

# Appendix A

## Air Content of Water

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

- the gas fraction in weight ratio  $\alpha_w$
- the gas fraction in volume ratio  $\alpha_v$
- 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  $10 * 10^{-6} kg/kg$ . 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 weighth ratio  $\alpha_w$ . 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:

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

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

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

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  $10^6 * \alpha_v$ .

$\alpha_v$  is found from  $\alpha_w$  by:

$$\alpha_v = \frac{\rho_{water}}{\rho_{air}} \alpha_w \quad (A.3)$$

in which  $\rho$  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  $\alpha_m$  is easily found from the weight ratio by

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

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 weight 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 Cavitation

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 cavitator.

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 [27]. 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.

The simplest conceivable body to investigate cavitation is the hemispherical headform. This is an axisymmetric body with a hemisphere as the leading contour. Its minimum pressure coefficient is -0.74. The hemispherical

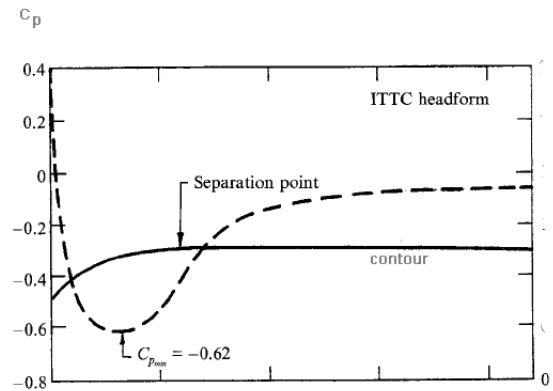


Figure B.1: Contour and Pressure Distribution on the ITTC Headform [38]

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 hemispherical 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-

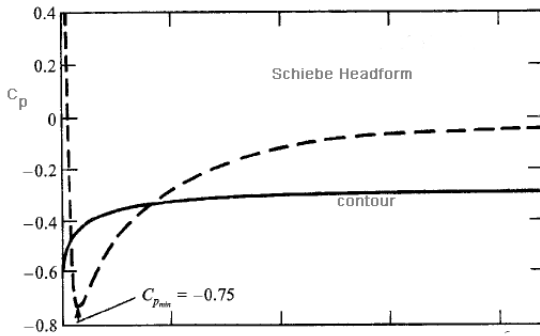
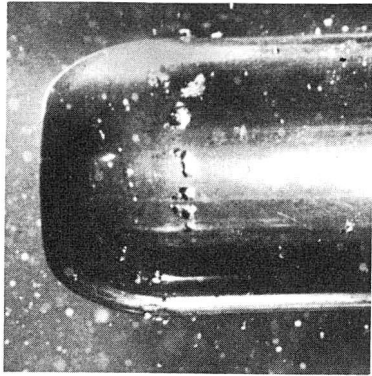


Figure B.2: Contour and Pressure Distribution of the Schiebe body [38]

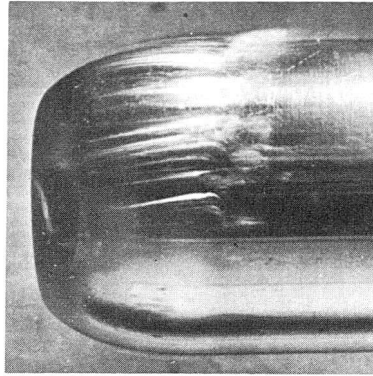
aration location and separation will disappear.

To avoid laminar separation another headform was developed by Schiebe ([56]) 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.

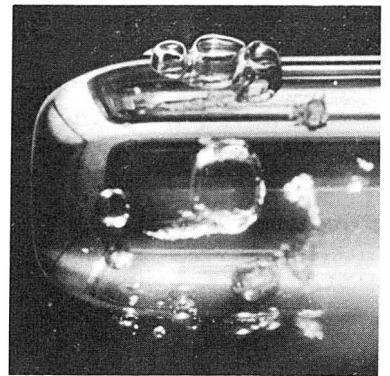
Many other headform shapes have been investigated with different minimum pressure coefficients and pressure recovery gradients.(e.g.[24])



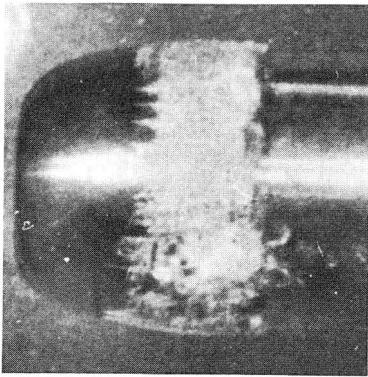
1. Rome



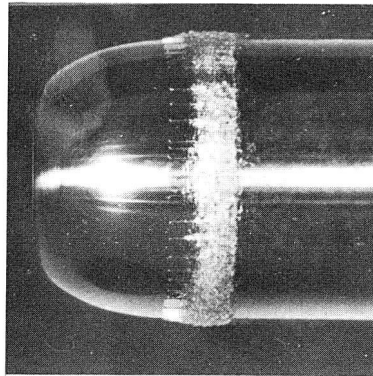
2. AEW



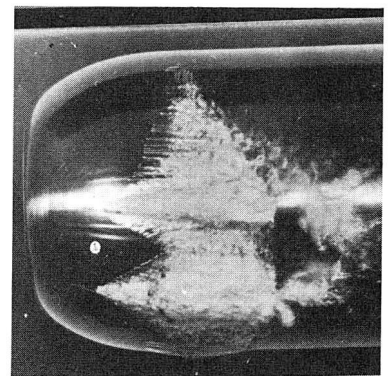
3. Delft



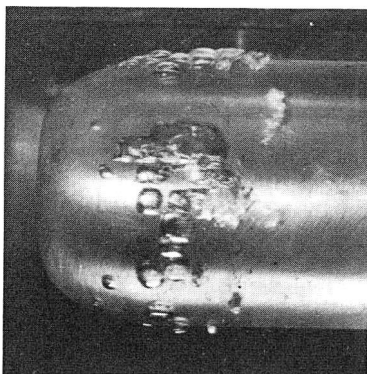
4. NPL



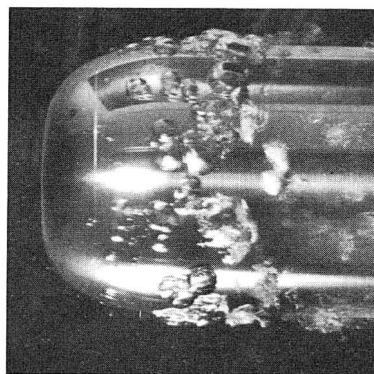
5. Cal. Tech.



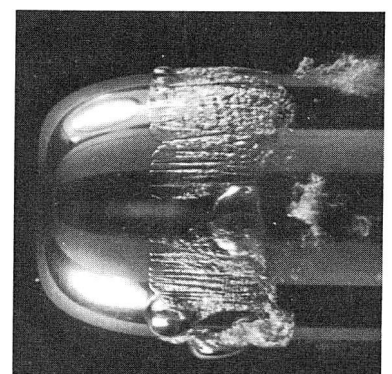
6. Cal. Tech.



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



$R_n$	$C_f \times 10^3$
$1 \times 10^5$	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
$1 \times 10^6$	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
$1 \times 10^7$	3.000
2	2.669
4	2.390
6	2.246
8	2.162
$1 \times 10^8$	2.083
2	1.889
4	1.721
6	1.632
8	1.574
$1 \times 10^9$	1.531
2	1.407
4	1.298
6	1.240
8	1.201
$1 \times 10^{10}$	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

$\rho$	density of water	$\frac{kg}{m^3}$	See Table C.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	$fracNm^2$	
$\frac{N}{m^2}$	equilibrium vapor pressure		
R	radius	$m$	
$Rn$	Reynolds number $\frac{V.L}{\nu}$ in which V and L are a velocity and a length scale		
$\mu$	dynamic viscosity of water	$\frac{kg}{m*sec}$	
$\nu$	kinematic viscosity of water	$\frac{m^2}{sec}$	$(\nu = \frac{\mu}{\rho})$ See Table C.2
$s$	surface tension	$Nm$	for water 0.075