

Chapter 2

INTRODUCTION

Objective: *An introduction of the phenomenon of cavitation, its history, occurrence and effects.*

Cavitation is the occurrence of vapor in a fluid due to local low pressures which are generated by high local flow velocities.

2.1 Cavitation and boiling

A general description of *cavitation* is the transition of fluid into vapor due to local reduction of the pressure. There are more ways to arrive at a transition of water into vapor and the most common method is *cooking* of water. There the transition of water into vapor is not due to a lower local pressure, but to an increase of the local temperature. The term cavitation is generally reserved for conditions in which the temperature of the bulk fluid is not changed. This distinction between cooking and cavitation is not always sharp, because both temperature and pressure effects can be present at the same time, e.g. in the flow around pipes in heat exchangers. In the case of hydraulics or hydrodynamics the bulk temperature during the process of cavitation is generally isothermal and the occurrence of vapor regions is due to local pressure reductions which are related with

the local flow velocities. In that case the phenomenon is called cavitation.

Cavitation is the transition of a fluid into vapor. That can be any fluid. An example is the occurrence of cavitation in blood as may occur in artificial heart valves [32] or cavitation in pumps and valves in which all types of fluids are used. In principle the local pressure in a fluid cannot be lower than the vapor pressure. If that occurs vapor will be generated from the fluid and the resulting volume increase will only be checked when the vapor pressure is reached. Reality is often more complex, as will be discussed in chapter 4.

2.2 Cavitation in water and other fluids

The pressure at which both vapor and fluid can be present in a fluid is called the equilibrium vapor pressure or shortly the *vapor pressure*. The main parameter of the vapor pressure is the temperature. For technical purposes a "standard" temperature of 15 degrees Celcius is often used. The vapor pressure of water in that condition is 1706 Pa. The data may vary between different sources. The differences are small, but may lead to confusion. For application in ship hydrodynamics the International Towing Tank Conference adopted a line with pressures as given in Appendix C.

2.3 Adverse effects of cavitation

The main effects of cavitation are adverse effects: noise, erosion, vibrations and disruption of the flow, which results in loss of lift and increase of drag.

Cavitation is known for its violent behavior. That is caused by the fact that vaporization of water and condensation of vapor are very fast processes, much faster than the dynamics of a vapor cavity. As a result the growth and collapse of a cavity is not slowed down by these processes. The violent behavior of cavitation has several adverse effects. Because cavitation is part of the flow, it can move rapidly from regions of low pressure into regions of a higher pressure. This leads to a very rapid *collapse*. The collapse is so rapid that the local speed of sound in the fluid is exceeded and shock waves occur. The consequence is that cavitation is very noisy and radiates noise over a wide range of frequencies, especially higher frequencies.

Also the local pressure rises very strongly at collapse, leading to damage of a nearby surface. This effect is called *erosion*. When larger amounts of vapor are involved the implosion of cavitation can cause pressure variations in the fluid, which lead to vibrations of the cavitating structure. The majority of the adverse effects of cavitation can be related with *erosion, noise and vibrations*.

Cavitation can also alter the flow. This is e.g. the case on propellers when the cavitation becomes extensive. In that case the flow over the blades and the lift of the blades is altered by the cavitation and the thrust of the propeller is strongly reduced. This is the so-called *thrust breakdown*. In valves cavitation can also block or choke the flow.

The volume of vapor in cavitation is much larger than the volume of the water that has evaporated. In cases of extensive cavitation this leads to large volume increases and

decreases when cavitation grows and collapses. The volume variations cause pressure fluctuations in the surrounding fluid, with structural vibrations as a result.

The properties of cavitation and its implosion can also be used, as will be mentioned below.

2.4 Examples of effects of cavitation

The focus of this course is on ship hydrodynamics and ship propellers. But cavitation occurs in many other situations, mostly with adverse effects. Cavitation in pumps is related to that on ship propellers, and the effects are the same. First the pump may be damaged at the location of cavitation, but with an increasing amount of cavitation the efficiency of the pump decreases. Cavitation can also occur in pipes and valves, especially when the temperature is high and the difference between the mean pressure and the vapor pressure is small. A rattling noise in the tap of a shower indicates cavitation and eventually will cause damage. Extensive cavitation can reduce the flow through a valve or pipe significantly.

Cavitation also occurs in dam overflows when the overflow accelerates the water locally. This may lead to large scale damage of the concrete. Local acceleration of the water also occurs when gates of sluices are closed or opened and cavitation may occur, generally resulting in erosion damage.

Cavitation also occurs in small fluid lines, such as in the heads of inkjet printers or diesel fuel injection [46]. The flow velocity in those lines is limited by cavitation.

Small fluid lines also occur in plants. Water

in a tree is predominantly sucked from the top through capillary vessels. This limits the height of a tree, because when the pressure at the top is too low, the fluid will cavitate and the flow will stop due to the occurrence of vapor. In times of drought vapor is indeed present in these capillary lines. When such a plant is watered abruptly it seems that implosion of the vapor cavities in those vessels can cause fatal damage to the capillary lines due to implosion of the cavities.

Cavitation is also used for specific purposes. The destructive effect of acoustic pressure waves focussed on kidney stones is due to cavitation. Cavitation is a main factor in the acoustic destruction of kidney stones (lithotripsy). The imploding cavities destruct the kidney stone. It is clear that the focussing is very important to avoid damage to tissue. This risk of damage due to cavitation is also a limitation in the application of acoustic diagnostics [30]. The destructive properties of cavitation are also used to destruct cancer cells. This is a way to remove cancer cells in a non-intrusive way. But when the energy density becomes too high cavitation in the tissue will also cause damage. Medical applications use very small nuclei to transport drugs. These nuclei are made to cavitate in locations where the drugs have to be applied [41]. Kato proposed cavitation as a means to kill unwanted biological life from e.g. ballast water of ships [23], [49].

Cavitation erosion is also used in underwater cleaning. A strong fluid jet which hits a surface will cause local cavitation and the implosions will remove fouling from the surface. It is also used in rock cutting and in cutting steel with high speed jets. Rock cutting in deep sea is notably more difficult due to the lack of cavitation in that environment.

2.5 History

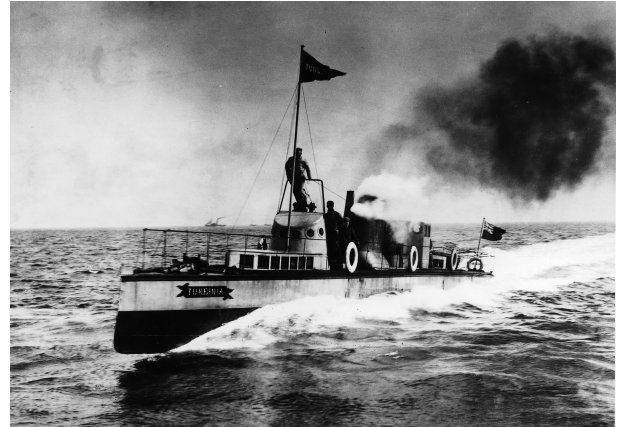


Figure 2.1: The Turbinia, used by Charles Parsons to obtain 30 knots ship speed

Cavitation entered its role in ship propellers around 1894, when Charles Parsons tried to establish a speed record by using a steam turbine for ship propulsion. The power of the steam turbine was enough for a small boat to run at 30 knots or more, but the problem was how to bring this power in the water by a propeller. The ship he used was the Turbinia, a 30 meter fast boat [6]. Sir Charles Parsons found that the propellers had an excessive slip, which means that they rotated much faster than the pitch of the propeller. He suspected that "there appears to be vacuum behind the blades". He made that visible by designing a small cavitation tunnel of about 60 cm in length with a 5 cm diameter propeller model, in which tunnel he applied stroboscopic illumination of the propeller by using a rotating mirror with the same rotation rate as the propeller.

There it became apparent that there was an empty space on and behind the propeller blade. The term cavitation was born, although Burill mentions in his paper that from unnamed sources it seems that R.E. Froude used the term cavitation first. After many propeller designs it took nine propellers on three shafts

to obtain a speed of more than 32 knots in 1897. He showed the possibilities of steam turbine propulsion by running the Turbinia unannounced on the Spithead Navy Review in 1897, which was held on the occasion of queen Victoria's diamond jubilee. The Turbinia was faster than any other ship and easily outran the Navy's patrol boats.

This was the beginning of a development of propeller design and cavitation testing. A larger cavitation tunnel was built at Wallsend in 1910.

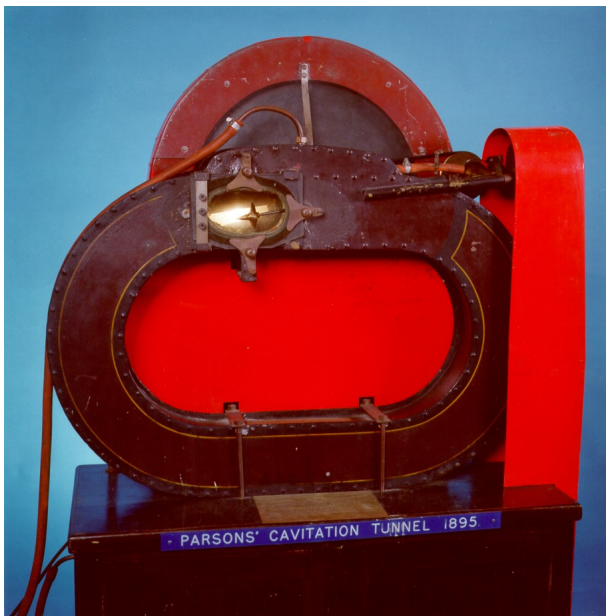


Figure 2.2: The first cavitation tunnel used by Charles Parsons

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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 $10 * 10^{-6} kg/kg$. 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 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:

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

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 $10^6 * \alpha_v$.

α_v is found from α_w by:

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

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

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

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 [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.

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

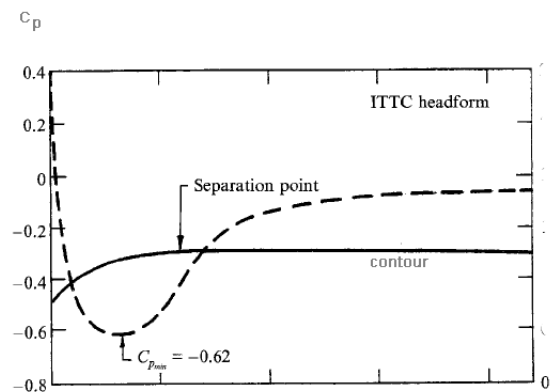


Figure B.1: Contour and Pressure Distribution on the ITTC Headform [31]

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-

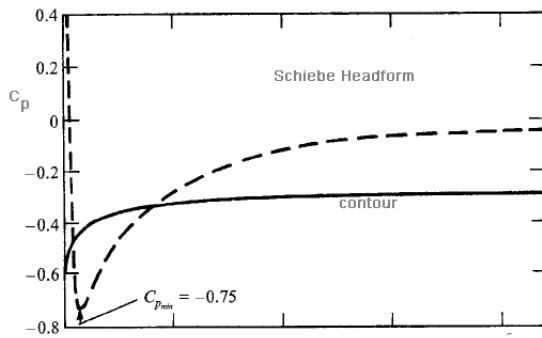
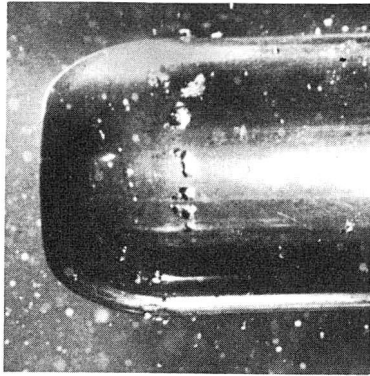


Figure B.2: Contour and Pressure Distribution of the Schiebe body [31]

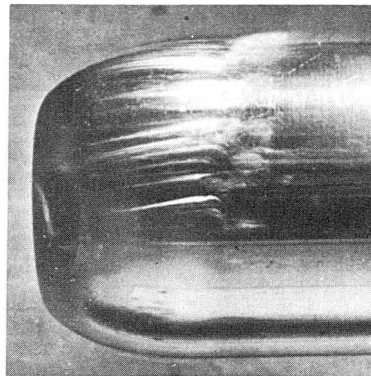
aration location and separation will disappear.

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.

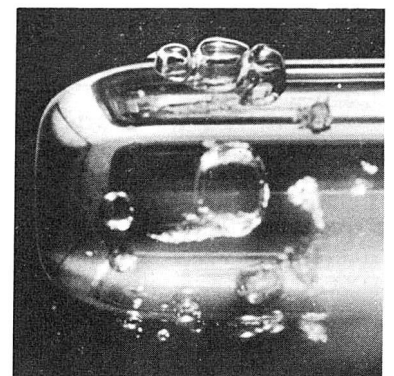
Many other headform shapes have been investigated with different minimum pressure coefficients and pressure recovery gradients.(e.g.[20])



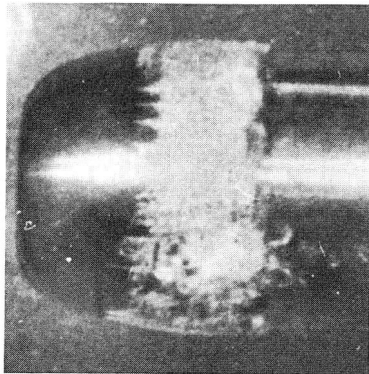
1. Rome



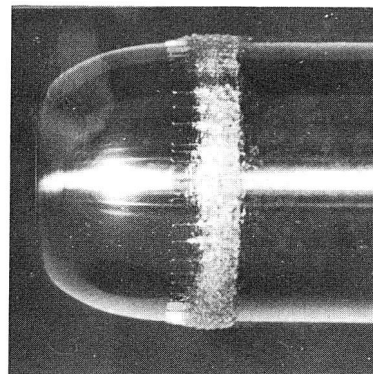
2. AEW



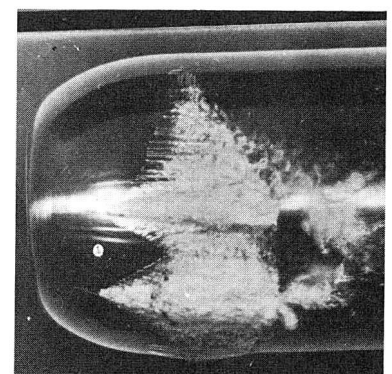
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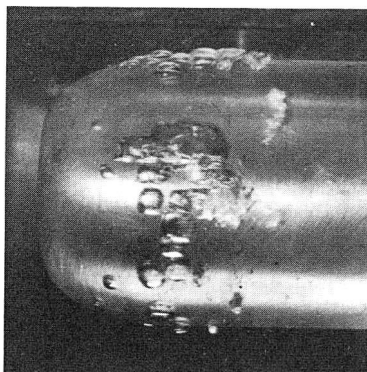
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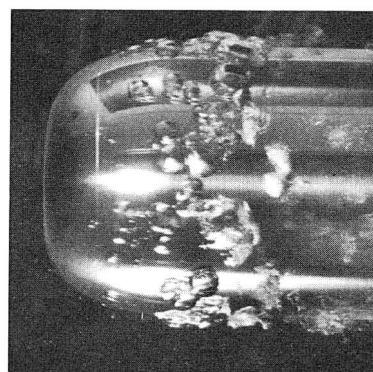
5. Cal. Tech.



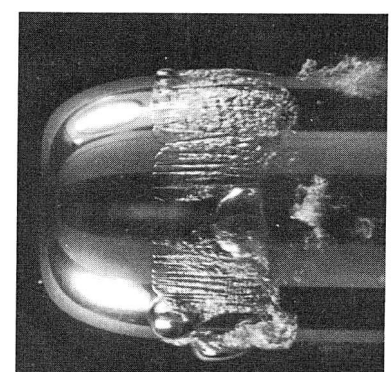
6. Cal. Tech.



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 <i>kg/m³</i>	density salt water <i>kg/m³</i>
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 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	$fracNm^2$	
$fracNm^2$			
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