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DE BRUXELLES**

Cooling Down a Coke Can
Experiment study

Fluid Mechanics and Transport Processes

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“Cooling down a coke can”

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Chapitre 1

Introduction

This report aims to explain the experiment done on the 06/10/2015 during the “Fluid Mechanics and Transport Processes” course at ULB. The experiment can be found at this address ¹.

The physical phenomena behind this experiment are related to the heat transfer processes.

The experiment consists on taking three coke cans and a bucket of ice and water. Each can is subject to a different treatment.

The first can is used to measure the initial temperature.

The second one is just put inside the above mentioned bucket.

The last coke can is spun inside the bucket at a speed of $1000rpm$.

The duration of the experiment is 60 seconds. At the end of this duration, the temperature of each coke can is measured.

«««< HEAD The result for this experiment were : 16 °C for the first can, 11.9 °C for the second and 11 °C for the spinning can.

The question here is how to explain this difference of temperature and the answer can be given by two phenomena : conduction and convection.

Both of those phenomena will be explained in the first part of this report.

In the second part, simplifying assumptions considered for the experiment will be explained, after what the different mathematical models used will be described.

The third part will be dedicated to explaining the reasons of the differences between the numerical data obtained and the measurements taken during the manipulation.

A global conclusion will finish these report.

===== »»»> origin/master

1. https://www.youtube.com/watch?v=MSwc_IAPh3E

Chapitre 2

Heat transfer processes

They are three different ways of transferring heat : conduction, convection and radiation. Due to its nature (heat exchange between two distant bodies at very different temperatures), radiation can be neglected for this experiment and will thus not be presented here.

2.1 Conduction

Thermal conduction is a heat transfer process without macroscopic movement of matter. It is initiated by a difference of temperature between contiguous bodies (or inside a body). This difference of temperature implies a difference of internal energy : the energy is higher in the warmer area than in the cooler. By diffusion and collisions between the particles, which can be molecules in a fluid or conduction electrons in a solid, particles in the warmer area transfer kinetic energy to the other particles, and make them move and/or vibrate faster. This creates a heat flow from the warmer area to the cooler until the system reaches thermal equilibrium. Furthermore, conduction is an irreversible process.

Conduction is described by the following general equation, which is demonstrated in Professor Jean-Marie Buchlin's course[3], Chapter 13.

$$\frac{\delta T}{\delta t} = \nabla \cdot (\alpha \nabla T) + \dot{Q}_v \quad (2.1)$$

This equation can not be used by itself because of its nature (second degree partial derivative equation). It thus needs boundary conditions linked to properties of the system. Those can be geometrical, physical, temporal or border conditions.

Boundary conditions used and simplifications of the above presented general equation will be discussed in chapter 3.

2.2 Convection

Convection refers to particular heat transfers in fluids. Convection occurs when some fluid is in movement. The movement lead to an advection (heat is transported by moving matter).

Convection is described as following :

$$Convection = Conduction + Advection \quad (2.2)$$

Therefore, it is easy to understand that convection is superior than conduction in fluids in a flux situation.

An important distinction can be made in convective heat transfers : convection can be natural or forced. Natural convection occurs mainly due to temperature differences which modify fluids density. Increasing the temperature amplifies thermal agitation which leads to a volume expansion along with a decreasing of density. Cold components are thus heavier and fall down while lighter hot components rise. This created a bulk fluid motion initiating a convective heat transfer called natural convection. Forced convection refers to a convective heat transfer due to surface forces which generates a movement in the fluid. This convective heat transfer has thus a great sensitivity to the velocity acquired by the fluid. The surfaces forces can be applied by either artificial ways such as fans or natural ways such as blowing wind. Both natural and forced convection can happen simultaneously but forced convection is usually the most significant, especially at high velocity.

The flow properties also have a major impact on convective heat transfers and can be expressed through dimensionless numbers. As convection depends on the flow (laminar, turbulent,...), we will discuss the equation to use in the next chapter.

Chapitre 3

Mathematical model

The idea behind mathematical models is to create a simplified version of a problem, that is accurate enough to predict the behaviour of a system, and at the same time simple enough to be resolved with few calculations.

This means that some simplifications of the above mentioned equations can be made, using the properties of the studied system.

General simplifying assumptions for the experiment will first be described and their validity will be discussed, then two simplified models will be presented : one for the non-spinning can and one for the spinning can.

3.1 General simplifying assumptions

The first assumption that will be considered is that the fluid contained in the can has properties similar to those of water. Coke is indeed an aqueous solution containing sugar and other ingredients, but at relatively low concentrations. Properties of water can be found in annex B and are extracted from “*Perry’s Chemical Engineers’ Handbook*”[2].

We also assume that the can is a perfect cylinder with an height of $h = 116mm$ and a diameter of $d = 66mm$ ¹. In reality, the shape of a can is a bit different in order to support pressure but this difference should not be significant in our calculations. The material used for cans is Aluminium and since it is extremely thin (less than $1mm$) and has an excellent thermal conductivity ($> 200 \frac{W}{K.m}$), its influence on heat transfers can be neglected. The considered model will thus be a cylinder of water laid under water maintained at another temperature and without any exchange of matter, as shown in figure 3.1.

Furthermore, the hypothesis that all heat exchanges between the can and the surrounding ice-cold water take place on the sides of the can and not on its top or bottom will be assumed. The

1. Those dimensions are standard for European Aluminium 330ml cans and can be found on webpackaging.com

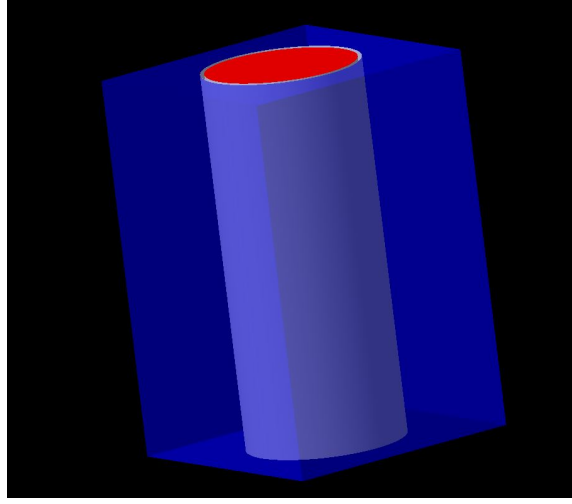


FIGURE 3.1 – The red cylinder is hotter water, the blue box is colder water. No matter exchanges, only heat transfer.

total surface of the can is given by :

$$\begin{aligned}
 Surface &= 2.Surfac_{circle} + Surfac_{rectangularside} \\
 \Leftrightarrow S &= 2(\pi(\frac{d}{2})^2) + \pi dh \\
 \Leftrightarrow S &= 30.8944cm^3
 \end{aligned} \tag{3.1}$$

Bottom and top circular surfaces have a total surface of $2xSurfac_{circle} = 2(\pi(\frac{d}{2})^2) = 6.8424cm^3$, which makes around 22.14% of the total surface. The reason why it was decided to ignore such a large portion of the can's area is that half of it is not even in contact with ice during the experiment (the system holding the can covers it's top and the non-spinning can is not totally in ice), reducing the area to consider at about 11% of total exchange area. This can still be seen as a large percentage. However, on one side we are trying to cool down a liquid on the bottom of the can and, on the other hand, cold fluids tend to be more dense than hot fluids. Therefore, the liquid in contact with the bottom part will be cooler, making the heat transfer far less efficient there.

The last general simplification made for this experiment is to consider the mix of ice and water surrounding the can as a continuous layer of water maintained at 0°C. This should be correct enough considering that there is a large quantity of melting ice in an isolated box. Indeed, liquid water is more flexible than ice, the can has a larger surface in contact with molten ice (thus water) than with the ice itself.

3.2 Simplified models

With these four simplifications in mind, two models will now be build, one for the non-spinning can and one for the spinning can.

3.2.1 Non-spinning can

Heat transfer processes in presence are conduction and natural convection. Natural convection appears because of the density change of fluid related to temperature : the cooler the fluid, the denser it is. There is no forced convection because there is no flux in the fluid.

The convective heat transfer coefficient for natural convection (in the can) is given by :

$$h_x = Ra^\alpha = cGr^\alpha Pr^\alpha \quad (3.2)$$

Where Gr is the Grashof number and Pr the Prandtl number. Prandtl can be found in annex B : water being at 16°C (about 290K), it gives $Pr = 7.56$.

Grashof number is calculated using the following formula (taken from annex C) :

$$Gr = \frac{\beta g \Delta T_{ref} d^3}{\nu^2} \quad (3.3)$$

Where :

- β is the volume expansion coefficient, given by $\frac{1}{\rho} \frac{\delta \rho}{\delta T}$. Using the tables in annex B, the following approximation can be made : $\beta = 1.001 \times 10^{-3} \frac{\frac{1}{1.000 \times 10^{-3}} - \frac{1}{1.001 \times 10^{-3}}}{5} = 1.998 \times 10^{-4} K^{-1}$.
- $g = 9.81 \frac{m}{s^2}$ is gravity.
- $\Delta T_{ref} = 16 - 0 = 16^\circ C$ is the difference of temperature between the water inside the can and the ice-cold water outside of it.
- $d = 66 \times 10^{-3} m$ is the diameter of the cylinder.
- $\nu = \frac{\mu}{\rho} = \frac{1080 \times 10^{-6}}{\frac{1}{1.001 \times 10^{-3}}} = 1.081 \times 10^{-6} \frac{m^2}{s}$ is water's kinematic viscosity.

All values used in our calculation can be verified in annex B.

Rayleigh number is thus :

$$Ra = GrPr = 7.56 \times \frac{1.998 \times 10^{-4} \times 9.81 \times 16 \times (66 \times 10^{-3})^3}{(1.081 \times 10^{-6})^2} = 5.8329 \times 10^7 \quad (3.4)$$

Since $Ra < 10^9$, the laminar case can be considered. Assuming that the ice-cold water around the can is at a constant temperature, it is now needed to determine which equation to use for Nusselt number.

The easiest approximation is to describe the cylinder as a rectangular enclosure, with H (the height of the enclosure) equal to $h = 116 mm$ and L (the characteristic length of the enclosure) equal to $\frac{d}{2} = 33 mm$. This gives an H on L ratio of $\frac{H}{L} = 3.352$. The equation 9-53 at page 555 of "Heat and Mass Transfer : Fundamentals and Applications" [4], chapter 9-5 will thus be used :

$$Nu = 0.22 \left(\frac{Pr}{0.2 + Pr} Ra \right)^{0.28} \left(\frac{H}{L} \right)^{-1/4} \quad (3.5)$$

$$\Leftrightarrow Nu = 2.3835 \times 10^1$$

and :

$$Nu = \frac{hL}{k}$$

$$\Leftrightarrow h = \frac{Nuk}{L} = \frac{2Nuk}{d} \quad (3.6)$$

$$\Leftrightarrow h = 4.3191 \times 10^2 \frac{W}{m^2 K}$$

Biot number is given by $Bi = \frac{hL}{k} = \frac{hd}{2k} = 23.8347 > 1$. This indicates that *the system can not be considered as a Lumped system*, the temperature inside the can is not homogeneous. But, as the temperature is measured manually by putting a thermometer inside the can, and as the size of the thermometer is not negligible compared to the small radius of the can, the system will be simplified by using the equations for a Lumped system in the case of sensible heat transfer :

$$\begin{aligned}
\rho C_p V \frac{dT}{dt} &= -h S_{tot} (T - T_{ext}) \\
\Leftrightarrow \frac{h S_{tot}}{\rho C_p V} dt &= \frac{1}{(T_{ext} - T)} dT \\
\Leftrightarrow \frac{4h}{\rho C_p d} dt &= \frac{1}{(T_{ext} - T)} dT \\
\Leftrightarrow \frac{4h}{\rho C_p d} t &= \ln\left(\frac{T_0 - T_{ext}}{T_f - T_{ext}}\right) \\
\Leftrightarrow e^{\frac{4h}{\rho C_p d} t} &= \frac{T_0 - T_{ext}}{T_f - T_{ext}} \\
\Leftrightarrow T_f &= T_{ext} + \frac{T_0 - T_{ext}}{e^{\frac{4h}{\rho C_p d} t}}
\end{aligned} \tag{3.7}$$

When we use the parameters of the experiment, this gives $T_f = 284.14K = 10.99^\circ C$ after $t = 60s$.

The fact that this value is quite far from what is observed in the experiment is due to some simplifications made here, like, for example, using the Lumped system equations, or some of the parameters choice.

Looking at the parameters, the approximation made for β can be refined if, instead of using the value approximated over the temperature interval, the value for β at $15^\circ C$ given in Appendix A-1, table A-9 of “Heat and Mass Transfer : Fundamentals and Applications” [4] : $\beta = 1.38 \times 10^{-4} K^{-1}$, is used. Injecting this in the model already adds some accuracy, with a temperature of $11.40^\circ C$ ($284.55K$).

Moreover, the values of β and Pr are not fixed, they depend on temperature. To get even more accurate results, “mean values” of those two numbers will be taken. In order to do so, since their evolution is small in the interval of temperatures (1.38×10^{-4} to 0.733×10^{-4} for β and 8.09 to 9.45×10^{-4} for Prandtl²), the assumption is made that their variation is linear and that the linear mean value on the interval can be used. In the end, it gives $\beta = 1.056 \times 10^{-4} K^{-1}$ and $Pr = 8.77$.

The same correction is used for k , ρ and C_p ; values for those parameters become $k = 0.584 \frac{W}{mK}$, $\rho = 999.4 \frac{kg}{m^3}$ and $C_p = 4189.5 \frac{J}{kgK}$.

Those corrections, when injected in the model, give $T_f = 284.77K = 11.62^\circ C$ after $t = 60s$. Biot number for this case is $Bi = 20.8$, still high. Even with this high Biot number, the value obtained seems acceptable, considering the simplifications made on the system. The error compared to the experimental result is about 2.38% (when taken in degrees Celsius), and the fact that the temperature measurement made during the experiment where not immediate and that the thermometer itself was warm has to be taken in account.

The code used for this part of the model can be found in annex D.1

2. Be warned that the values for Prandtl are different than the one used before : this is due to the fact that it was decided to use values from the same source (“Heat and Mass Transfer : Fundamentals and Applications” [4]) here to ensure they are calculated the same way. This also shows the differences that can be observed for the same number, depending of the source and the temperatures it uses as standards

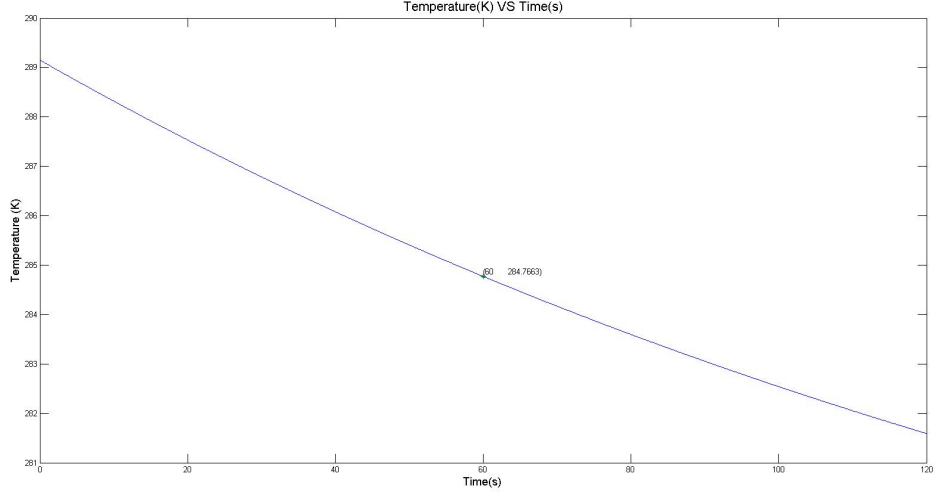


FIGURE 3.2 – Graph of temperature versus time for the non-spinning can. The star marks the 60s point.

Graph 3.2 gives the evolution of temperature(K) with time(s) for the last model with enhanced approximations of water's parameters.

3.2.2 Spinning can

For this model, simplifying assumptions made in section 3.2.1 will be used, concerning Prandtl number (Pr), the density of water (ρ), the volume expansion coefficient for water (β), the specific heat of water (C_p) and thermal conductivity of water (k).

In this case, the hot water cylinder shown in red on figure 3.1 is spinning at $\Omega = 1000rpm = 1.6667 \times 10^1 \frac{rounds}{s}$. This can be considered as a flow along a plate, the plate being the interface between hot and cold water, at a certain speed U .

The speed of cold water on the side of the water is not exactly equal to U . Indeed, water begins to spin around the can. The speed's distribution outside of the can is decreasing quickly, with a maximum on the can's surface. This maximum is given by $U_{max} = \Omega \pi d = 3.4558 \frac{m}{s}$. The speed quickly drops to zero since ice is slowing the water. The linear approximation made before will be used again and the flow will be considered as having a "mean" speed of $U = \frac{U_{max}}{2} = 1.7279 \frac{m}{s}$.

Knowing this speed, the calculation of Reynolds number $Re = \frac{\rho U L}{\mu}$ can be made. The characteristic length L for this problem is the circumference of the can, since the speed is tangent to the can, which gives $L = \pi d$. ν is the dynamic viscosity of water and can be found on table 9, Annex-1 of "Heat and Mass Transfer : Fundamentals and Applications" [4]. The same approach as before will be kept and the "mean" value of μ on the interval will be considered. This value is $\mu = 1.2225 \times 10^{-3}$. Reynolds is thus $\Re = \frac{999.4 \times 1.7279 \times 0.116}{1.2225 \times 10^{-3}} = 1.6386 \times 10^5$.

The next step is to use the formula for a flow on a flat plate (see annex C page 4). The Reynolds

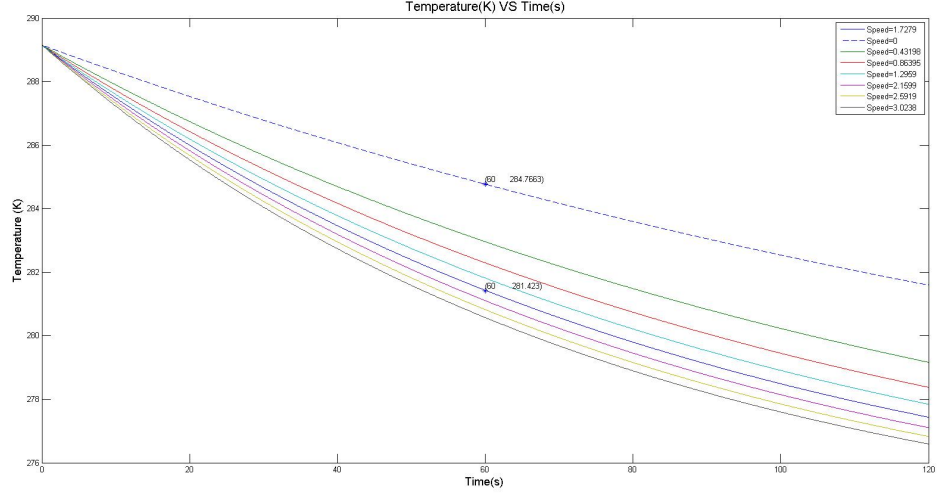


FIGURE 3.3 – Graph of temperature versus time for the spinning can for speeds ranging from $\Omega = 0rpm$ to $\Omega = 1750rpm$, steps of $250rpm$

number calculated before is $Re < 3 \times 10^5$, meaning that we are in laminar regime :

$$Nu_{out} = \frac{1}{2} 0.332 Pr^{\frac{1}{3}} \sqrt{Re} \quad (3.8)$$

$$Nu_{out} = 1.3857 \times 10^2$$

h can now be calculated :

$$h_{out} = \frac{Nu_{out} k}{L} = 3.9029 \times 10^2 \frac{W}{m^2 K} \quad (3.9)$$

Biot number is given by $Bi = \frac{h_{out}}{\frac{4k}{d} + h_{in}}$ (equation from [1]) where h_{in} was calculated for natural convection in the non-spinning case 3.2.1. Biot is thus $Bi = 9.671 \times 10^{-1}$, which is lower than the critical value of 1. Using the lumped system equation 3.7 is therefore perfectly correct.

With $h = h_{out} + h_{in}$ and for $t = 60s$, the final temperature is $T = 281.42K = 8.27^\circ C$.

Graph 3.3 shows the relation between temperature and time for different rotation speeds, ranging from $\Omega = 0rpm$ to $\Omega = 1750rpm$, with steps of $250rpm$. It can clearly be observed that at higher speeds, the can is cooled down more quickly.

Chapitre 4

Comparison between reality and the mathematical model

This section is about the difference between the mathematical model and the reality. A simple look at the measurement done underlines that the mathematical model does not perfectly correspond to the reality. The temperature observed in the non-spinning case are 11.9 °C in reality and 11.61 °C in the mathematical model. For the spinning case, they are respectively 11 °C and 8.27°C. The main reason of this difference is that the mathematical model is based on simplified assumptions.

The first one was to consider that the fluid inside the can has the same properties as water. This approximation leads to errors on the value of some calculated parameters such as the kinematic viscosity used to calculate the Grashof number. Moreover this number has a direct impact on the value of the convective coefficient h because it is used to calculate the Nusselt number ($N_u = \frac{hL}{k}$).

The second one is that the surface of the can is described as a perfect cylinder and that some part of the surface are not taken into account because their influence is negligible. This also leads to slight differences with the reality.

However the result obtained before are close from the actual value, especially for the non-spinning case. The main difference between the two cases is the velocity of the spinning can. Even if this velocity is measured with good precision, the mathematical model considers $V_{fluid} = V_{screwdriver}$ on the surface of the can and the viscosity of the fluid (reducing the speed) is not taken into account, leading to significant lack of precision in the calculation of the convective coefficient h . This inaccuracy can be explained by the sensitivity of the forced convection to the velocity of the fluid as shown in graph 3.3.

The precision of the measurement is an other point of argument. Indeed, the temperatures inside of the two cans were not measured at the same moment, allowing for the second can to warm up. Moreover the thermometer used had a non-negligible size compared to the can. It is then impossible to know the exact temperature on a point. Therefore the system has to be considered as homogeneous which is not exactly the case in actual practice.

Finally, the experiment was only done once, we can thus not ensure we did not make any mistake during the manipulation. Concluding on the precision of our model compared to only one experiment would be presumptuous.

Chapitre 5

Conclusion

As seen in the previous section there are differences between the theoretical model and the reality. These differences can be explained by the different approximations done in the model and by experimental errors. However, even if the mathematical model does not perfectly fit the reality, it puts in evidence the general behaviour of the system which is the point of this study.

The general behaviour of the two different cases underlines the impact of forced convection, natural convection and conduction in heat transfers and on this basis some conclusion about heat transfer processes can be made.

First, because of the flow properties of the fluid, the conductive heat transfer is negligible in comparison with convective heat transfers and can be omit.

Then, it is necessary to distinguish natural and forced convection. As seen on the graph 3.3, at high speed, forced convection becomes far more important than natural convection, which leads to the difference of final temperature in the two studied cases.

Looking at this different phenomena with an engineer point of view, the possibilities offered by forced convection appear clearly relevant, not only for a can cooling systems but also in various other applications where it could accelerate heat transfer processes.

Annexe A

Sources

“Perry’s Chemical Engineers’ Handbook”[2], a reference book for chemical properties of various elements.

This book has been chosen because it has very complete tables that give properties of the water at different temperatures. Those properties were measured and validated and include data from NASA experiments, which should lead to a relative precision and reliability.

“MECA-H-300 Phénomènes de Transport, Notes de Cours”[3].

This is the reference book from MECA H-3001. It has been written by Jean-Marie BUCHLIN, who was this course’s teacher before Pr Parente. Pr Buchling now works at Institut Von Karman for Fluid Dynamics. Equations presented were all validated and published in international scientific papers.

“Heat and Mass Transfer Fundamentals and Applications”[4].

Written by two well known scientists in the field of fluid mechanics, this book is the new reference book for Pr Parente’s course. It presents equations and discussions for various heat transfer cases, along with a set of validated charts of materials properties. The edition used is the fifth, that was published in 2014 after a set of corrections.

“Course materials for 10.37 Chemical and Biological Reaction Engineering”[1].

This article was published by Pr Adrian for his course at the MIT. Even if it is an open course, we assume that the MIT gives quality courses that should be considered as valid. Furthermore, the equations presented here are based on equations given in “Heat and Mass Transfer Fundamentals and Applications”[4], which gives weight to both of these sources.

webpackaging.com.

This website was used to get the dimensions of a can. Using a commercial website to get scientific numbers is not a good idea but we have good reasons to believe those dimensions are correct enough for this report. The first reason is that as this website is specialised in selling those packaging to other companies, the dimensions given should be at least standardised. The second reason is that we did not require extremely accurate measures : our system is not that sensitive to dimensional changes, as long as they are below 5%. Finally, those dimensions were checked by measuring the can by our own means and the results were similar.

Pr Parente. Formula Sheet Meca H-300, Transport course notes, October 2015, given in annex C. This formula sheet is extracted from Pr Parente's course. This document was handed out to students during the course. It is an extract of the course's slides that can be found on <http://mecapp42.ulb.ac.be/atm/foldercours/phtransport/phtransport>. These equations are also described in "MECA-H-300 Phénomènes de Transport, Notes de Cours"[3] and/or "Heat and Mass Transfer Fundamentals and Applications"[4].

Annexe B

Water Thermo-Physical Properties

These chart can be are extracted from “Perry’s Chemical Engineers’ Handbook”, Chapter 2[2].

TABLE 2-352 Saturated Water Substance—Temperature (SI units)

Temp., K	Pressure, bar ^a	Volume, m ³ /kg		Enthalpy, kJ/kg		Entropy, kJ/(kg·K)		Specific heat, C _p , kJ/(kg·K)		Viscosity, Ns/m ²		Thermal conductivity, W/(m·K)		Prandtl no.		Surface tension, N/m	Temp., K
		Condensed†	Vapor	Condensed†	Vapor	Condensed†	Vapor	Condensed†	Vapor	Condensed†	Vapor	Condensed†	Vapor	Condensed†	Vapor		
150	6.30–11	1.073–3	9.55+9	–539.6	2273	–2.187	16.54	1.155				3.73					150
160	7.72–10	1.074–3	9.62+8	–525.7	2291	–2.106	15.49	1.233				3.52					160
170	7.29–9	1.076–3	1.08+8	–511.7	2310	–2.026	14.57	1.311				3.34					170
180	5.38–8	1.077–3	1.55+7	–497.8	2328	–1.947	13.76	1.389				3.18					180
190	3.23–7	1.078–3	2.72+6	–483.8	2347	–1.868	13.03	1.467				3.04					190
200	1.62–6	1.079–3	5.69+5	–467.5	2366	–1.789	12.38	1.545				2.91					200
210	7.01–6	1.081–3	1.39+5	–451.2	2384	–1.711	11.79	1.623				2.79					210
220	2.65–5	1.082–3	3.83+4	–435.0	2403	–1.633	11.20	1.701				2.69					220
230	8.91–5	1.084–3	1.18+4	–416.3	2421	–1.555	10.79	1.779				2.59					230
240	3.72–4	1.085–3	4.07+3	–400.1	2440	–1.478	10.35	1.857				2.50					240
250	7.59–4	1.087–3	1.52+3	–381.5	2459	–1.400	9.954	1.935				2.42					250
255	1.23–3	1.087–3	956.4	–369.8	2468	–1.361	9.768	1.974				2.38					255
260	1.96–3	1.088–3	612.2	–360.5	2477	–1.323	9.590	2.013				2.35					260
265	3.06–3	1.089–3	400.4	–351.2	2486	–1.281	9.461	2.052				2.31					265
270	4.69–3	1.090–3	265.4	–339.6	2496	–1.296	9.255	2.091				2.27					270
273.15	6.11–3	1.091–3	206.3	–333.5	2502	–1.221	9.158	2.116				2.26					273.15
273.15	0.00611	1.000–3	206.3	0.0	2502	0.000	9.158	4.217	1.854	1750–6	8.02–6	0.569	0.0182	12.99	0.815	0.0755	273.15
275	0.00697	1.000–3	181.7	7.8	2505	0.028	9.109	4.211	1.855	1652–6	8.09–6	0.574	0.0183	12.22	0.817	0.0753	275
280	0.00990	1.000–3	130.4	28.8	2514	0.104	8.980	4.198	1.858	1422–6	8.29–6	0.582	0.0186	10.26	0.825	0.0748	280
285	0.01387	1.000–3	99.4	49.8	2523	0.178	8.857	4.189	1.861	1225–6	8.49–6	0.590	0.0189	8.51	0.833	0.0743	285
290	0.01917	1.001–3	69.7	70.7	2532	0.251	8.740	4.184	1.864	1080–6	8.69–6	0.598	0.0193	7.36	0.841	0.0737	290
295	0.02617	1.002–3	51.94	91.6	2541	0.323	8.627	4.181	1.868	959–6	8.89–6	0.606	0.0195	6.62	0.849	0.0727	295
300	0.03531	1.003–3	39.13	112.5	2550	0.393	8.520	4.179	1.872	855–6	9.09–6	0.613	0.0196	5.83	0.857	0.0717	300
305	0.04712	1.005–3	27.90	133.4	2559	0.462	8.417	4.178	1.877	769–6	9.29–6	0.620	0.0201	5.20	0.865	0.0709	305
310	0.06221	1.007–3	22.93	154.3	2568	0.530	8.318	4.178	1.882	695–6	9.49–6	0.628	0.0204	4.62	0.873	0.0700	310
315	0.08132	1.009–3	17.82	175.2	2577	0.597	8.224	4.179	1.888	631–6	9.69–6	0.634	0.0207	4.16	0.883	0.0692	315
320	0.1053	1.011–3	13.98	196.1	2586	0.649	8.151	4.180	1.895	577–6	9.89–6	0.640	0.0210	3.77	0.894	0.0683	320
325	0.1351	1.013–3	11.06	217.0	2595	0.727	8.046	4.182	1.903	528–6	10.09–6	0.645	0.0213	3.42	0.901	0.0675	325
330	0.1719	1.016–3	8.82	237.9	2604	0.791	7.962	4.184	1.911	489–6	10.29–6	0.650	0.0217	3.15	0.908	0.0666	330
335	0.2167	1.018–3	7.09	258.8	2613	0.854	7.881	4.186	1.920	453–6	10.49–6	0.655	0.0220	2.88	0.916	0.0658	335
340	0.2713	1.021–3	5.74	279.8	2622	0.916	7.804	4.188	1.930	420–6	10.69–6	0.660	0.0223	2.66	0.925	0.0649	340
345	0.3372	1.024–3	4.683	300.7	2630	0.977	7.729	4.191	1.941	389–6	10.89–6	0.665	0.0226	2.45	0.933	0.0641	345
350	0.4163	1.027–3	3.846	321.7	2639	1.038	7.657	4.195	1.954	365–6	11.09–6	0.668	0.0230	2.29	0.942	0.0632	350
355	0.5100	1.030–3	3.180	342.7	2647	1.097	7.588	4.199	1.968	343–6	11.29–6	0.671	0.0233	2.14	0.951	0.0623	355
360	0.6209	1.034–3	2.645	363.7	2655	1.156	7.521	4.203	1.983	324–6	11.49–6	0.674	0.0237	2.02	0.960	0.0614	360
365	0.7514	1.038–3	2.212	384.7	2663	1.214	7.456	4.209	1.999	306–6	11.69–6	0.677	0.0241	1.91	0.969	0.0605	365
370	0.9040	1.041–3	1.861	405.8	2671	1.271	7.394	4.214	2.017	289–6	11.89–6	0.679	0.0245	1.80	0.978	0.0595	370
373.15	1.0133	1.044–3	1.679	419.1	2676	1.307	7.356	4.217	2.029	279–6	12.02–6	0.680	0.0248	1.76	0.984	0.0589	373.15
375	1.0815	1.045–3	1.574	426.8	2679	1.328	7.333	4.220	2.036	274–6	12.09–6	0.681	0.0249	1.70	0.987	0.0586	375
380	1.2869	1.049–3	1.337	448.0	2687	1.384	7.275	4.226	2.057	260–6	12.29–6	0.683	0.0254	1.61	0.995	0.0576	380
385	1.5253	1.053–3	1.142	469.2	2694	1.439	7.218	4.232	2.080	248–6	12.49–6	0.685	0.0258	1.53	1.004	0.0566	385
390	1.794	1.058–3	0.980	490.4	2702	1.494	7.163	4.239	2.104	237–6	12.69–6	0.686	0.0263	1.47	1.013	0.0556	390
400	2.455	1.067–3	0.731	532.9	2716	1.605	7.058	4.256	2.158	217–6	13.05–6	0.688	0.0272	1.34	1.033	0.0536	400
410	3.302	1.077–3	0.553	575.6	2729	1.708	6.959	4.278	2.221	200–6	13.42–6	0.688	0.0282	1.24	1.054	0.0515	410
420	4.370	1.088–3	0.425	618.6	2742	1.810	6.865	4.302	2.291	185–6	13.79–6	0.688	0.0293	1.16	1.075	0.0494	420
430	5.699	1.099–3	0.331	661.8	2753	1.911	6.775	4.331	2.369	173–6	14.14–6	0.685	0.0304	1.09	1.10	0.0472	430

440	7.333	1.110-3	0.261	705.3	2764	2.011	6.689	4.36	2.46	162-6	14.50-6	0.682	0.0317	1.04	1.12	0.0451	440
450	9.319	1.123-3	0.208	749.2	2773	2.109	6.607	4.40	2.56	152-6	14.85-6	0.678	0.0331	0.99	1.14	0.0429	450
460	11.71	1.137-3	0.167	793.5	2782	2.205	6.528	4.44	2.68	143-6	15.19-6	0.673	0.0346	0.95	1.17	0.0407	460
470	14.55	1.152-3	0.136	838.2	2789	2.301	6.451	4.48	2.79	136-6	15.54-6	0.667	0.0363	0.92	1.20	0.0385	470
480	17.90	1.167-3	0.111	883.4	2795	2.395	6.377	4.53	2.94	129-6	15.88-6	0.660	0.0381	0.89	1.23	0.0362	480
490	21.83	1.184-3	0.0922	929.1	2799	2.479	6.312	4.59	3.10	124-6	16.23-6	0.651	0.0401	0.87	1.25	0.0339	490
500	26.40	1.203-3	0.0766	975.6	2801	2.581	6.233	4.66	3.27	118-6	16.59-6	0.642	0.0423	0.86	1.28	0.0316	500
510	31.66	1.222-3	0.0631	1023	2802	2.673	6.163	4.74	3.47	113-6	16.95-6	0.631	0.0447	0.85	1.31	0.0293	510
520	37.70	1.244-3	0.0525	1071	2801	2.765	6.093	4.84	3.70	108-6	17.33-6	0.621	0.0475	0.84	1.35	0.0269	520
530	44.58	1.268-3	0.0445	1119	2798	2.856	6.023	4.95	3.96	104-6	17.72-6	0.608	0.0506	0.85	1.39	0.0245	530
540	52.38	1.294-3	0.0375	1170	2792	2.948	5.953	5.08	4.27	101-6	18.1-6	0.594	0.0540	0.86	1.43	0.0221	540
550	61.19	1.323-3	0.0317	1220	2784	3.039	5.882	5.24	4.64	97-6	18.6-6	0.580	0.0583	0.87	1.47	0.0197	550
560	71.08	1.355-3	0.0269	1273	2772	3.132	5.808	5.43	5.09	94-6	19.1-6	0.563	0.0637	0.90	1.52	0.0173	560
570	82.16	1.392-3	0.0228	1328	2757	3.225	5.733	5.68	5.67	91-6	19.7-6	0.548	0.0698	0.94	1.59	0.0150	570
580	94.51	1.433-3	0.0193	1384	2737	3.321	5.654	6.00	6.40	88-6	20.4-6	0.528	0.0767	0.99	1.68	0.0128	580
590	108.3	1.482-3	0.0163	1443	2717	3.419	5.569	6.41	7.35	84-6	21.5-6	0.513	0.0841	1.05	1.84	0.0105	590
600	123.5	1.541-3	0.0137	1506	2682	3.520	5.480	7.00	8.75	81-6	22.7-6	0.497	0.0929	1.14	2.15	0.0084	600
610	137.3	1.612-3	0.0115	1573	2641	3.627	5.318	7.85	11.1	77-6	24.1-6	0.467	0.103	1.30	2.60	0.0063	610
620	159.1	1.705-3	0.0094	1647	2588	3.741	5.259	9.35	15.4	72-6	25.9-6	0.444	0.114	1.52	3.46	0.0045	620
625	169.1	1.778-3	0.0085	1697	2555	3.805	5.191	10.6	18.3	70-6	27.0-6	0.430	0.121	1.65	4.20	0.0035	625
630	179.7	1.856-3	0.0075	1734	2515	3.875	5.115	12.6	22.1	67-6	28.0-6	0.412	0.130	2.0	4.8	0.0026	630
635	190.9	1.935-3	0.0066	1783	2466	3.950	5.025	16.4	27.6	64-6	30.0-6	0.392	0.141	2.7	6.0	0.0015	635
640	202.7	2.075-3	0.0057	1841	2401	4.037	4.912	26	42	59-6	32.0-6	0.367	0.155	4.2	9.6	0.0008	640
645	215.2	2.351-3	0.0045	1931	2292	4.223	4.732	90	54-6	54-6	37.0-6	0.331	0.178	12	26	0.0001	645
647.31	221.2	3.170-3	0.0032	2107	2107	4.443	4.443	∞	∞	45-6	45.0-6	0.238	0.238	∞	∞	0.0000	647.31

*1 bar = 10^5 N/m².

†Above the solid line, the condensed phase is solid; below it, liquid.

‡Critical temperature.

NOTE: The notations 6.30-11, 1.073-3, 9.55-49, etc. signify 6.30×10^{-11} , 1.073×10^{-3} , 9.55×10^9 , etc.

Tables 2-351 and 2-352 are provided for general use. Tables to higher precision are available over certain ranges and for various properties. The most current internationally accepted tables are found in Haar, L., J. S. Gallagher, and G. S. Kell, *NBS/NRC Steam Tables*, Hemisphere, Washington, DC, 1984 (320 pp.). These do not tabulate certain properties at saturation states. A revised release on the IAPWS Skeleton Tables 1985 for the thermodynamic properties of ordinary water substance, Sept. 1983 (15 pp.), is apparently the latest international publication. In *J. Phys. Chem. Ref. Data* **17**, 4 (1988): 1439-1540, H. Sato, M. Uematsu, and others review existing steam tables and present the 1985 formulation of skeleton tables. Property codes and programs include Cheng, S. C. and C. Nguyen, *Modeling and Simulation on Microcomputers*, 1989 (R. W. Allen, ed.), S. C. S. Intl., San Diego, 1989 (pp. 138-141); Garland, W. J. and B. J. Hand, *Nucl. Engng. & Des.*, **113**, (1989): 21-34; Dickey, D. S., *Chem. Eng.*, **98**, 9 (1991): 207-8 and **98**, 11: 235-6; Muneer, T. and S. M. Scott, *Proc. Inst. Mech. Eng.*, **205** (1991): 25-29; and *Energy Convers. Mgmt.*, **31**, 4 (1991): 315-325. Useful pictorial representations of 20 properties as a function of both temperature (to 800°C) and pressure (to 1000 bar) are given by Carilli, U., J. Buch, et al., *Warmwasser- u. Stoff.*, **1** (1968): 202-213. Property equations for the range 0-500°C are given by Charters, W. W. S. and H. A. Sadafi, *Res. Int. Froid*, **10**, (Mar. 1987): 105-6; Gordon, S., NASA Tech. Paper 1906, 1982 gives detailed tables for ice from 0 K. Ice and snow properties are reviewed by Fukusako, S., *Int. J. Thermophys.*, **11**, 2 (1990): 353-372. See also Wagner, W., A. Saul, et al., *J. Phys. Chem. Ref. Data*, **23**, 3 (1994): 515-525; and Table 2-358.

Annexe C

Formula Sheet

The following formula sheet was given and demonstrated at Pr. Parente's course "MECA-H3001 : Fluid mechanics and transfer processes".

Formula sheet MECA-H-300

Transport Phenomena

October 2015

The definition of the dimensionless numbers as well as the physical understanding of the terms of the equations must be known.

Part I: Momentum

Local Equations

- **Newton's Law:**

$$\tau_{xy} = -\mu \frac{\partial u}{\partial y}$$

- **Mass conservation:**

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0$$

- **Navier-Stokes equations:**

- Laminar flow, incompressible and Newtonian fluid:

$$\rho \frac{D\mathbf{V}}{Dt} = -\nabla P + \mu \nabla^2 \mathbf{V} + \mathbf{F}$$

- **Euler equation:**

$$\rho \frac{D\mathbf{V}}{Dt} = -\nabla P + \rho \mathbf{F}$$

- **Bernoulli equation**

$$\rho \frac{V^2}{2} + P + \rho g z = C^{te} = P_{tot}$$

- **Laminar boundary layer equation for a flat plate:**

$$\frac{\partial u^2}{\partial x} + \frac{\partial uv}{\partial y} = \frac{\mu}{\rho} \cdot \frac{\partial^2 u}{\partial y^2}$$

- Boundary layer thickness: $\delta = \frac{5x}{\sqrt{Re_x}}$

- Friction coefficient: $C_f = \frac{0,664}{\sqrt{Re_x}}$

Integral method :

- **Mass conservation:**

$$\frac{d[m]_{tot}}{dt} = \rho V_{n>1} S_1 - \rho V_{n>2} S_2$$

- **Momentum:**

$$\rho \frac{d\mathcal{P}_{tot}}{dt} = -\Delta_1^2 \left[\rho V^2 + P \right] S - F_{paroi} + m_{tot} g$$

- **Boundary layer :**

- Boundary layer thickness: $\delta^{**} = \delta \int_0^1 \left(\frac{u}{U_{\text{ext}}} - \frac{u^2}{U_{\text{ext}}^2} \right) \cdot d\left(\frac{y}{\delta}\right)$
- Friction coefficient: $C_f = 2 \frac{d\delta^{**}}{dx}$

- **Pressure drops**

☛ **Distributed pressure drops:** $\Delta P_{\text{tot}} = \lambda \frac{L}{D} \frac{\rho U^2}{2}$

- Laminar regime: $\lambda = \frac{64}{\text{Re}_{D_h}}$
- Turbulent regime, smooth walls: **Blasius** $\lambda = \frac{0,316}{\text{Re}_{D_h}^{0,25}}$
- Turbulent regime, smooth/rough transition: **Colebrook** $\frac{1}{\sqrt{\lambda}} = 1,14 - 0,87 \ln \left(\frac{0,25}{\text{Re}_{D_h} \sqrt{\lambda}} \right)$
- Turbulent regime, rough walls: **Nikuradse** $\frac{1}{\sqrt{\lambda}} = 1,14 - 0,87 \ln \left(\frac{0,25}{\text{Re}_{D_h} \sqrt{\lambda}} + \frac{2,5}{\text{Re}_{D_h} \sqrt{\lambda}} \right)$

☛ **Concentrated pressure drops:** $\Delta P_{\text{tot}} = K \frac{\rho U_2^2}{2}$

- Values of K for different configurations:

Elbow

r_c/D	K_e
1	0,35
2	0,19
4	0,16
6	0,21
8	0,28
10	0,32

Contraction

D_2/D_1	K_e
0	0,5
0,2	0,49
0,4	0,42
0,6	0,27
0,8	0,20
0,9	0,1

Diffuser

D_1/D_2	K_E
0	1
0,2	0,87
0,4	0,70
0,6	0,41
0,8	0,15

Part II : Energy

Local equations

- **Fourier's Law:**

$$q_y = -k \cdot \frac{dT}{dy}$$

- **Heat transfer with heat source ($k=C^{te}$) :**

$$\rho C \frac{\partial T}{\partial t} = k \nabla^2 T + \dot{q}_v$$

- Laplacian in Cartesian coordinates $\nabla^2 T = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}$
- Laplacian in cylindrical coordinates: $\nabla^2 T = \frac{\partial^2 T}{\partial x^2} + \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right)$
- Laplacian in spherical symmetry: $\nabla^2 T = \frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{\partial T}{\partial r} \right)$

- **Boundary conditions:**

Diriclet: $T_{\text{paroi}} = T_o(s_{\text{paroi}}, t)$

Neuman: $q_{\text{paroi}} = -k \frac{\partial T}{\partial n} \Big|_{\text{paroi}} = q_o(s_{\text{paroi}}, t)$

Mixed: $q_p = -k \frac{\partial T}{\partial n} \Big|_p = h (T_p - T_f)$

- h = convective heat transfer coefficient

- **Semi-infinite Solid**

- Step of temperature: $\Theta = \frac{T - T_f}{T_o - T_f} = \frac{2}{\sqrt{\pi}} \operatorname{erf} \left(\frac{x}{2\sqrt{\alpha t}} \right)$

• α = thermal diffusivity

- Periodic perturbation (ω) with amplitude A_o : $\Theta = \frac{T - T_o}{A_o} = e^{-x\sqrt{\frac{\omega}{2\alpha}}} \cos \left(\omega t - x\sqrt{\frac{\omega}{2\alpha}} \right)$

- **Heat equation for a moving fluid 2D:**

- Laminar flow, incompressible and Newtonian fluid, constant thermal conductivity:

$$\rho C_p \left(u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} \right) = k \frac{\partial^2 T}{\partial y^2} + \mu \left(\frac{\partial u}{\partial y} \right)^2$$

Global equations

- **Thermal Resistance :**

- Series: $\mathfrak{R}_{\text{th,tot}} = \frac{T_1 - T_2}{\dot{q}} = \sum_{i=1}^N \mathfrak{R}_{\text{th},i} = \sum_{i=1}^N \frac{\delta_i}{S k_i}$

- Parallel: $\frac{\dot{Q}}{T_1 - T_2} = \frac{1}{\mathfrak{R}_{th,tot}} = \sum_{i=1}^N \frac{1}{\mathfrak{R}_{th,i}}$
- Global exchange coefficient: $\frac{1}{h_{tot}} = S \mathfrak{R}_{th,tot} = \sum_{i=1}^N \frac{\delta_i}{k_i} + \sum_{i=1}^N \frac{1}{h_i}$

- **Lumped systems**

$$\frac{dU}{dt} = hS_{tot}(T_{ext} - T)$$

1. Sensible heat transfer (heating up or cooling down):

$$\rho_s C_s V \frac{dT}{dt} = -hS_{tot}(T - T_{ext})$$

2. Latent heat transfer (fusion or evaporation):

$$\rho \mathcal{L}_{SL} S \frac{de}{dt} = hS_{tot}(T - T_{ext})$$

- **Contact temperature**

$$T_c = \frac{b_1 T_1 + b_2 T_2}{b_1 + b_2} \neq f(t) \quad \text{Effusivity} \quad b = \sqrt{k\rho C}$$

- **Forced convection correlation (gas and liquids)**

- Flat plate, laminar regime $Re_x < 3 \cdot 10^5$ $Nu_x = \frac{h_x x}{k_f} = 0,332 Pr^{1/3} \sqrt{Re_x}$
- Flat plate, turbulent regime $Nu_x = \frac{h_x x}{k_f} = 0,029 Pr^{0,43} Re_x^{0,8}$
- Mean coefficient over L $\overline{Nu}_L = \frac{1}{n} \cdot Nu_x \text{ (en } x = L)$
- n exponent of Re_x
- Laminar boundary layer $\overline{Nu}_L = \frac{\bar{h} \cdot L}{k_f} = 0,664 \cdot Pr^{1/3} \cdot \sqrt{Re_L}$
- Laminar then turbulent boundary layer $\overline{Nu}_L = 0,036 \cdot Pr^{0,43} (Re_L^{0,8} - Re_c^{0,8}) + 0,664 \cdot Pr^{1/3} \cdot Re_c^{0,5}$
- $Re_c = 2 \times 10^5$
- Around a cylinder $40 \leq Re_D \leq 10^5$: $\overline{Nu}_D = (0,4 Re_D^{0,5} + 0,06 Re_D^{2/3}) Pr^{0,4}$
- Around a sphere $3,5 \leq Re_D \leq 8 \cdot 10^4$: $\overline{Nu}_{sph} = 2 + \overline{Nu}_{cyl}$
- In a tube
 - Laminar with $T_{wall} = C^{te}$: $Nu_D = 3,66$
 - Laminar with $q_{wall} = C^{te}$: $Nu_D = 4,36$
 - Turbulent: $Nu_D = 0,023 Re_D^{0,8} Pr^{0,4}$

- **Natural convection correlations (gas and liquids)**

- Isothermal vertical flat plate

- Laminar $10^4 < Ra < 10^9$: $Nu_L = 0,59Ra_L^{1/4}$
- Turbulent $10^9 < Ra < 10^{13}$: $Nu_L = 0,10Ra_L^{1/3}$

- Constant heat flux vertical flat plate

- Laminar $10^5 < Ra < 10^{11}$: $Nu_L = 0,750 [Ra_L^*]^{0,20}$
- Turbulent $2 \cdot 10^{13} < Ra < 10^{16}$: $Nu_L = 0,645 [Ra_L^*]^{0,22}$

- Around a vertical cylinder

$$Nu_D = C Ra_D^n$$

Ra_D	C	n
$10^{-10} - 10^{-2}$	0,675	0,058
$10^{-2} - 10^2$	1	0,148
$10^2 - 10^4$	0.85	0,188
$10^4 - 10^7$	0,48	1/4
$10^7 - 10^{12}$	0,125	1/3

- Around a sphere $10^5 \leq Ra_D \leq 10^9$

$$Nu_D = 2 + 0,5Ra_D^{1/4}$$

- Vertical plate in confined space

$$Nu_e = \frac{k_e}{k_f} = C \cdot Ra_e^n \cdot \left[\frac{L}{e} \right]^{-m}$$

	Ra_e	C	n	m
Gas				
	2000-2.10 ⁵	0,197	1/4	1/9
	2.10 ⁵ -10 ⁷	0,073	1/3	1/9
Liquid	<2000	1	0	0
	10 ⁴ -10 ⁷	0,45	1/4	0,3
	10 ⁶ -10 ⁹	0,046	1/3	0

- Horizontal plate in confined space

$$Nu_e = \frac{k_e}{k_f} = C \cdot Ra_e^n$$

	Ra_e	C	n
Gas	< 1700	1	0
	1700 - 7000	0,059	0,4
	7000 - 3,2 10 ⁵	0,212	1/4
	> 3,2 10 ⁵	0,061	1/3
Liquid	<1700	1	0
	1700 - 6000	0,012	0,6
	6000 - 3,7 10 ⁴	0,375	0,2
	3,7 10 ⁴ - 10 ⁸	0,13	0,3
	> 10 ⁸	0,057	1/3

- **Energy balance by radiation** $\alpha_\lambda + \tau_\lambda + \rho_\lambda = 1$
- **Stefan-Boltzmann Law's** $M^o = \int_0^\infty M_\lambda^o d\lambda = \sigma T^4$ avec $\sigma = 5,67 \cdot 10^{-8} \text{ W/m}^2 \cdot \text{K}^4$
- **Radiosity of a grey body** $J = \epsilon M^o + \rho E$
- **Heat flux density lost by a grey body** $q_{\text{perdue}} = \epsilon M^o - \alpha E = J - E$
- **Radiative heat flux between two grey bodies**

$$\mathcal{Q}_{\text{ray}} = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1 - \epsilon_1}{\epsilon_1 S_1} + \frac{1}{S_1 F_{12}} + \frac{1 - \epsilon_2}{\epsilon_2 S_2}}$$
- **Radiative heat transfer coefficient** $h_r = G(\epsilon, F) \cdot \sigma \cdot (T_1^2 + T_2^2)(T_1 + T_2)$

- **Total energy equation**

$$\frac{d[E_c + E_i + E_p]_{\text{tot}}}{dt} = -\Delta_1^2 \left[\left\langle \rho \left(\frac{V^2}{2} + e_i + \frac{p}{\rho} + gz \right) V_n \right\rangle S \right] + \mathcal{Q} + \bar{\mathcal{W}}$$

- **Mechanical energy equation for an incompressible fluid**

$$\frac{d[E_c + E_p]_{\text{tot}}}{dt} = -\Delta_1^2 \left[\left\langle \rho \left(\frac{V^2}{2} + \frac{p}{\rho} + gz \right) V_n \right\rangle S \right] + \bar{\mathcal{W}} - \mathcal{E}_v$$

- **Generalized Bernoulli equation for a flow in a pipe**

$$-\Delta_1^2 \left[\left\langle \rho \left(\frac{V^2}{2} + \frac{p}{\rho} + e_p \right) V_n \right\rangle S \right] = \mathcal{E}_v$$

- **Internal energy equation for an incompressible fluid**

$$\frac{d[E_i]_{\text{tot}}}{dt} = -\Delta_1^2 \left[\left\langle \rho e_i V_n \right\rangle S \right] + \mathcal{Q} + \mathcal{E}_v$$

Part III : Mass

- Fick's Law**

$$j_A(x) = -\rho \mathcal{D}_{AB} \cdot \frac{d\omega_A}{dx} \quad \text{with} \quad \mathcal{D}_{AB} = \mathcal{D}_{BA} = \mathcal{D}$$

- Diffusion into a moving fluid**

$$\begin{aligned} \vec{n}_A - \omega_A (\vec{n}_A + \vec{n}_B) &= -\rho \mathcal{D} \nabla \omega_A \quad \text{with} \quad \omega_A = \frac{\rho_A}{\rho} \\ - \text{Absolute flux density} \quad \vec{n}_A &= \rho_A \vec{u}_A = \vec{j}_A + \rho_A \vec{U} \\ - \text{Barycentric velocity} \quad \vec{U} &= \frac{\rho_A \vec{u}_A + \rho_B \vec{u}_B}{\rho} \end{aligned}$$

- Molecular diffusion evaporation of a liquid in a column L**

- Mass fraction distribution $\frac{1 - \omega_A(z)}{1 - \omega_{A,0}} = \left[\frac{1 - \omega_{A,L}}{1 - \omega_{A,0}} \right]^{\frac{z}{L}}$
- Evaporation mass flow $\dot{m}_A \approx \left[\mathcal{D} \frac{M_A}{\mathcal{R} T} \cdot \frac{S}{L} \right] (P_{\text{sat}}(T) - P_{A,L})$
- Saturation pressure (T in °C) : $P_{\text{sat}}(T) = 10^{7,625 \frac{T}{241+T} + 2,787}$
- Mass Diffusivity (T in °C et P in Pa) : $\mathcal{D} = \frac{2,26}{P} \left(\frac{T + 273,15}{273,15} \right)^{1,81}$

- Mass boundary layer**

$$u \frac{\partial \rho_A}{\partial x} + v \frac{\partial \rho_A}{\partial y} = \mathcal{D} \frac{\partial^2 \rho_A}{\partial y^2}$$

- Correlation of forced convection mass transfer**

$$j_{A,p} = -\mathcal{D}_{AB} \cdot \frac{d\rho_A}{dy} \bigg|_{y=0} = h_m (\rho_{A,p} - \rho_{A,\text{ext}})$$

Same expressions of the heat transfer, replacing Nu with Sh and Pr with Sc.

- Perfect gas equation:**

$$p_v = \rho_v \frac{\mathcal{R}}{M_v} T_v \quad \text{with} \quad \mathcal{R} = 8314 \text{ J/kmol.K}$$

Annexe D

Codes

The following codes were used to calculate the models and obtain the different graphs. The reader should be advised this code is only usable for this work and should not be reused as it takes in account parameters and simplifying assumptions made for this particular experiment.

D.1 Non-spinning model

```
t = linspace(0,120,1210);
Pr=8.77;
beta=1.056*10^(-4);
rho=999.4;
k=.584;
Cp=4189.5;
Ra=Pr*(beta*9.81*16*(.066)^(3))/(1.081*10^(-6))^2;
Nu=0.22*(Pr*Ra/(0.2+Pr))^(0.28) *(0.116/0.033)^(-1/4);
h=Nu*k/.033;
T60=(16./(exp((4*h*60)/(rho*4184*.066))))
Tf=273.15 +(16./(exp((4*h*t)/(rho*Cp*.066))));
plot(t,Tf,60,T60+273.15,'*')
strValues = num2str([60 T60+273.15]);
text(60,T60+273.15, strcat('(',strValues,')'), '
    VerticalAlignment','bottom');
title('Temperature(K) VS Time(s)')
xlabel('Time(s)')
ylabel('Temperature (K)')
```

D.2 Non-spinning model

```
t = linspace(0,120,1210);
Pr=8.77;
beta=1.056*10^(-4);
```

```

rho=999.4;
k=.584;
Cp=4189.5;
mu=.0012225;
U=1.7279;
Ra=Pr*(beta*9.81*16*(.066)^(3))/(1.081*10^(-6))^2;
Nuin=0.22*(Pr*Ra/(0.2+Pr))^(0.28) *(0.116/0.033)^(-1/4);
hin=Nuin*k/.033;
Re=rho*U*.116/mu;
Nuout=.5*.332*Pr^(1/3)*sqrt(Re);
hout=Nuout*k/.2073451151;
h=hin+hout;
T60=(16./(exp((4*h*60)/(rho*4184*.066))))
Tf=273.15 +(16./(exp((4*h*t)/(rho*Cp*.066)))));

U0=0;
Re0=rho*U0*.116/mu;
Nuout0=.5*.332*Pr^(1/3)*sqrt(Re0);
hout0=Nuout0*k/.2073451151;
h0=hin+hout0;
T600=(16./(exp((4*h0*60)/(rho*4184*.066))))
Tf0=273.15 +(16./(exp((4*h0*t)/(rho*Cp*.066)))));

U2=.25*U;U3=.5*U;U4=.75*U;U5=1.25*U;U6=1.5*U;U7=1.75*U;
Re2=rho*U2*.116/mu;Re3=rho*U3*.116/mu;Re4=rho*U4*.116/mu;Re5
=rho*U5*.116/mu;Re6=rho*U6*.116/mu;Re7=rho*U7*.116/mu;
Nuout2=.5*.332*Pr^(1/3)*sqrt(Re2);
Nuout3=.5*.332*Pr^(1/3)*sqrt(Re3);
Nuout4=.5*.332*Pr^(1/3)*sqrt(Re4);
Nuout5=.5*.332*Pr^(1/3)*sqrt(Re5);
Nuout6=.5*.332*Pr^(1/3)*sqrt(Re6);
Nuout7=.5*.332*Pr^(1/3)*sqrt(Re7);
hout2=Nuout2*k/.2073451151;
hout3=Nuout3*k/.2073451151;
hout4=Nuout4*k/.2073451151;
hout5=Nuout5*k/.2073451151;
hout6=Nuout6*k/.2073451151;
hout7=Nuout7*k/.2073451151;
h2=hin+hout2;h3=hin+hout3;h4=hin+hout4;h5=hin+hout5;h6=hin+
hout6;h7=hin+hout7;
Tf2=273.15 +(16./(exp((4*h2*t)/(rho*Cp*.066)))));
Tf3=273.15 +(16./(exp((4*h3*t)/(rho*Cp*.066)))));
Tf4=273.15 +(16./(exp((4*h4*t)/(rho*Cp*.066)))));
Tf5=273.15 +(16./(exp((4*h5*t)/(rho*Cp*.066)))));
Tf6=273.15 +(16./(exp((4*h6*t)/(rho*Cp*.066)))));
Tf7=273.15 +(16./(exp((4*h7*t)/(rho*Cp*.066)))));

```

```

plot(t,Tf,t,Tf0,'b--',t,Tf2,t,Tf3,t,Tf4,t,Tf5,t,Tf6,t,Tf7
      ,60,T60+273.15,'b*',60,T600+273.15,'b*')
strValues = num2str([60 T60+273.15]);
text(60,T60+273.15,strcat('(' ,strValues ,')'),'
      VerticalAlignment','bottom');
strValues0 = num2str([60 T600+273.15]);
text(60,T600+273.15,strcat('(' ,strValues0 ,')'),'
      VerticalAlignment','bottom');
legend(strcat('Speed=',num2str(U)),strcat('Speed=',num2str(
      U0)),strcat('Speed=',num2str(U2)),strcat('Speed=',num2str
      (U3)),strcat('Speed=',num2str(U4)),strcat('Speed=',
      num2str(U5)),strcat('Speed=',num2str(U6)),strcat('Speed='
      ,num2str(U7)));
title('Temperature(K) VS Time(s)')
xlabel('Time(s)')
ylabel('Temperature (K)')

```

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