Chapter 3

Physics of cavitation: GAS CONTENT AND NUCLEI

Objective: *General description of the behavior of gas bubbles which act as cavitation nuclei*

The beginning of cavitation is called cavitation inception. Inception is a special topic, because in the initial formation of cavitation nuclei are involved and once cavitation occurs these nuclei loose their meaning. In this chapter the need of nuclei will be explained and the presence of nuclei in fluids investigated.

3.1 Cohesive Forces

The initial formation of vapor (cavitation inception) is complicated, because pure water can withstand much lower pressures than the equilibrium vapor pressure without vaporization. This is due to the mutual attraction or *cohesion*of the water molecules. A classical experiment dating back to 1950 is that of Lyman J.Briggs [4], a soil physicist who after his retirement (at age 77!) did investigate the tension strength of fluids. He used a capillary Z-shaped tube rotating horizontally in a centrifuge. This created a calculable pressure in the center of the tube. The water remained inside the tube as long as no vapor was formed. The maximum tension (negative pressure)as a function of temperature was obtained at 10 degrees Celcius and amounted to 277 bars (27.7 MPa)! Although this value was reduced to some 20 bars near the freezing point, it remained far away from the equilibrium vapor pressure. Similar experiments were carried out much earlier by Berthelot (1950) and Dixon(1909), See [5].It required careful attention of cleaning and purification of the water to obtain these high tensions, and still the theoretical tensile strength of water molecules is even much higher [5]. In practical circumstances one may conclude that **pure water does not cavitate**. It should be kept in mind that it is very difficult to make "pure" water [7]. Contaminations of some sort are unavoidable in practice, and these contaminations determine the tensile strength of water.

The cohesive forces between water molecules are much greater than the forces between water molecules and other materials, the *adhesive* forces. It means that the next weak spot in water is the wall of the container or the surface of a wing in the low pressure region. So when a low pressure occurs on a surface, cavitation will start at the surface. However,the tensile strength due to these adhesive forces between e.g. metals and water is still orders of magnitude higher than the equilibrium vapor pressure.

In practice the main mechanism of inception is the growth of small gas bubbles called *nuclei*,which are present in the water. These nuclei are small bubbles, filled with air (or other gases) and vapor. The diameter can vary from a few microns to nearly visible bubbles of the order of 1 mm. That seems queer, because in standing water at atmospheric conditions gas bubbles will generally disappear due to two mechanisms: bubble rise and dissolution. To understand the behavior of nuclei it is useful to describe these two phenomena first.

3.2 Rising bubbles

In standing water a bubble will rise to the surface due to the difference between the weight of the bubble and the weight of the displaced water. This difference causes a buoyancy force on the bubble. Neglecting the weight of the air in the bubble this force F is equal to the weight of water displaced by the bubble:

$$F = \frac{\rho_w * \pi * D_b^3 * g}{6}$$

, in which ρ_w is the specific mass of water and D_b is the bubble diameter.
The subsequent rise velocity is determined by the drag D_b of the bubble. That is a complicated matter, but the simplest solution is a solution of the Navier-Stokes equation in which the kinematic forces are negligible relative to the viscous forces. The drag of the bubble is thus completely due to friction along the bubble wall wilt a laminar boundary layer and this condition is expressed in non-dimensional terms as a low Reynolds number $Re_b = \frac{V_b D_b}{\nu}$, in which nu is the kinematic viscosity of water and V_b is the bubble velocity. In this equation it is also assumed that the bubble remains spherical, which is applicable for small bubbles at low velocities. The drag of a bubble can then be written as

$$D_b = 3\pi\mu D_b V_b$$

in which μ is the dynamic viscosity of water (related to the kinematic viscosity ν by $\nu = \frac{\mu}{\rho}$. The rise velocity of a bubble can then simply be written by equating the rise force F_D with the bubble drag, which results in *Stokes' law*:

$$V_b = \frac{g * D^2}{18 * \nu} \tag{3.1}$$

This equation is useful to estimate the time needed for a bubble to rise out of the measurement volume. Consider e.g. a nucleus of 100 microns ($100 * 10^{-}6$ m)in diameter. As we will see later in chapter 4, such a nucleus is sufficient in many cases to bring the cavitation inception pressure close to the vapor pressure. Such a nucleus reaches a rising speed (from eq. 3.1of

$$\frac{9.81 * 10^{-}8}{18 * 10^{-}6} = 0.55 * 10^{-}2 m/sec$$

or approximately 5 mm/sec. In a towing tank the upper layer of 1 meter depth will be free of such nuclei after a few minutes. Nuclei of 10 microns take 100 times as much time, so a few hours.
At sea the turbulent motions in the upper layer of the water are often in sufficient motion to keep nuclei mixed up forever. But after a storm the nuclei content of the upper layer of the sea can contain much more larger nuclei. The storm itself creates these nuclei by breaking waves and the increased wave motions prevent the rise to the surface or at least delay it considerably. However, over time they will rise to the surface.

3.3 Dissolving bubbles

Another mechanism for gas bubbles to disappear is dissolution. In that case the gas bubbles disappear because the air dissolves in the surrounding water due to *diffusion* and the vapor in the bubble condensates because of the *surface tension*.

Water can absorb a lot of air and it is very important to distinguish between dissolved air and free air. Free air is present in the form of bubbles. The majority of the air in water is dissolved and dissolved air has no significant effect on the cohesive forces in the water.
At 15 degrees Celcius in atmospheric conditions the amount of air that can be dissolved in one cubic meter of water is about 25-30g (25-30 liters in atmospheric conditions). This is expressed as the *gas concentration* $C = 3 * 10^-2 kg/m^3$. In that case the water is *saturated.* In that condition there is no net transfer of air molecules through the free surface. The air content of water is often expressed as the fraction of the maximum amount of gas that can be absorbed: the *saturation rate.* For the calculation of the air content in in various units see Appendix A. Note that the saturation rate can be exceeded considerably without gas coming out of solution immediately. In that case the water is *oversaturated* or *supersaturated* and this can amount to two or three times the saturation rate.

As mentioned bubbles in water contain air and vapor. Dalton's law states that the total pressure exerted by a gaseous mixture is equal to the sum of the partial pressures of each individual component in a gas mixture. This empirical law was observed by John Dalton in 1801. So the pressure inside of a bubble is the sum of the partial pressures of air and vapor. The partial pressure of vapor is the equilibrium vapor pressure. In many conditions the vapor pressure can be neglected and a bubble can be considered as a pure gas bubble.

Transport of gas through the bubble wall is governed by Henry's law (formulated by William Henry in 1803), which states that at a constant temperature, the amount of a given gas dissolved in a given type and volume of liquid is directly proportional to the partial pressure of that gas in equilibrium with that liquid. The coefficient is called Henry's constant, but this "constant" is temperature dependent.
When the water is not saturated, there will be a mass flow through the bubble wall and the bubble will disappear because the free air goes into solution. Even when the water is saturated, small bubble will disappear because the pressure inside a bubble is higher than in the surrounding fluid due to the surface tension, as will be discussed later.

Contrary to evaporation, diffusion is a relatively slow process. Evaporation takes place at the surface of a bubble only, but diffusion extends over a much thicker layer of fluid around the bubble. At the bubble wall the saturation rate of the water will immediately be such that the partial pressure of the dissolved air is equal to the partial pressure of the air in the bubble. When the saturation rate of the bulk of the water is different, air molecules will migrate to or from the bubble. Over a certain distance a concentration gradient will form.

The mass flow m in kg/m^3 through the wall of a bubble with radius R can be written as

$$\frac{dm}{dt} = 4\pi R^2 D_g (\frac{dC_g}{dr})_R \tag{3.2}$$

in which D_g is a diffusion coefficient (m^2/sec) and C_g is the gas concentration in (kg/m^3). The gradient $(\frac{\partial C_g}{\partial r})_R$ is the gradient of the gas concentration at the bubble wall.
When the vapor is neglected and the gas density remains the same the mass change is

$$\frac{dm}{dt} = \rho_g \frac{d(4/3\pi R^3)}{dt}$$

and from eq.3.2 the bubble radius changes as

$$\frac{dR}{dt} = \frac{D_g}{\rho_g} (\frac{dC_g}{dr})_R \tag{3.3}$$

Eppstein and Plesset [9] gave an approximate solution for the concentration gradient:

$$(\frac{dC_g}{dr})_R = (\frac{1}{R} + \frac{1}{(\pi D_g t)^{1/2}})(C_{g\infty} - C_{gR}) \tag{3.4}$$

in which the length $(\pi D_g t)^{1/2}$ can be regarded as a diffusion boundary layer thickness. For small bubbles this thickness is much larger than the radius R, so eq. 3.4 can be written as

$$(\frac{dC_g}{dr})_R = (\frac{(C_{g\infty} - C_{gR})}{R}$$

and eq.3.3 can be integrated and written as

$$R^2 = R_0{}^2 + \frac{2D_g(C_{g\infty} - C_{gR})}{\rho_g}t \tag{3.5}$$

The time to go completely into solution is when R=0 in eq.3.5 and when $C_{g\infty} - C_{gR}$ is negative:

$$t = \frac{R_0{}^2\rho_g}{2D(C_{gR} - C_{g\infty})} \tag{3.6}$$

The diffraction coefficient D_g is close to $2 * 10^{-9} m^2/sec$.

An example can give a rough idea about time scales. Consider a bubble with a diameter of 100 microns ($R = 0.5 * 10^-5m$) in water at atmospheric pressure with a saturation rate of 50%. The saturation rate of the water at the bubble wall will be 100 %. The concentration gradient is then estimated as $1.5 * 10^{-2} kg/m^3$ and with $\rho_g = 1$ this means that $\frac{(C_{g\infty} - C_{gR})}{\rho_g} = -1.5 * 10-2$. From eq.3.6 it follows that the time for the bubble to dissolve is 41 seconds. When submerged at 1 m below the surface, such a bubble will not reach the surface (at 5mm/sec), but go into solution. At a time $t = 41$ the term $(\pi Dt)^{1/2}$ is $5 * 10^-4$, which is still an orders of magnitude larger than the initial radius $R_0 = 5^{-5}$. It is therefore justified to neglect this term in eq.3.4.

Surface tension will reduce this time for a bubble to dissolve, but these approximations can be used to determine a time scale. It follows that the diffusion rate is low when compared to the time scale of bubble dynamics in a flow. However, when the existence of gas bubbles in a fluid is considered, small bubbles will tend to go into solution.

3.4 Mechanisms to sustain nuclei

From the foregoing it is still unexplained why there are so many nuclei in water. One mechanism that can keep nuclei in the water without rising to the surface is the combination of gas and solid particles. For that mechanism we have to consider the *surface tension* of a fluid. The difference in bond between cohesion between the water molecules and adhesion between water and air molecules causes *surface tension.* The cohesion attracts the molecules at a free surface and prevent these molecules to mix with the air. The result is also a tension on the surface molecules, which curves the surface in the neighborhood of a solid wall. The surface tension makes that a small gas bubble tends to be spherical. The surface tension increases the pressure inside a spherical gas bubble with an amount of $2s/R_b$ Pa, in which s is the surface tension and R_b the bubble radius. The surface tension of water in contact with air at 15 degrees Celcius is 0.075 Nm and the sensitivity to the temperature is not very strong.

Consider again a nucleus of $0.1mm$ diameter in a fluid of 1 bar ($10^5 Pa$). The pressure

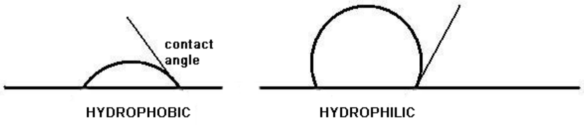

Figure 3.1: Contact Angle

inside the bubble is higher than the surrounding pressure due to the surface tension. The difference is $0.15/10^-4 = 1500 Pa$. Note that this is of the same magnitude as the vapor pressure. When the bubble is only 10 microns in diameter the surface tension increases the pressure with 15000 Pa!. The surface tension will increase the diffusion of gas into the fluid and thus decrease the time required to go into solution and this is increasing with decreasing bubble size.

Surface tension also causes a contact angle at the interface of water-gas-solid. This contact angle depends on the molecular forces in the water, the gas (air) and the material. Two types of material can be distinguished. On hydrophobic surfaces the contact angle is larger than 90 degrees, and air bubbles have the tendency to stick to the surface. In hydrophilic surfaces the contact angle is smaller than 90 degrees and air bubbles have the tendency to detach from the surface (Fig. 3.1).

When the surface is not flat but has the shape of a crevice, the schematic model is as in Fig. 3.2.

The material in Fig.3.2 is hydrophobic. The pressure inside the gas bubble will be lower than in the water due to the surface tension. When the water is not saturated an equilibrium is possible where no net gas diffusion takes place and the bubble is stable. The density of the particle and bubble together can in principle be equal to water and the nucleus is stable. Note that this model was first used by Edmund Newton Harvey [16], a biologist working on bioluminescence and interested in nuclei in blood.

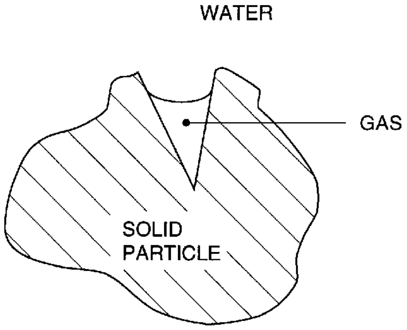

Figure 3.2: Gas Pocket in a Crevice

Diffusion can also be prevented by a molecular skin on the surface of the nucleus, as was already assumed by Fox and Herzfeld in 1964 [14]. A variation on this assumption was used by Yount [50], who assumes a skin of surface active molecules that make the nucleus stable. Morch [38],[39] showed that gas could not only be present in crevices, as Harvey assumed, but also in slightly concave surfaces on solid particles and that the effective radius of these thin gas remains could be larger than the size of the solid particle.

Experiments have shown that solid particles are important for the tensile strength of water. Filtering of water delays cavitation inception and increases the tensile strength of the water [24]. But also pre-pressurization can strongly increase the tensile strength of water by driving the nuclei attached to the solid particles into solution before the low pressure occurs. Nuclei with an organic skin seem to be crushed at some pressure and thus can go into solution also.

3.5 Mechanisms to generate nuclei

As discussed in previous sections, diffusion and gravity will remove nuclei from water. However, in general there are still ample nuclei in regular tap water and also in sea water. At sea, the breaking of waves is a major source of bubbles in the water and the mixing effect of these waves and the related turbulence will prevent small nuclei to rise to the surface. Biological life in the water can also produce free gases and in combination with biological matter it can be a source of nuclei. Actually the tensile strength of sea water in prototype conditions is close to zero and cavitation inception will thus take place at the vapor pressure. //

In test facilities this is different. First of all the amount of organic or solid matter may be less in clean test facilities, but also the size of the nuclei required for inception is larger. And these larger nuclei are not always available in sufficient numbers. So in test facilities like cavitation tunnels and depressurized towing tanks the nuclei content is always a point of concern. Locations where nuclei are formed are low pressure regions in a flow, especially when sharp edges cause local flow separation. These edges may occur on a very small scale, such as on surface roughness.

3.6 Nuclei measurements

It is not easy to measure the size distribution of nuclei. These techniques will be discussed later. Measurements indicate that there are many small nuclei in water. Gates [15] compiled such measurements in his thesis and shown in Fig. 3.3. The size range of the nuclei measured is from 5 microns to 500 microns. The number of nuclei is expressed as the *number density* Nd, which is the number of nuclei in a small small size range divided by the size range. Its unit is therefore m^-4.

The range of number densities is between 10^{10} and 10^{14}. It helps to get a feeling for those numbers. When the number density is 10^{12} and we consider nuclei in the range of 50-100 microns (a size range of $50*10*-6m$) it means that there are $50*10^{-6}*10^{12} = 50*10^{6}$ nuclei per cubic meter or, more imaginable, 50 nuclei per cubic centimeter. The average distance between the nuclei is then $2.5mm$.

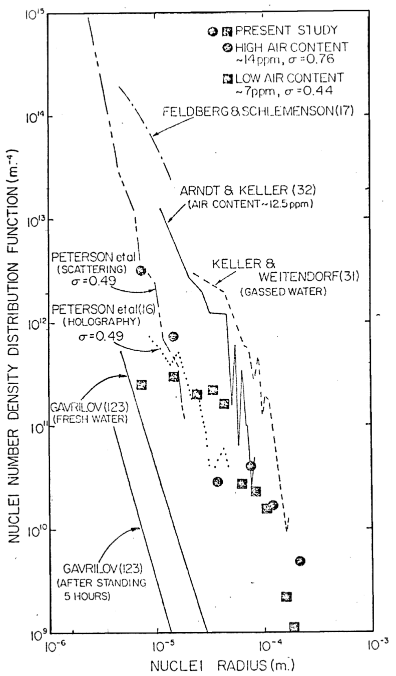

Figure 3.3: Nuclei densities

Fig. 3.3 also shows that this amount can easily vary with a factor 100 depending on the circumstances. Even when there are $50*10^{6}$ nuclei of in average 75 microns in diameter in $1m^3$ of water, this means that there is a volume of $1.1*10^{-5}m^3$ of free gas per m^3 of water. In atmospheric conditions this is also $1.1*10^{-5}kg$ and this is the *free air content* in $1m^3$. This is still only a third of the dissolved air content of $C = 3*10^-2kg/m^3$. In general the amount of free air will be (much) smaller then the amount of dissolved air. So when there is a mechanism to bring air out of solution and create bubbles, this will not immediately deplete the dissolved air content. It is also important to note that the dissolved air content has little or no effect on cavitation inception.

From Fig.3.3 it can be seen that the nuclei are predominantly small. These small nuclei can easily be transported through the fluid by currents and water motions such as waves. But they would still dissolve over time . This seems to be significantly reduced by the presence of an organic skin on the surface of a nucleus. When the nuclei dissolve, the reduction of the radius makes the skin thicker and this ultimately stops the diffusion, making the nuclei stable.

Since in sea water ample nuclei are available not much attention has been given to their origin and presence. However, for model tests the required nuclei size is larger, as explained in chapter refchincept, and these nuclei are often scarce or not available in test facilities. This makes that nuclei distributions dominate the problem of scaling of cavitation inception and the mechanisms of dissolving and rising nuclei have to be considered when test facilities are used.

3.7 Bubble Screening

A phenomenon which is often observed is that cavitation does not take place in the minimum pressure location with a minimum pressure significantly below the vapor pressure. This occurs even in conditions with ample free nuclei in the incoming flow. Since this is observed spedifically in cases when the boundary layer is still laminar in hte minimum pressure region, it was suspected that this delay in inception was caused by a local lack of nuclei. It means that the incoming flow contains enough nuclei , but that they are inhibited to enter the low pressure region. The interpretation of what happens is only tentative because it is very difficult to verify experimentally. A possible explanation is The common explanation is that *bubble screening* occurs. In a pressure gradient nuclei experience a force, similar to the rising force in a gravitational field. Near the leading edge of a foil there is a strong pressure gradient along the foil surface, but also perpendicular to the wall outside the boundary layer (the pressure in a thin boundary layer is constant perpendicular to the wall). This pressure gradient perpendicular to the wall is is especially strong near the stagnation point and, in opposite direction, near the minimum pressure location. Near the stagnation point the pressure gradient will move the nuclei away from the wall. In the minimum pressure region the nuclei are moved towards the wall. As a result the path of the nuclei will not follow the streamlines, but follow a path away from the wall, as sketched in Fig 3.4. The path of the nuclei may thus avoid the minimum pressure close to the wall. The pressure gradient thus has a screening effect and this effect will be greater with increasing size of the nuclei.

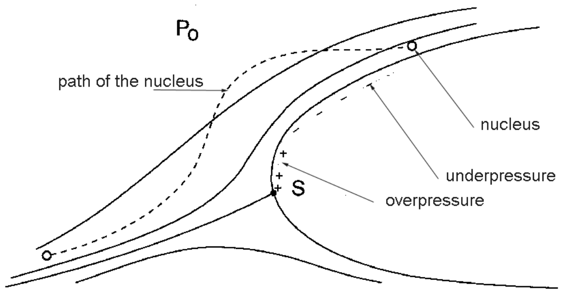

Figure 3.4: Path of a Nucleus in the Pressure Field near the Leading Edge of a Foil

Calculations of the path of nuclei were first made by Johnsson and Hsieh [22] in 1966, assuming a certain drag coefficient of nuclei and assuming that they remained spherical.

Although bubble screening is a plausible hypothesis, experimental evidence is difficult to obtain.

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Appendix A

Air Content of Water

The amount of air dissolved in water α can be expressed in many ways. The most common ways in literature are

- the gas fraction in weight ratio α_w
- the gas fraction in volume ratio α_v
- the molecule ratio
- the saturation rate
- the partial pressure of air

A.1 Solubility

Air is a mixture of 21 percent oxygen, 78 percent nitrogen and one percent of many other gases, which are often treated as nitrogen. The specific mass of gases involved in air are:

Oxygen (O_2)	1.429	kg/m^3
Nitrogen (N_2)	1.2506	kg/m^3
Air	1.292	kg/m^3

The maximum amount of gas that can be dissolved in water, the solubility), depends on pressure and temperature. It decreases with increasing temperature and increases with increasing pressure. The solubility of oxygen in water is higher than the solubility of nitrogen. Air dissolved in water contains approximately 36 percent oxygen compared to 21 percent in air.The remaining amount can be considered as Nitrogen. Nuclei which are in equilibrium with saturated water therefore contain 36 percent oxygen. But nuclei which are generated from the air above the water contain 21 percent oxygen. Since the ratio between oxygen and nitrogen is not fixed, it is difficult to relate measurements of dissolved oxygen (by osmose) to measurements of dissolved air (from e.g a van Slijke apparatus).

The amount of oxygen dissolved in water at atmospheric pressure at 15 degrees Celcius is approximately $10 * 10^{-}6kg/kg$. For nitrogen this value is about $15 * 10^{-}6$, so the solubility of air in water is the sum of both: $25 * 10^{-}6$. Here the dissolved gas contents are expressed as a weigth ratio α_w.Air is very light relative to water and the weight ratio is very small. This ratio is therefore often expressed as parts per million (in weight), which is $10^6 * \alpha_w$.

A.2 The Gas Fraction in Volume Ratio

The volume of gas dissolved per cubic meter of water depends on temperature and pressure. Therefore this volume ratio is expressed in *standard conditions* of 0 degrees Celcius and 1013 mbar (atmospheric conditions). The dependency of the volume of water on temperature and pressure is neglected. The volume of the dissolved air is then described by the law of Boyle-Gay-Lussac:

$$\frac{p * Vol}{273 + T} = constant \tag{A.1}$$

The volume fraction at (p,T) can be related to the volume fraction in standard conditions:

$$\alpha_v = \alpha_v(p,T)\frac{273p}{(273+T)1013} \tag{A.2}$$

The gas fraction in volume ratio is dimensionless (m^3/m^3). Be careful because sometimes this is violated by using cm^3/l ($1000*\alpha_v$) or parts per million (ppm) which is $10^6 * \alpha_v$.

α_v is found from α_w by:

$$\alpha_v = \frac{\rho_{water}}{\rho_{air}}\alpha_w \tag{A.3}$$

in which ρ is the specific mass in kg/m^3. At 15 deg. Celcius and 1013 mbar pressure the specific mass of water $\rho_w = 1000kg/m^3$ and the specific mass of air is $1.223kg/m^3$, so for air $\alpha_v = 813\alpha_w$.

A.3 The Gas Fraction in Molecule ratio

The dissolved amount of gas can also be expressed as the ratio in moles(Mol/Mol). Molar masses may be calculated from the atomic weight in combination with the molar mass constant (1 g/mol) so that the molar mass of a gas or fluid in grams is the same as the atomic weight.
The molar ratio α_m is easily found from the weight ratio by

$$\alpha_w = \alpha_m\frac{M_(water)}{M_(gas)} \tag{A.4}$$

in which M is the molar weight, which is 18 for water, 16 for oxygen(O_2) and 28 for Nitrogen (N_2). For air a virtual molar weigth can be defined using the ratio of oxygen and nitrogen of 21/79 this virtual molar weight of air is about 29.

A.4 The saturation rate

The saturation rate is the amount of gas in solution as a fraction of the maximum amount that can go in solution in the same conditions. Since the saturation rate is dimensionless. It is independent of the way in which the dissolved gas or the solubility is expressed. The saturation rate is important because it determines if and in which direction diffusion will occur at a free surface. The saturation rate varies with temperature and pressure, mainly because the solubility of gas changes with these parameters.

A.5 The partial pressure

Sometimes the amount of dissolved gas is expressed as the partial pressure of the gas (mbar or even in mm HG). This is based on Henry's law, which states that the amount of gas dissolved in a fluid is proportional to the partial pressure of that gas. In a van Slijke apparatus a specific volume of water is taken and subjected to repeated spraying in near vacuum conditions (a low pressure decreases the solubility). This will result in collecting the dissolved in a chamber of specific size. By measuring the pressure in that chamber the amount of dissolved gas is found. Note that this pressure is not directly the partial pressure. A calibration factor is required which depends on the apparatus.

Appendix B

Standard Cavitators

A standard cavitator is a reference body which can be used to compare and calibrate cavitation observations and measurements. Its geometry has to be reproduced accurately and therefore an axisymmetric headform has been used as a standard cavitatior.

Such an axisymmetric body has been investigated in the context of the ITTC (International Towing Tank Conference).This is a worldwide conference consisting of towing tanks (and cavitation tunnels) which have the goal of predicting the hydrodynamic behavior of ships. To do that model tests and calculations are used. They meet every three years to discuss the state of the art and to define common problem areas which have to be reviewed by committees. The ITTC headform has a flat nose and an elliptical contour [22]. Its characteristics are given in Fig B.1.

This headform has been used to compare cavitation inception conditions and cavitation patterns in a range of test facilities. The results showed a wide range of inception conditions and also a diversity of cavitation patterns in virtually the same condition, as illustrated in Fig B.3. This comparison lead to the investigation of viscous effects on cavitation and cavitation inception.

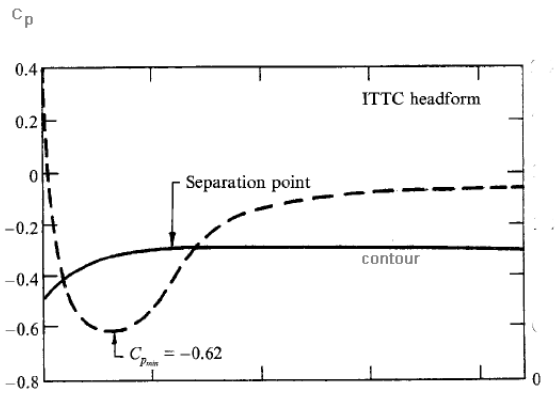


Figure B.1: Contour and Pressure Distribution on the ITTC Headform [31]

The simplest conceivable body to investigate cavitation is the hemispherical headform. This is an axisymmetric body with a hemispere as the leading contour. Its minimum pressure coefficient is -0.74. The hemisperical headform was used to compare inception measurements in various cavitation tunnels. However, it was realized later on that the boundary layer flow on both the ITTC and on the hemisperical headform was not as simple as the geometry suggested. In most cases the Reynolds numbers in the investigations was such that the boundary layer over the headform remained laminar and the pressure distribution was such that a laminar separation bubble occurred, in the position indicated in Fig. B.1. This caused viscous effects on cavitation inception and made the headform less suitable as a standard body. Note that the location of laminar separation is independent of the Reynolds number. When the Reynolds number becomes high transition to turbulence occurs upstream of the sep-

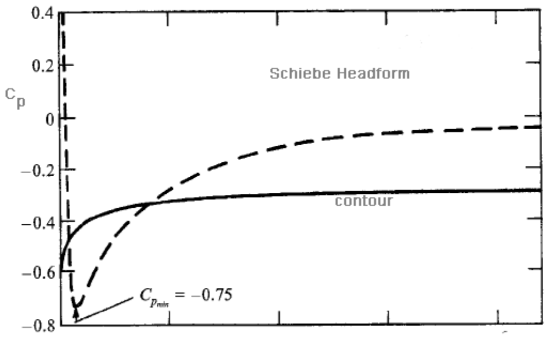
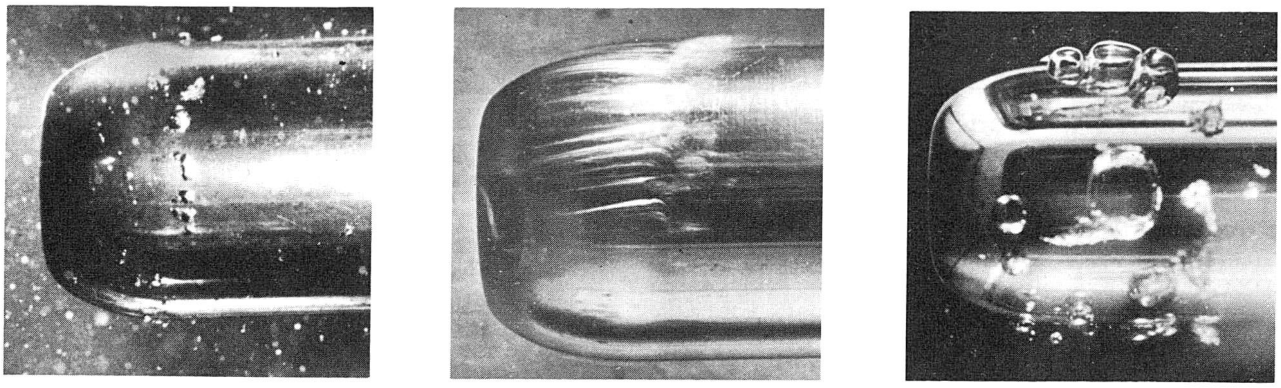


Figure B.2: Contour and Pressure Distribution of the Schiebe body [31]

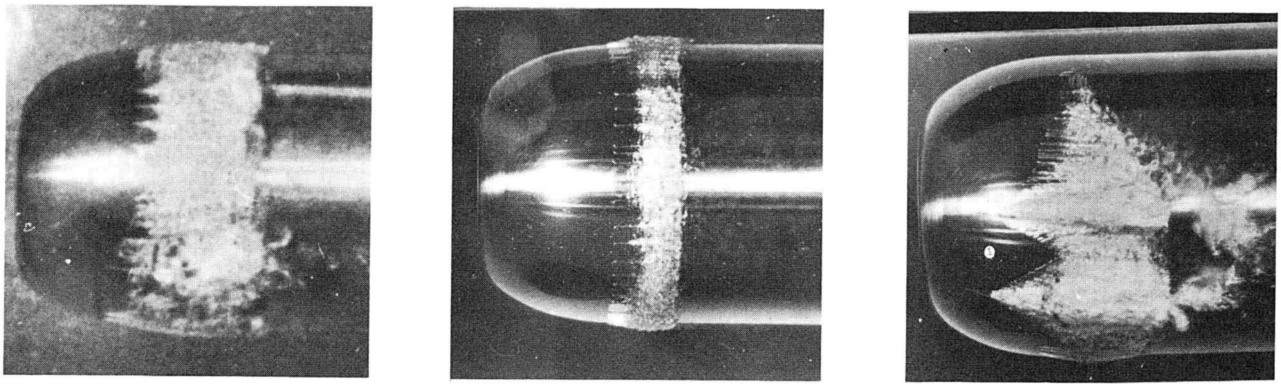
aration location and separation will disappear.

To avoid laminar separation another headform was developed by Schiebe ([43]) and this headform bears his name ever since. The contour and pressure distribution on the Schiebe headform are given in Fig. B.2. This headform has no laminar separation and transition to a turbulent boundary layer will occur at a location which depends on the Reynolds number.

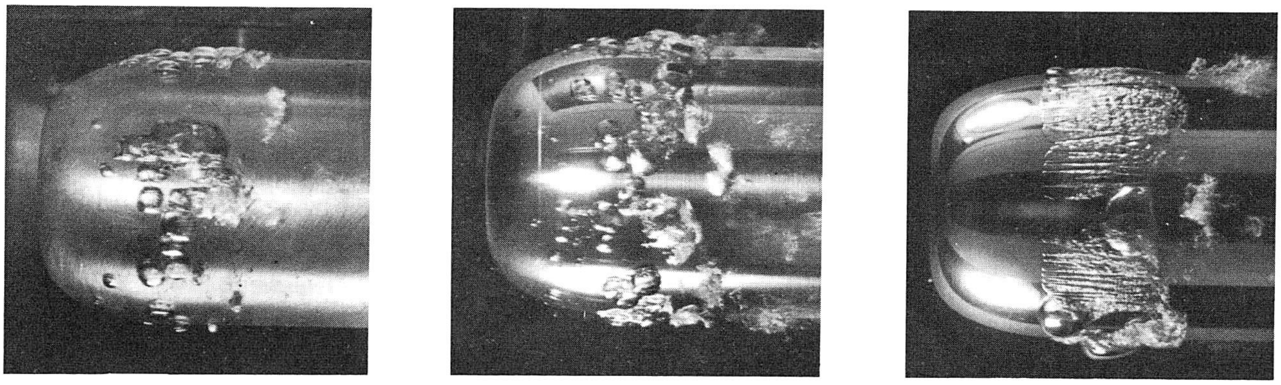
Many other headform shapes have been investigated with different minimum pressure coefficients and pressure recovery gradients.(e.g.[20])



1. Rome 2. AEW 3. Delft



4. NPL 5. Cal. Tech. 6. Cal. Tech.



7. SSPA 8. SSPA 9. SSPA

Figure B.3: Comparative measurements of cavitation inception on the ITTC headform source:ITTC

Appendix C

Tables

T Celcius	p_v N/m^2
0	608.012
2	706.078
4	813.951
6	932
8	1069
10	1226
12	1402
14	1598
15	1706
16	1814
18	2059
20	2334
22	2638
24	2981
26	3364
28	3785
30	4236
32	4756
34	5315
36	5943
38	6619
40	7375

Table C.1: Vapor pressure of Water.

Temp. deg. C.	kinem. visc. fresh water $m^2/sec \times 10^6$	kinem. visc. salt water $m^2/sec \times 10^6$
0	1.78667	1.82844
1	1.72701	1.76915
2	1.67040	1.71306
3	1.61665	1.65988
4	1.56557	1.60940
5	1.51698	1.56142
6	1.47070	1.51584
7	1.42667	1.47242
8	1.38471	1.43102
9	1.34463	1.39152
10	1.30641	1.35383
11	1.26988	1.31773
12	1.23495	1.28324
13	1.20159	1.25028
14	1.16964	1.21862
15	1.13902	1.18831
16	1.10966	1.15916
17	1.08155	1.13125
18	1.05456	1.10438
19	1.02865	1.07854
20	1.00374	1.05372
21	0.97984	1.02981
22	0.95682	1.00678
23	0.93471	0.98457
24	0.91340	0.96315
25	0.89292	0.94252
26	0.87313	0.92255
27	0.85409	0.90331
28	0.83572	0.88470
29	0.81798	0.86671
30	0.80091	0.84931

Table C.2: Kinematic viscosities adopted by the ITTC in 1963

R_n	$C_f \times 10^3$
1×10^5	8.333
2	6.882
3	6.203
4	5.780
5	5.482
6	5.254
7	5.073
8	4.923
9	4.797
1×10^6	4.688
2	4.054
3	3.741
4	3.541
5	3.397
6	3.285
7	3.195
8	3.120
9	3.056
1×10^7	3.000
2	2.669
4	2.390
6	2.246
8	2.162
1×10^8	2.083
2	1.889
4	1.721
6	1.632
8	1.574
1×10^9	1.531
2	1.407
4	1.298
6	1.240
8	1.201
1×10^{10}	1.17x

Table C.3: Friction coefficients according to the ITTC57extrapolator.

Temp. deg. C.	density fresh water kg/m^3	density salt water kg/m^3
0	999.8	1028.0
1	999.8	1027.9
2	999.9	1027.8
3	999.9	1027.8
4	999.9	1027.7
5	999.9	1027.6
6	999.9	1027.4
7	999.8	1027.3
8	999.8	1027.1
9	999.7	1027.0
10	999.6	1026.9
11	999.5	1026.7
12	999.4	1026.6
13	999.3	1026.3
14	999.1	1026.1
15	999.0	1025.9
16	998.9	1025.7
17	998.7	1025.4
18	998.5	1025.2
19	998.3	1025.0
20	998.1	1024.7
21	997.9	1024.4
22	997.7	1024.1
23	997.4	1023.8
24	997.2	1023.5
25	996.9	1023.2
26	996.7	1022.9
27	996.4	1022.6
28	996.2	1022.3
29	995.9	1022.0
30	995.6	1021.7

Table C.4: Densities as adopted by the ITTC in 1963.

Appendix D

Nomenclature

ρ	density of water	$\frac{kg}{m^3}$	See TableC.4
C_g	gas concentration	kg/m^3	see Appendix A
D_g	diffusion coefficient	m^2/sec	representative value $2 * 10_9$
D	diameter	m	
F_d	drag	N	
g	acceleration due to gravity	$\frac{m}{sec^2}$	Taken as 9.81
Nd	number density of nuclei	m^-4	
p_g	gas pressure	$fracNm^2$	
$fracNm^2$			
p_v	equilibrium vapor pressure		
R	radius	m	
μ	dynamic viscosity of water	$\frac{kg}{m*sec}$	
ν	kinematic viscosity of water	$\frac{m^2}{sec}$	($\nu = \frac{\mu}{\rho}$)See Table C.2
s	surface tension	Nm	for water 0.075