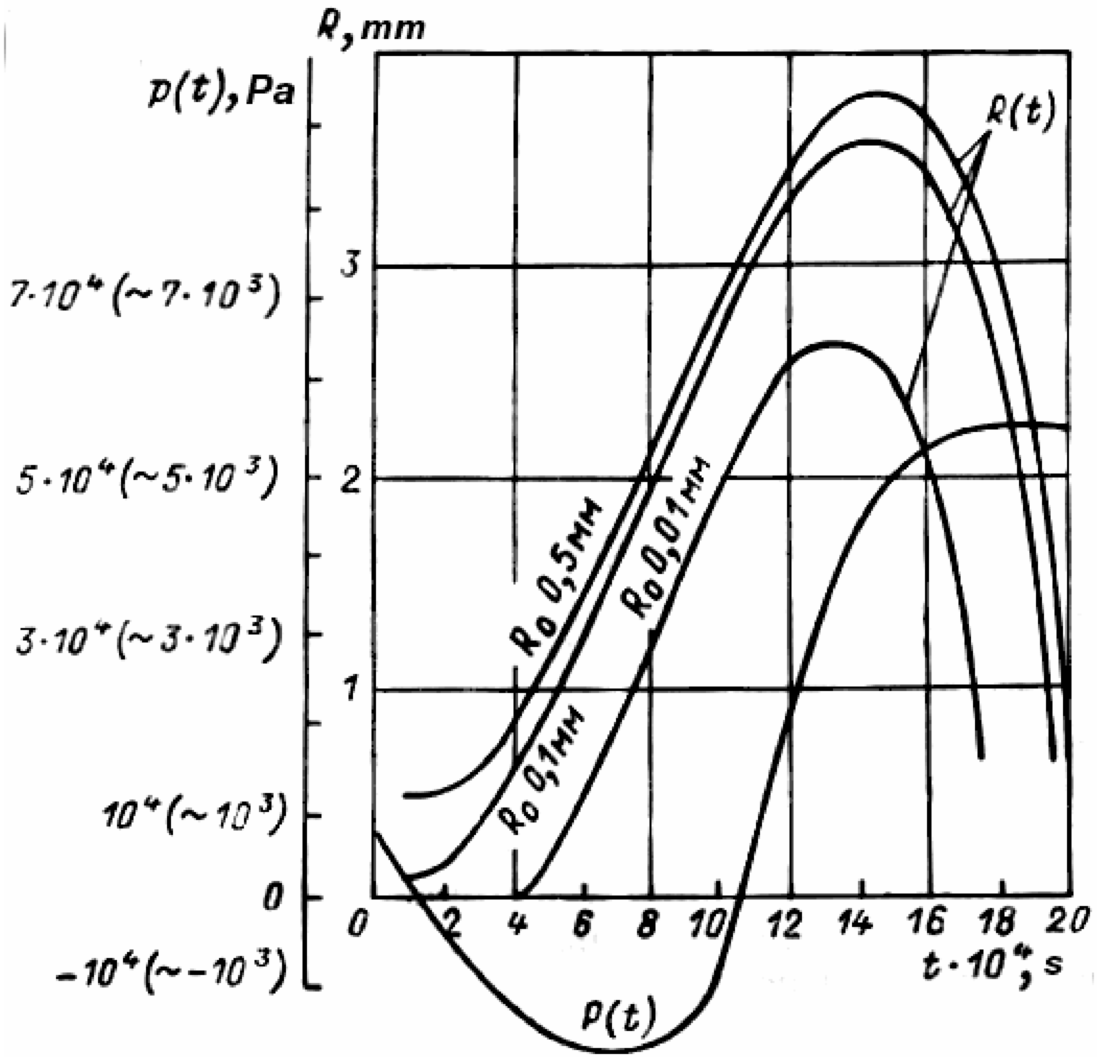
$$R\frac{d^2R}{dt^2}+\frac{3}{2}\left(\frac{dR}{dt}\right)^2+4\frac{\mu}{\rho R}\frac{dR}{dt}=-\frac{p_\infty+\frac{2A}{R}-p_v-p_g}{\rho}$$

R **– bubble radius**

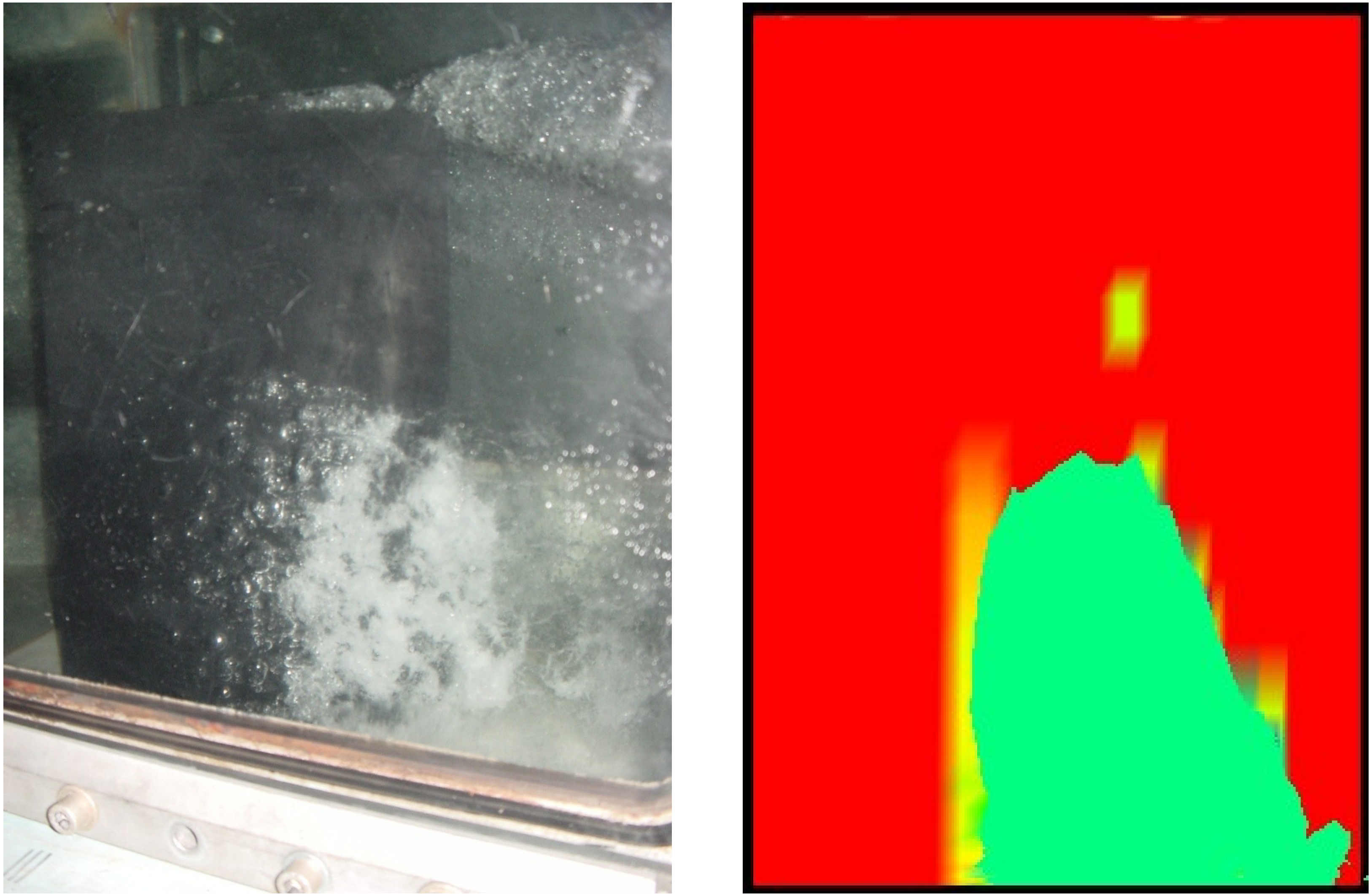
A **– surface tension of the liquid**

John Strutt
lord Rayleigh
1842 1919

History of development and desinence of cavitation bubbles having different initial radii

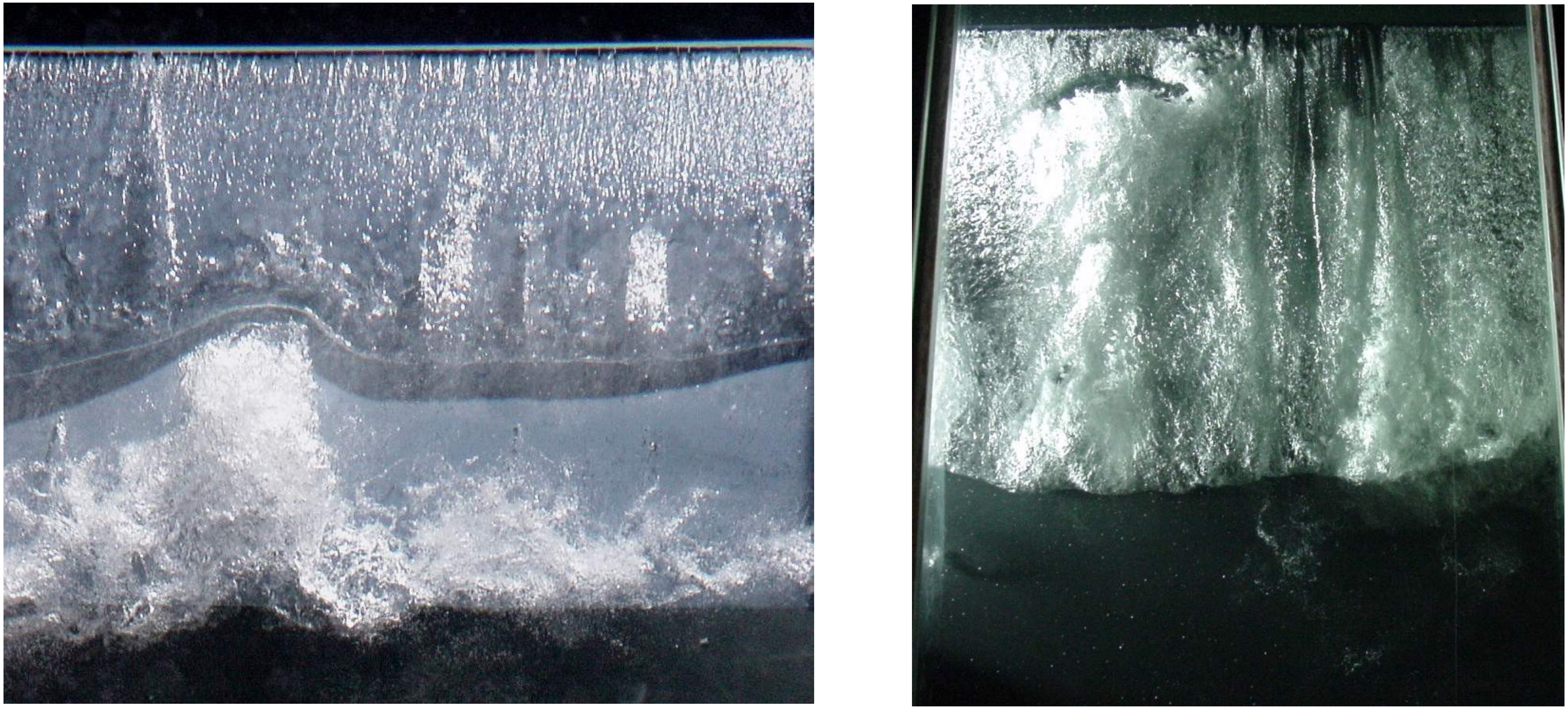


Comparison of calculated and observed extent of cavitation

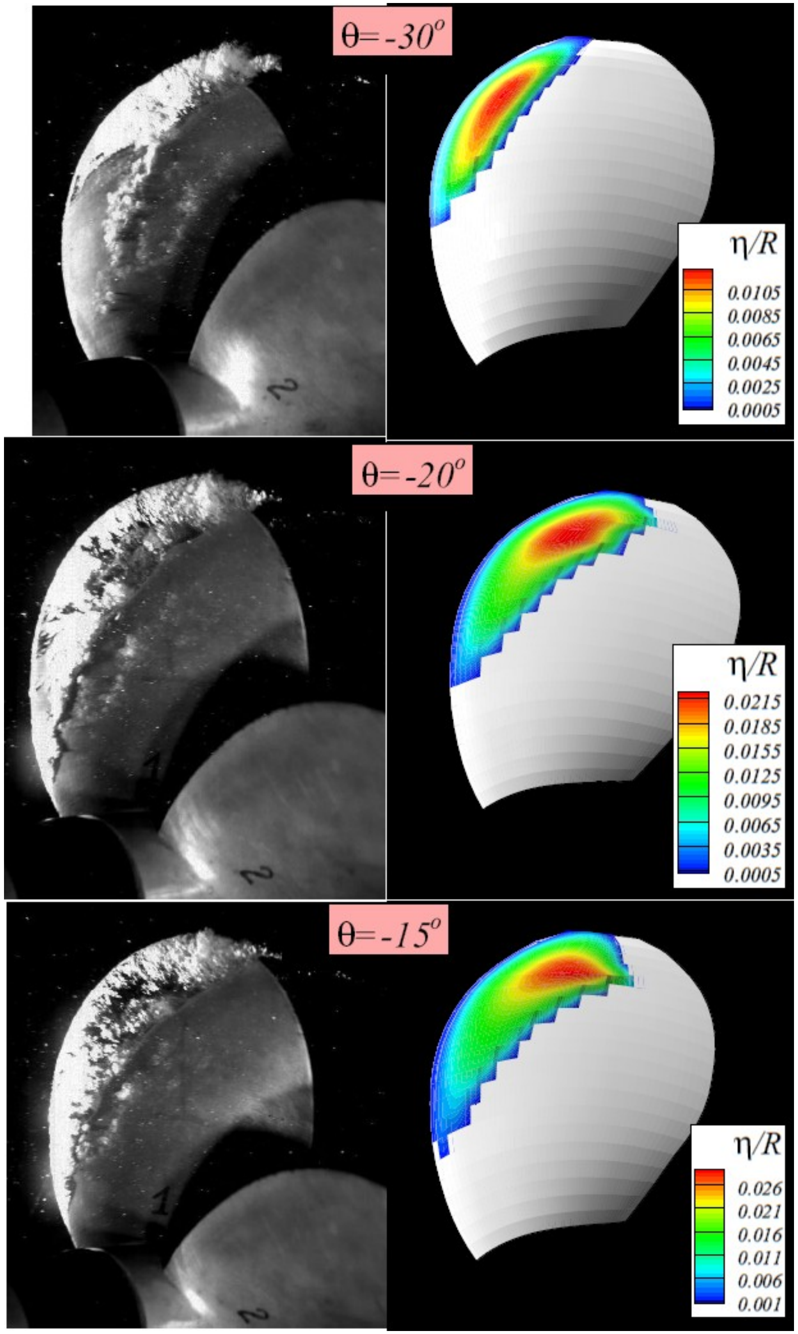


Forms of cavitation

Sheet cavitation



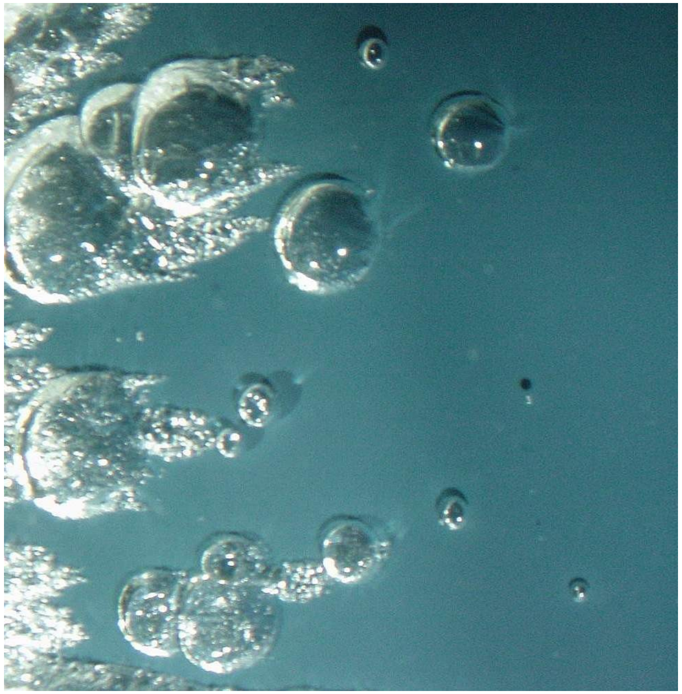
Generation of sheet cavitation requires high tensile stresses (i.e. deep reduction of pressure), acting sufficiently long to cause growth of a large number of microbubbles, which can then form a big sheet cavity.



Computational determination of sheet cavitation is relatively easy – see an example of predicted sheet cavitation on a marine propeller using the boundary element method

Forms of cavitation

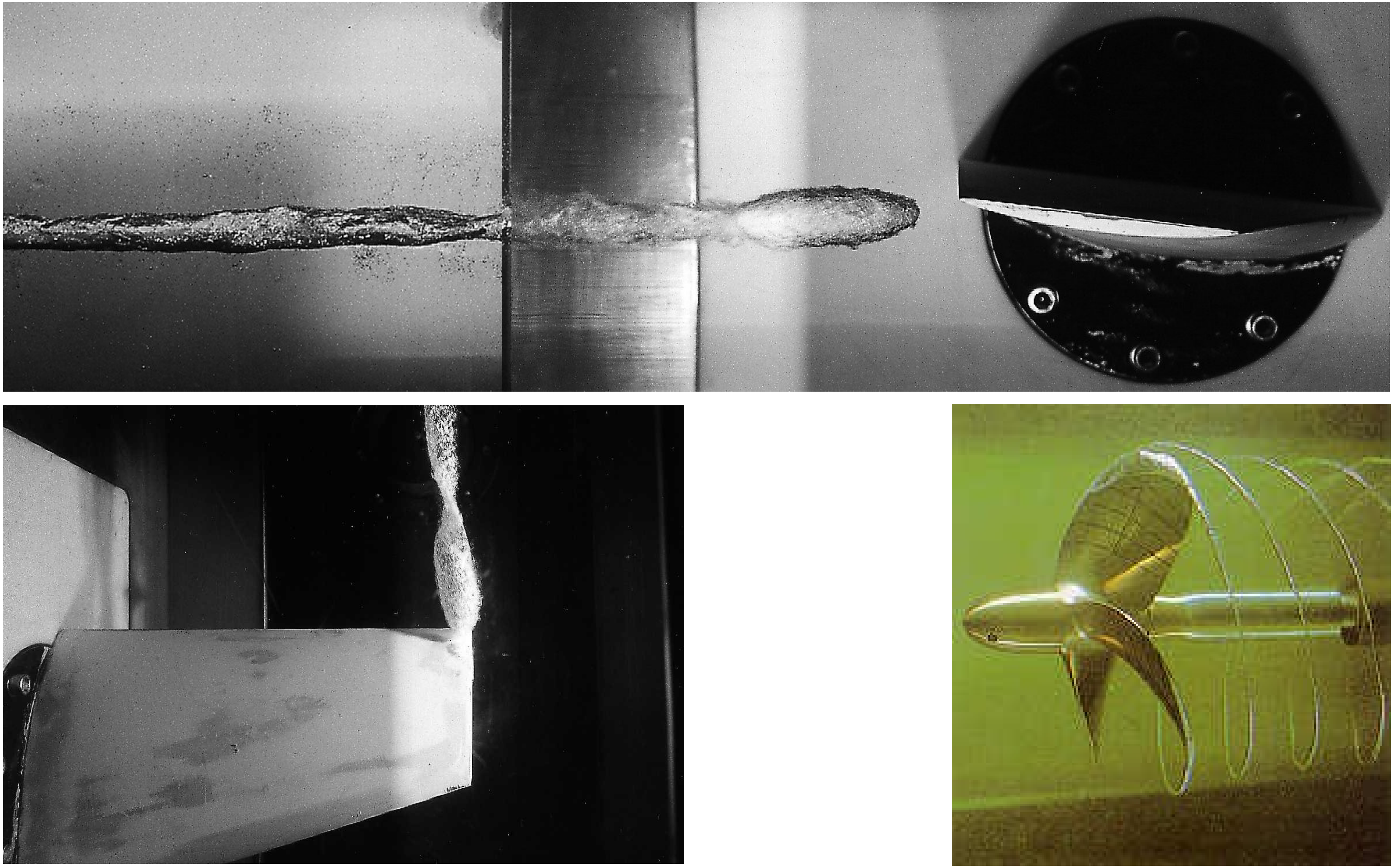
Bubble cavitation



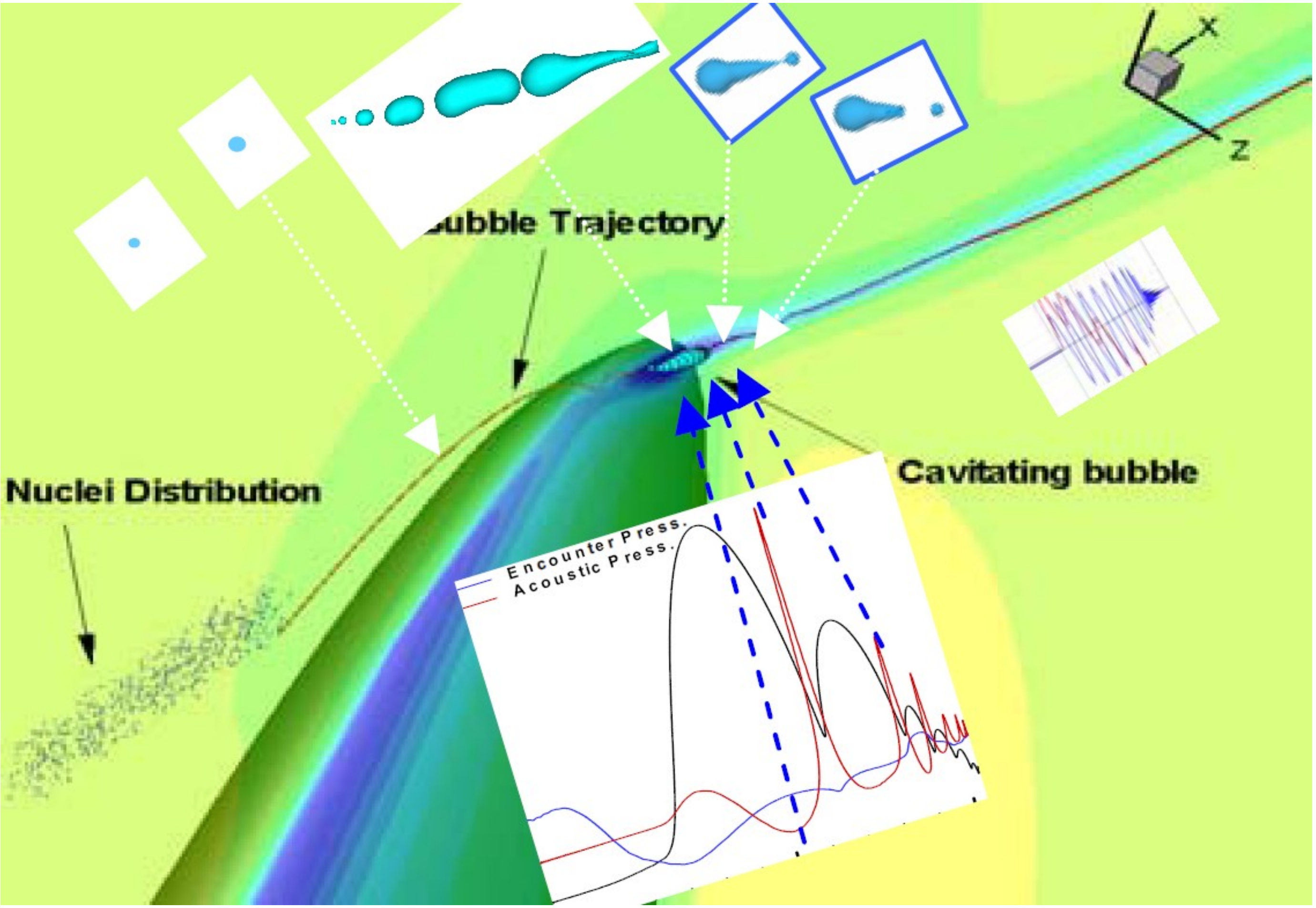
Bubble cavitation appears with relatively small tensile stresses (i.e shallow underpressure), which can induce growth only of the largest microbubbles. These large microbubbles are so few and so far apart, that they are unable to form a large sheet cavity.

Forms of cavitation

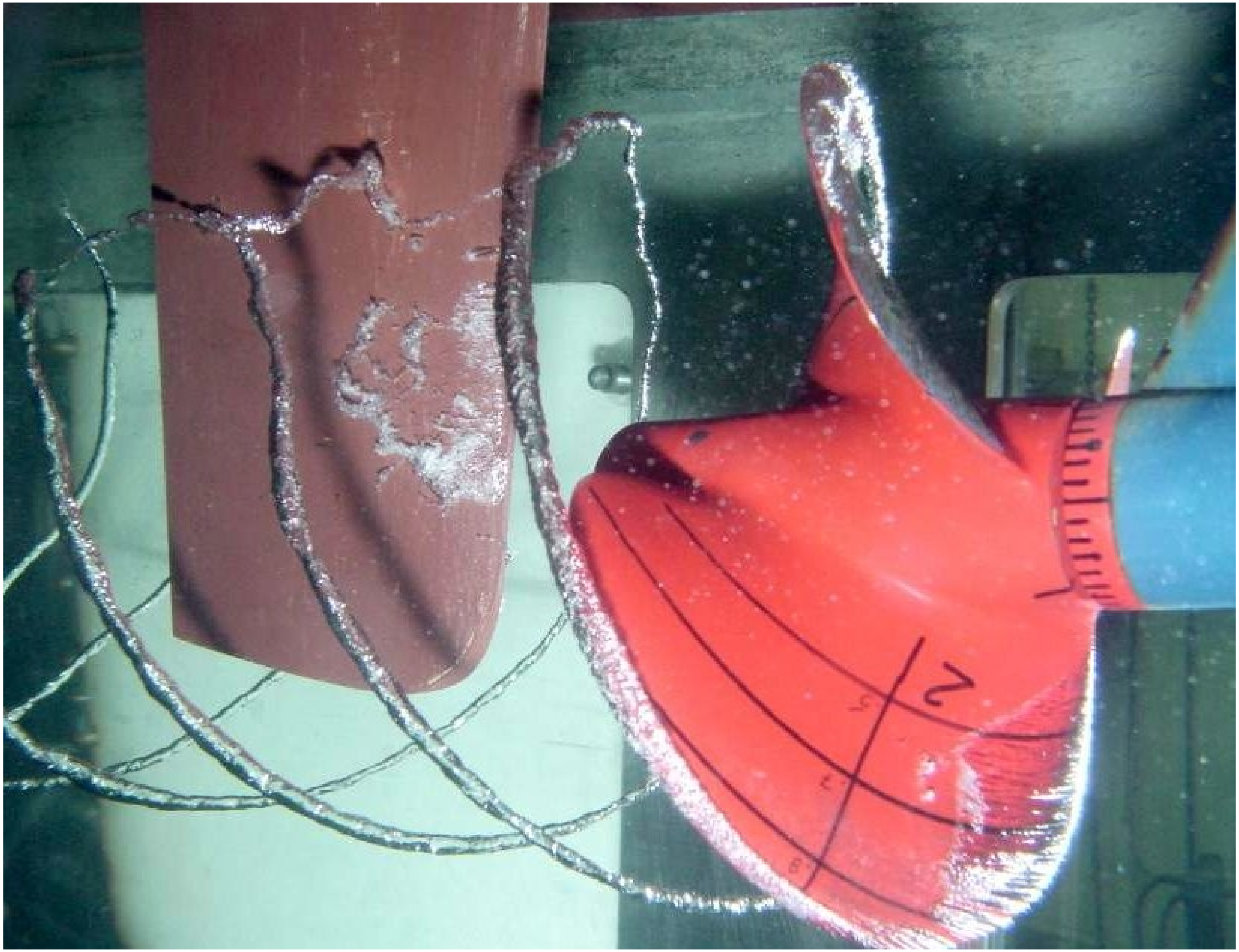
Vortex cavitation



Scheme of formation of vortex cavitation



Vortex cavitation appears when the microbubbles flow into the region of strongly reduced pressure in the centre of a vortex generated behind the tip of a lifting foil. These microbubbles grow rapidly and then they join together into one long vortex – the cavitating kernel of the tip vortex.

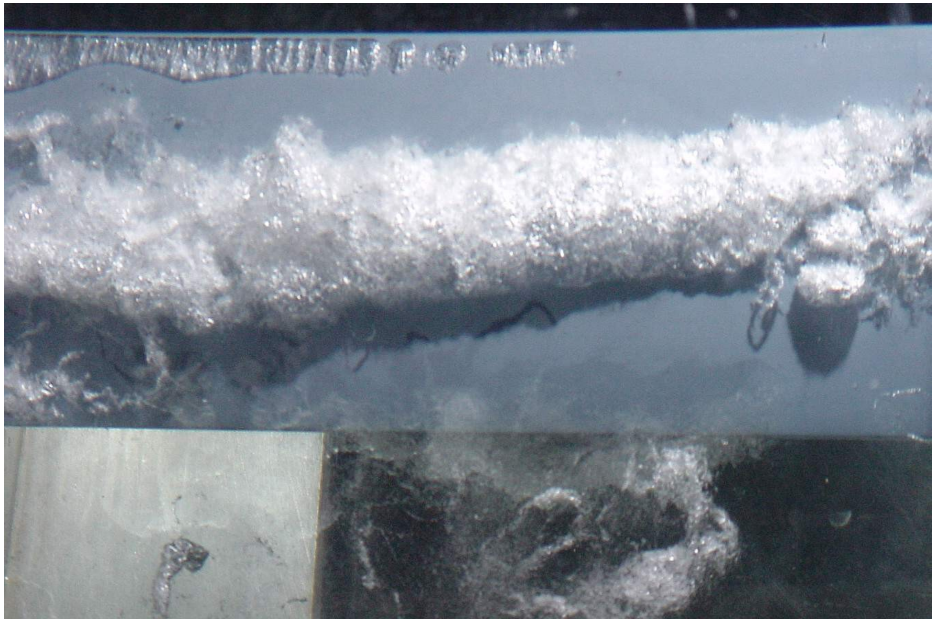


Cavitating tip vortex behind a marine propeller, deformed by interaction with the rudder

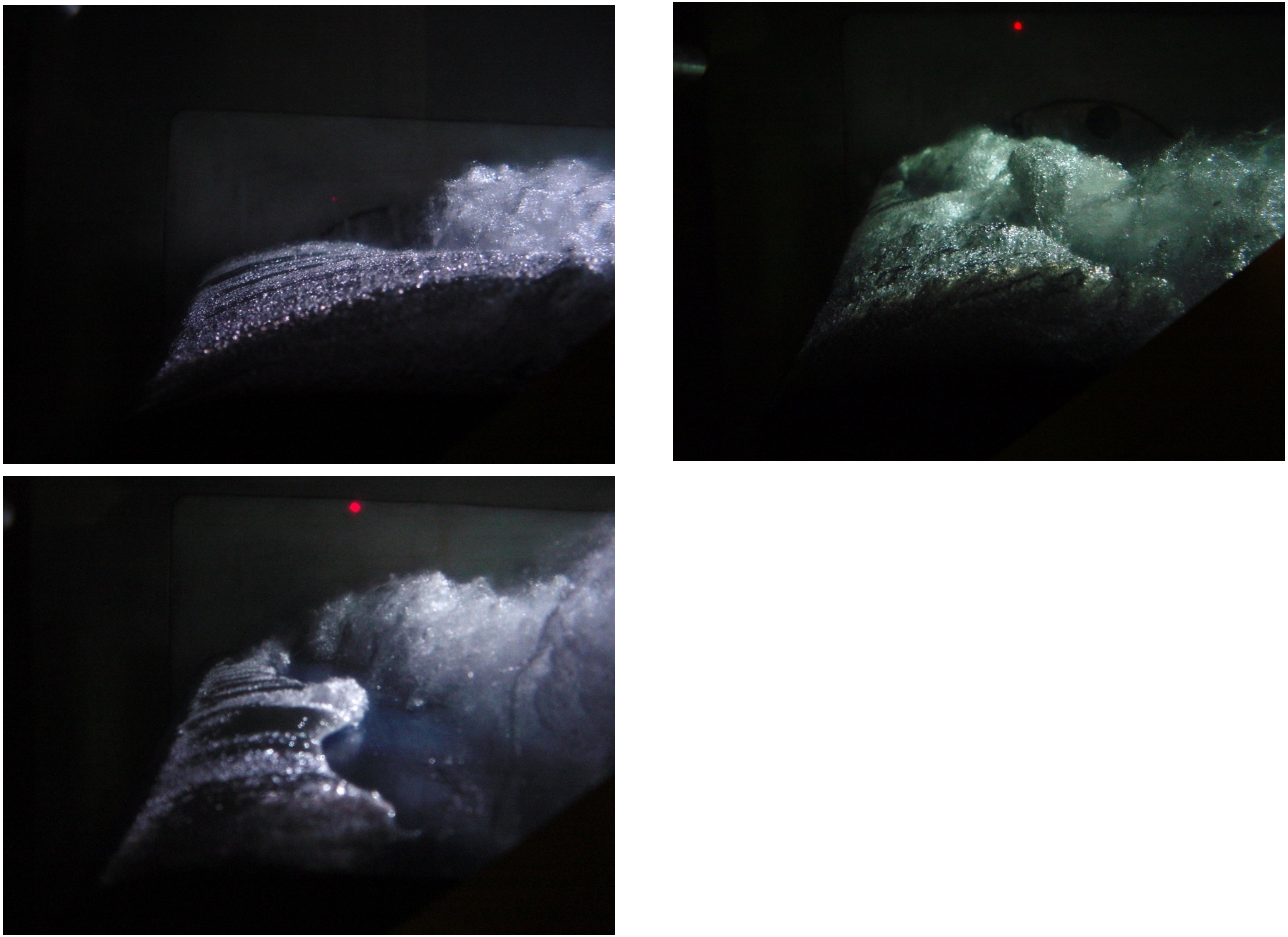
Transient forms of cavitation

Cloud cavitation

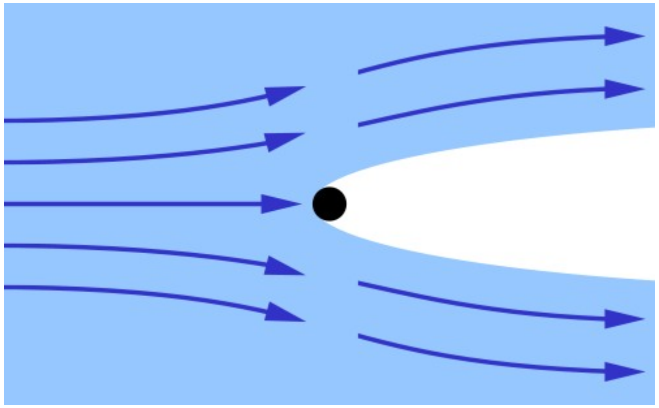
Inherent instability of the sheet cavity causes separation of the rear parts of the sheet bubble, which then under the action of increasing pressure disintegrate into clouds of small bubbles displaying stochastic behaviour.

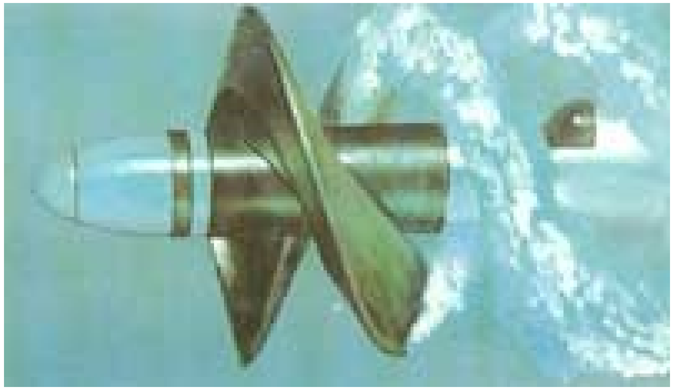


Different pictures of cloud cavitation ona hydrofoil



Supercavitation





Supercavitation takes place when the cavity covers the entire solid object and extends far downstream behind its trailing edge. In such a flow the solid object generates less lift and almost no frictional drag. On the other hand the form drag does not change or even grows. The zone of collapse of the supercavity is located far behind the solid object, without any contact with its surface, thus eliminating the danger of cavitation erosion. Because of that very fast ships are often equipped with so called supercavtiating propellers.

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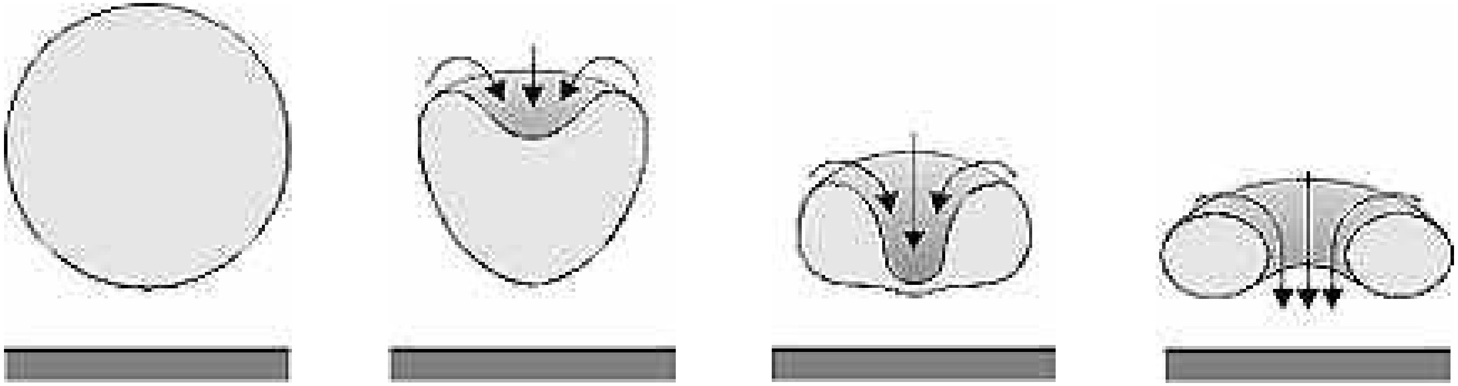
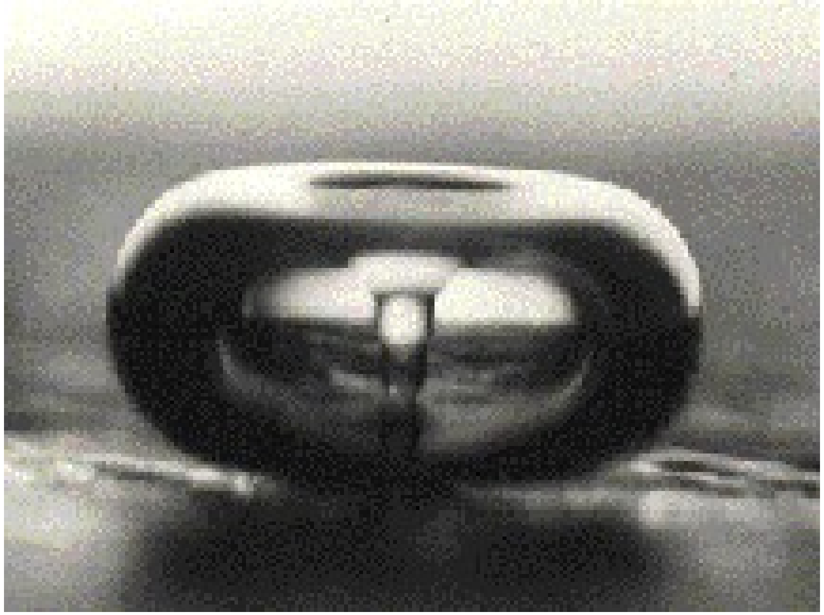
Desinence (collapse) of cavitation

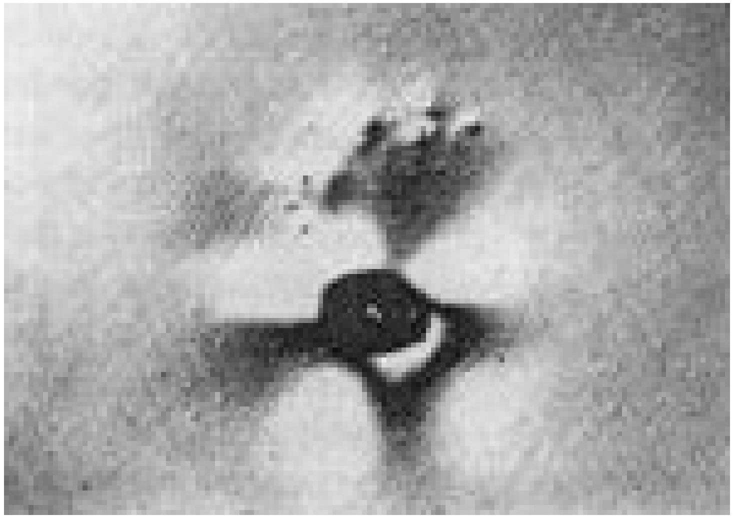
The process of desinence (implosion) of a cavitation bubble flowing along a solid wall in the zone of increasing pressure



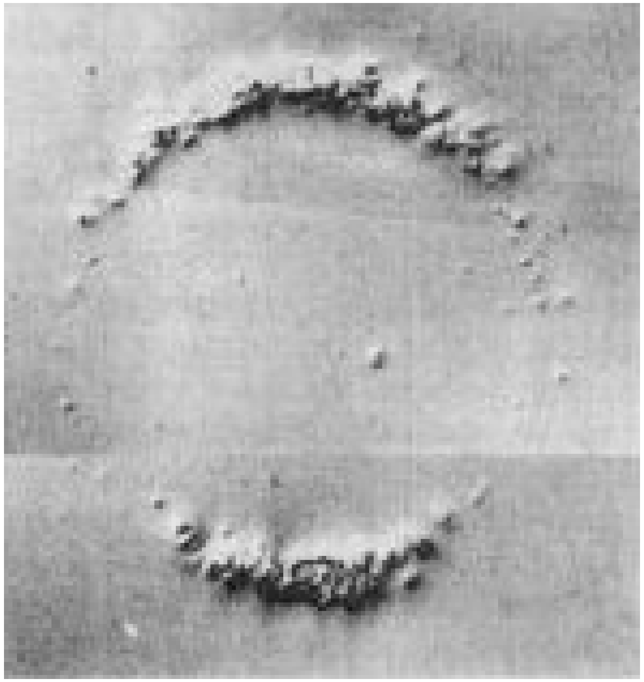


Strongly enlarged photo of a bubble in the final collapse phase (bubble diameter ←about 1mm)

Implosion of the bubbles near the wall may cause cavitation erosion damage to the surface



If implosion takes place very close to the wall, then the high energy stream of liquid passes through the bubble and strikes the wall. This steam generates extremely high pressure (thousands bars) and leaves a single erosion ←mark



If the implosion takes place a little further from the wall, then the energy of the stream is quickly reduced by inertia of the surrounding liquid and it cannot damage the surface. The toroidal bubble then disintegrates into a ring of small bubbles, which collapse independently, leaving a ring-shaped erosion mark .

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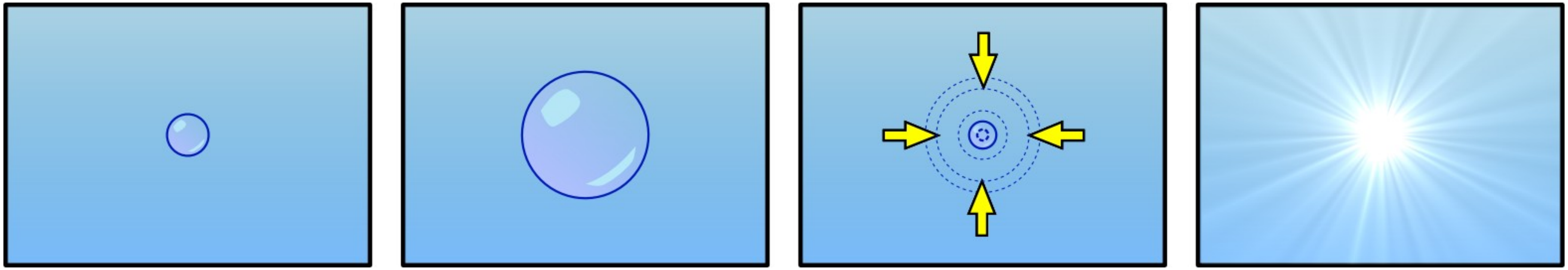
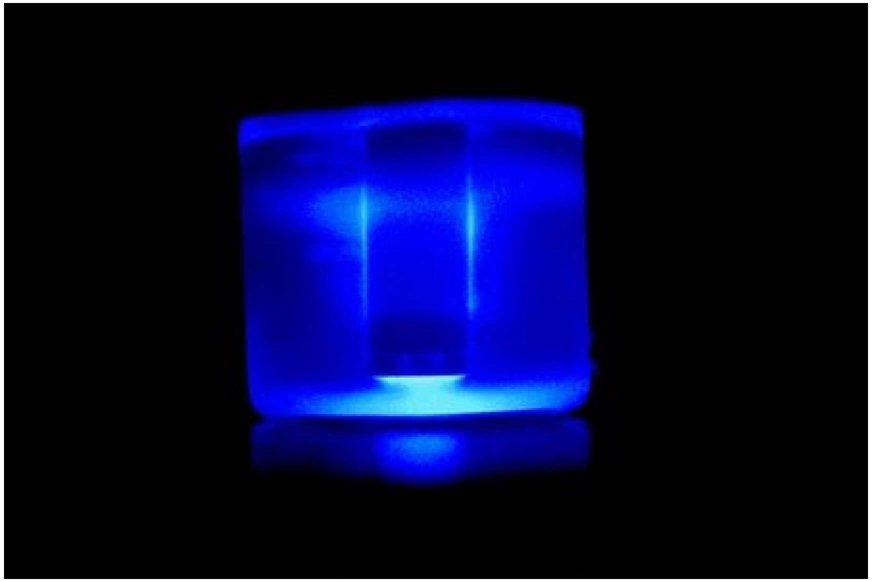
Sonoluminescence

In the final phases of cavitation bubble collapse often the emission of light is observed. This phenomenon is called sonoluminescence





It was discovered in 1934 in Cologne (Germany) during research concerning sonars for location of submarines. In the collapse phase the gas inside the bubble is heated to a very high temperature. It converts into plasma, emitting flashes of ligth of energy 1 – 10 [mW] and duration 30 – 500 picoseconds. By inducing bubble continuous oscillations the repeatable, quasi steady flashes may be generated.

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