



**ECOLE
POLYTECHNIQUE
DE BRUXELLES**

Cooling Down a Coke Can
Experiment study

Fluid Mechanics and Transport Processes

Nathan DE PRYCK

Miquel KEGELEIRS

Mischa MASSON

December 2015



“Cooling down a coke can”

**Experiment study by Nathan De Pryck, Miquel Kegeleirs and Mischa Masson
Université Libre de Bruxelles
2015-2016.**

TO BE WRITTEN

Table des matières

1	Introduction	2
2	Heat transfer processes	3
2.1	Conduction	3
2.2	Convection	3
3	Mathematical model	5
3.1	General simplifying assumptions	5
3.2	Simplified models	6
3.2.1	Non-spinning can	7
3.2.2	Spinning can	9
4	Reality and mathematical model	10
5	Conclusion	11
A	Water Thermo-Physical Properties	12
B	Formula Sheet	15
C	Codes	23
C.1	Non-spinning model	23

Chapitre 1

Introduction

This report outlines the physics behind an experiment produced during the MECA-H-3001 “Fluid Mechanics and Transport Processes” course of the ULB (Université Libre de Bruxelles) on Friday, the sixteenth of October 2015.

The experiment can be found at this address¹ and was described as following :

- Three coke cans were available as well as a bucket of ice and water (at 0°C) and a drill to spin the can inside the bucket.
- One of the cans was used to determine the initial temperature (16°C) of the fluid (essentially water) inside the can.
- One can was left inside the bucket for 60 seconds and a final temperature of 11.9°C was measured as a result of the conductive heat transfer with the surrounding fluid.
- One can was spun inside the bucket for 60 seconds at about 1000 rounds per minute, and a final temperature of 11°C was measured as a result of the convective and conductive heat transfer.

In the first chapter, convective and conductive processes that are related to the experiment will be described. Those phenomena will then be applied to the problem via a mathematical model, including a discussion of simplifications brought to the problem in order to simplify calculations. This model will be compared to the experimental results, then a discussion on it’s reliability followed by a conclusion on mathematical models in general will be presented.

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, making them moving or vibrating 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[2], 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 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 :

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

Seeing this, 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. Those 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.

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(Mathematical model, chapter 3).

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, but simple enough to be resolved with few calculations.

This means that some simplifications of the equations seen before 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 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 A and are extracted from “*Perry’s Chemical Engineers’ Handbook*”[1].

Another assumption is that the can is a perfect cylinder with an height of $h = 116mm$ and a diameter of $d = 66mm$ ¹. In the reality, the shape of a can is a bit different to support pressure but difference should not be significant in present 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 matter exchange, as shown in figure 3.1.

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

1. dimensions are standard ones for European Aluminium 330ml cans, those can be found on webpackaging.com

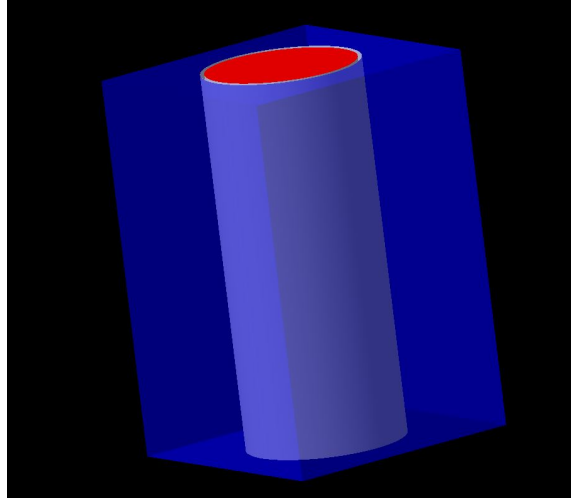


FIGURE 3.1 – The red cylinder is hotter water, the blue box is colder water. No matter exchanges, only heat transfer.

surface of the can is given by :

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

Bottom and top circular surfaces have a total surface of $2 \times Surface_{circle} = 2\left(\pi\left(\frac{d}{2}\right)^2\right) = 6.8424cm^3$, this is thus about 22.14% of total surface. Reason why it was decided to ignore such a large portion of the can's area is because half of it is not even in contact with ice during the experiment (the system holding the can covers it's top and 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, but as it is on the bottom of the can and as we are trying to cool down a liquid, the liquid in contact with the bottom part will be cooler, making heat transfer far less efficient there because cold fluids tend to be more dense than hot fluids.

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; and as liquid water is more flexible than ice, the can has a larger surface in contact with molten ice (and thus water) than with 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 A : water being at 16°C (about 290K), it gives $Pr = 7.56$.

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

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

Where :

- β is the volume expansion coefficient, given by $\frac{1}{\rho} \frac{\delta \rho}{\delta T}$. Using the tables in annex A, 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.
- $d = 33 \times 10^{-3} m$ is the diameter of the cylinder.
- $\nu = \frac{\mu}{\rho} = \frac{1080 \times 10^{-6}}{1.001 \times 10^{-3}} = 1.081 \times 10^{-6} \frac{m^2}{s}$ is water's kinematic viscosity.

All values used come from annex A.

Rayleigh number is thus :

$$Ra = GrPr = 7.56 \times \frac{1.998 \times 10^{-4} \times 9.81 \times 16 \times (33 \times 10^{-3})^3}{(1.081 \times 10^{-6})^2} = 5.8329 \times 10^7 \quad (3.4)$$

Since $Ra < 10^9$, the laminar case should 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" [3], 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 :

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

This, when using the parameters of the experiment, would have given $T_f = 284.14K = 10.99^\circ C$ after $t = 60s$.

This value is quite far from what is observed in the experiment. This 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” [3] : $\beta = 1.38 \times 10^{-4} K^{-1}$ 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 now 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 $Pr = 8.77$.

To be even more accurate, the same correction can be made for k , ρ and C_p ; values for those parameters becoming $k = 0.584 \frac{W}{mK}$, $\rho = 999.4 \frac{kg}{m^3}$ 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.

2. Be warned that the values for Prandtl are different than the one used before : this is due to the fact it was decided to use values from the same source (“Heat and Mass Transfer : Fundamentals and Applications” [3]) 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

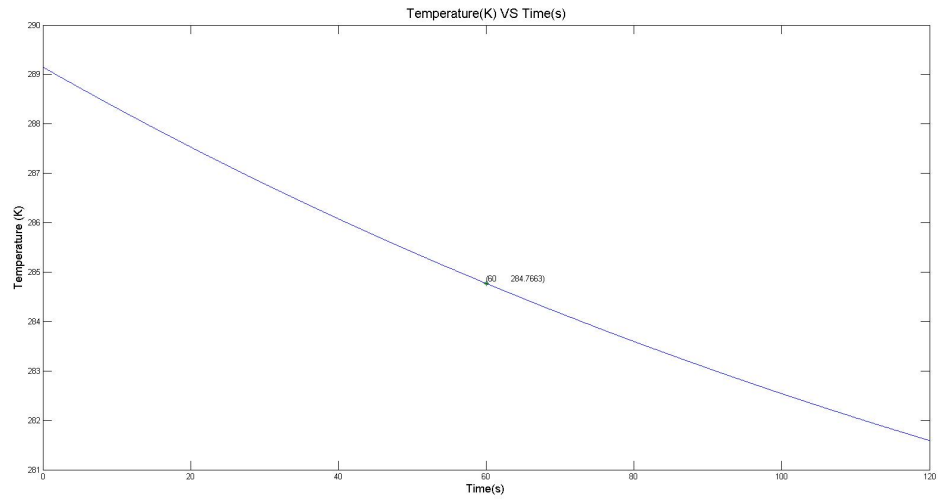


FIGURE 3.2 – Graph of temperature versus time for the non-spinning can. The star marks the 60s point.

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

Graph 3.2 gives the evolution of temperature(K) with time(s) for the last model with enhanced approximations of Prandtl and β .

3.2.2 Spinning can

Chapitre 4

Comparison between reality and the mathematical model

Chapitre 5

Conclusion

Annexe A

Water Thermo-Physical Properties

These chart can be are extracted from “Perry’s Chemical Engineers’ Handbook”, Chapter 2[1].

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 B

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:**

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

- **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** $\frac{1}{\sqrt{\lambda}} = 1,14 - 0,87 \ln \left(\frac{0,25}{\text{Re}_{D_h} \sqrt{\lambda}} + \frac{0,0015}{\text{Re}_{D_h} \sqrt{\lambda}} \right)$

☛ **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: $T_{\text{paroi}} = T_o(\dot{s}_{\text{paroi}}, t)$

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

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**

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

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

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

2. Latent heat transfer (fusion or evaporation):

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

- **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 C

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.

C.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)')
```

Bibliographie

- [1] Robert H. PERRY Don W. GREEN. *Perry's Chemical Engineers' Handbook*, chapter 2. McGraw-Hill, 7th edition, 1997.
- [2] Jean-Marie BUCHLIN. *MECA-H-300 Phénomènes de Transport, Notes de Cours*. PUB-ULB, 2005.
- [3] Afshin J. GHAJAR Yunus A. ÇENGEL. *Heat and Mass Transfer Fundamentals and Applications*. McGraw-Hill Professional, 5th edition, 2014.