Modeling & Simulation of a cooling tower with extended uses

by

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Preface

This master thesis was carried out at the department of chemical engineering, Kemicentrum.

I would like to thank Anders Holmqvist for always being available for all possible questions, guiding me through this thesis. I would like to thank Bernt Nilsson for the enthusiasm and positivity that he always provides, making this work a pleasurable experience.

At last I would like to thank my sparring partner Matilda Lundberg for working alongside me in this project, as well as Marcus and Fredrik for sharing this time and making it fun.

Abstract

In this work, an existing cooling tower, created for educational purposes, was modelled and simulated. The model was solved in Matlab using the built in function ode15 and it was evaluated by implementing both absorption and process control. The implementations were performed in the simulation only.

The model was deemed to be fit for the existing tower although there were unfortunately some uncontrollable effects that couldn’t be quantified. This resulted in that the results from the simulation are slightly different from the experimental. The absorption and the process control were easily incorporated and performed well in the model.

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1 Introduction

Cooling towers are most commonly used to cool water in industries. Often, the big hyperbolic cooling towers made of concrete, see figure 1.1, are associated with generating electricity when they in fact only cool water. The purpose of a cooling tower is to keep a process from raising temperatures too high were they either can be dangerous or lower the efficiency. By using a cooling tower, the plant is kept safe and operational.

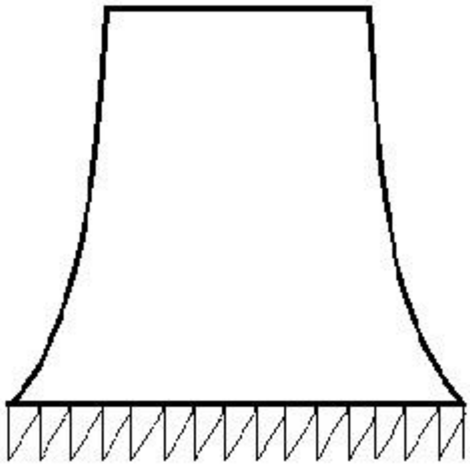


Figure 1.1. A cooling tower made of concrete. The air is sucked in from below and flows upward when heated by the water. This produces warm and humid air which leaves the top and condenses into a cloud, making it look like an enormous chimney.

1.1 Aim

A model often describes complex system and captures a blue print. This is done with the help of parameters taken from real settings, for example lengths and velocities. Some parameters are more difficult and abstract and will have to be estimated or calculated, for example the rates of mass and heat transfer. Models are often presented in a way that's easily comprehensible. They help with the understanding of complex systems and sometimes help predict how it behaves in various situations. Models are also easier to share with others which help with the spread of knowledge and having models ready at hand for various processes is a resource. When a new project is started there is a benefit in having a starting point and a model that works in that field. This work contributes to that starting point.

The purpose of this project was to create a dynamic model of a cooling tower. Since most models are static, this new model can e.g. be used to study process control. The tower that's placed in apparathallen in Kemicentrum was investigated and used as a base for the model. The data from the work can also be used in other courses where the equipment is studied.

Earlier models focus mostly on developing a static solution for how the cooling tower will act at specific instances, but reality is not static. The purpose with dynamic models, as in this work, is to look at how changes occur and the rate of the effect.

2 Literature review and theory

The main objective of a cooling tower is to remove excess heat in various processes. There are principally two kinds of cooling towers, dry and wet. There is no evaporation in dry towers since there is no direct contact of water and air. The cooling is caused only by the heat exchange or convective cooling. Since heat exchange is relatively poor in air, the surface area need to be large to compensate. In the wet cooling towers the air is in direct contact with water and the cooling is caused mostly by evaporation and is much more efficient. A plume is formed in these towers which is a cloud of very small droplets [1].

There is also the option of counter-flow and crossflow design (there also exists co-current flow but it is seldom used). Figure 1.1 above is an example of a cooling tower with a counterflow that uses a natural draft of air. There are also counterflow towers that use forced draft, one of which has been modelled in this work with regards to process control. [2]

Heating, ventilation and air-conditioning systems all demand a large amount of energy. This is why it's essential to know about and operate them efficiently in regards to the environment and sustainability. [3]

A gas and water column is modelled dynamically from an existing experimental setup. The gas comes from under the column and is air with the same characteristics as the surroundings. The water comes from above through a shower head that sprays and distribute the water. The two phases meet and a mass and a heat exchange occur. The air that passes will evaporate some water and take up the heat while the water will be cooled from both the cooler air and the evaporation. The evaporation demands energy which is why the water is cooled. The cooling of the air in this regard is negligible. The seemingly more simple heat exchange will transfer heat from the water to the air where the loss of heat in water in this regard is negligible.

The exact results of this study is secondary, instead the focus lies in finding correct models and working with them in a meaningful way.

2.1 Film theory

When a model is needed for the contact and transfers over a liquid and a gas, film theory is very useful. It says that there are two very shallow layers exactly at the surface between the two phases where the transport of mass and energy occurs. You have transport into the layers from each side and then a transport over between the layers as well. In this work, there is a transport of water into the thin film of air and then out into the bulk. The transfer rates have to be found which can be complicated. The theory also becomes inherently complicated due to the fact that mass and energy transport are coupled at the interface. [4]

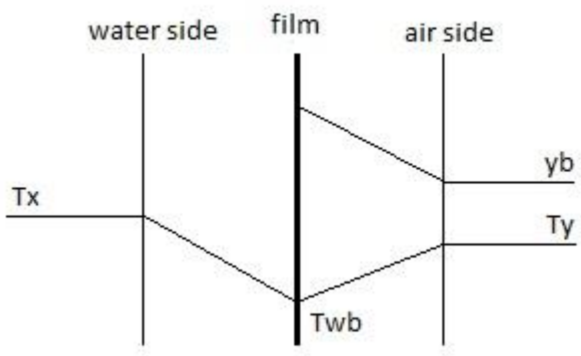


Figure 2.1. In film theory, the thin film layers can be viewed closely like this with concentrations and temperatures marked on both sides. To the left, in the water bulk, no concentration is shown since y_b is already water.

The mass transport rate of water into the air is directly dependent on the relationship between the humidity in the air bulk and the absolute humidity in the air film, which is considered saturated [2]. This means that the absolute humidity will increase in the interface since the temperature increases as well. The temperature at the interface is the wet bulb temperature which is explained below. See also figure 2.1 for the wet bulb temperature.

The mass transfer in absorption was in a study calculated by using two flowing phases that with a constant Henry's constant [5]. A similar approach will be used in this work where the relation between the partial pressure in the air phase and the concentration in the water will influence the mass transfer rate.

2.2 Wet bulb temperature

The wet bulb temperature is the temperature that is showed on a wet thermometer that is hanging in a stream of air. The temperature of the air and its humidity are both affecting the wet bulb temperature and shortly it can be described as the temperature the thermometer shows when the energy supply from the air is as great as the heat of evaporation of the water. The temperature that's used at the interface in film theory is assumed to be the wet bulb temperature.

The difference between the wet bulb temperature and the output temperature of water is known as the *approach* and is generally about 3 to 8 degrees Celsius. If the wet temperature would be the same as the interface temperature, all heat for vaporization would by definition come from the air and no cooling of the water would happen. [6]

2.3 Mollier diagram

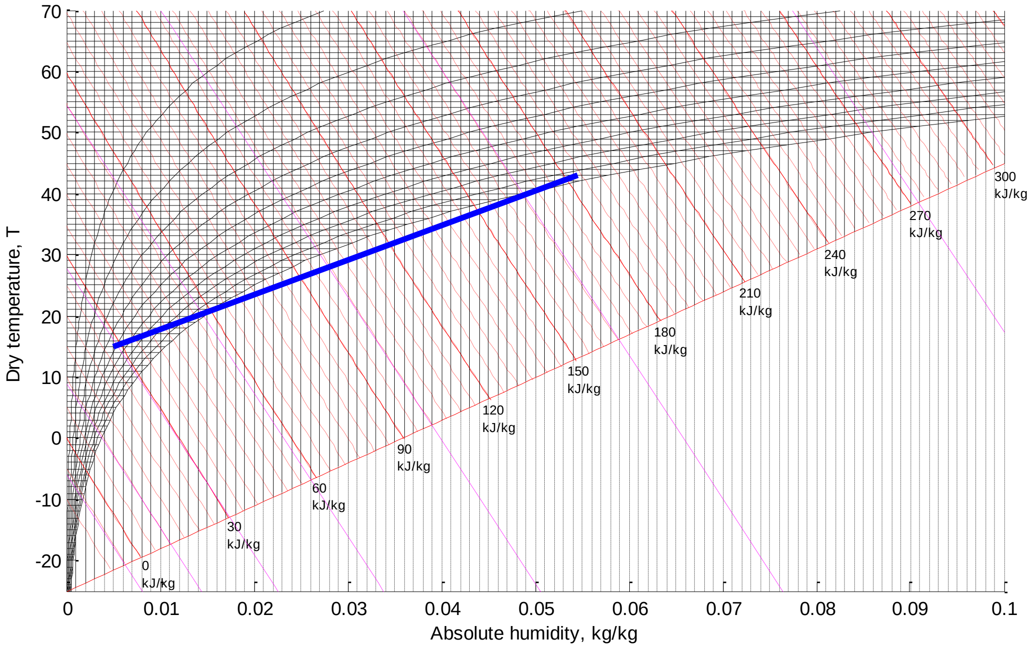


Figure 2.2. A Mollier diagram that plots the humidity of air vs the dry temperature. The thick line represents one example of how the air's characteristics can change when going through the cooling tower. Antoine's equation was used to calculate the bent lines representing the relative humidities. The lines of constant enthalpy are calculated through a simple correlation to humidity and temperature. The wet enthalpy lines are estimated from tabular data [7].

The Mollier diagram in figure 2.2 is a diagram that plots temperature versus absolute humidity. Many things can be estimated at a quick glance from this diagram and it has many applications. The thick line in this diagram is an example of how the properties of air can be changed when it travels through the cooling tower used in this work. It's easy to see the change in enthalpy as the temperature is increased as well as the humidity.

2.4 Dry and wet area

The dry area is the area of all packing combined. The size of the dry area of the packing can be found in tabulations in books on the subject of chemical engineering. This can be done for many different kinds of packing and sizes. It can also be calculated if you know the density of the packing.

The size of the film area between water and air is an important factor for the effectivity of the column. This area is called the wet area and differs greatly from the dry area due to the fact that there is a lot of dead zones in the column where there is no water.

Since the packing in this work is made up of cut plastic tubes of various heights, there is no formal description of the density or the area in square meters per cubic meters. The packing was assumed to have about the same characteristics as Raschig rings which also are hollow cylinders. The following relation was used to describe the correlation between the wet area and the dry [8]. Many of the parameters are described in table 3.1.

$$\frac{a_w}{a_{tot}} = 1 - \exp\left(-1.45\left(\frac{\sigma_c}{\sigma_L}\right)^{0.75}\left(\frac{L_w^*}{a\mu_L}\right)^{0.1}\left(\frac{L_w^{*2}a}{\rho_L^2 g}\right)^{-0.05}\left(\frac{L_w^{*2}}{\rho_L\sigma_L a}\right)^{0.2}\right) \quad (1)$$

2.5 Mass and heat transfer coefficient

The theoretical mass and heat transfer coefficients can be estimated from literature. They of course consist of several factors which are hard to estimate and will change over time. The following correlation was used in this work to estimate the mass coefficient [8].

$$\frac{k_G}{a}\frac{RT}{D_v} = K_5\left(\frac{V_w^*}{a\mu_v}\right)^{0.7}\left(\frac{\mu_v}{\rho_v D_v}\right)^{\frac{1}{3}}\left(ad_p\right)^{-2.0} \quad (2)$$

The Lewis factor is used to correlate the heat coefficient from the mass coefficient which usually is approximated to 1. This means that the heat coefficient can be approximated to be equal to the mass coefficient. [9]

2.6 Spray pattern

The spray pattern at the nozzle exit is an important part of how the liquid is distributed in the tower which the overall performance and efficiency of the tower. A uniform spread across the fill gives optimal performance. The referenced article provides a method for finding the optimal nozzle pattern for individual towers and fills. [10]

2.7 Efficiency

Efficiency has been measured before with equation 3.

$$\eta = \frac{T_{w,in} - T_{w,out}}{T_{w,in} - T_{wb}} \quad (3)$$

Efficiency is an important factor for sustainability. Cooling towers are common in the industry and they have to be able to handle the input from other processes which is generally not controlled. There is a lot to be gained from looking at the efficiency, in financial terms. [11]

2.8 Absorption

Gases that are harmful for the environment or other gases that a plant might want to keep from being let out can be absorbed and collected. This is done in an absorption tower where the air is pumped through a tower where it meets a lot of water. The film theory can also be applied here. The gas will be absorbed with help from Henry's constant.

2.9 Process control

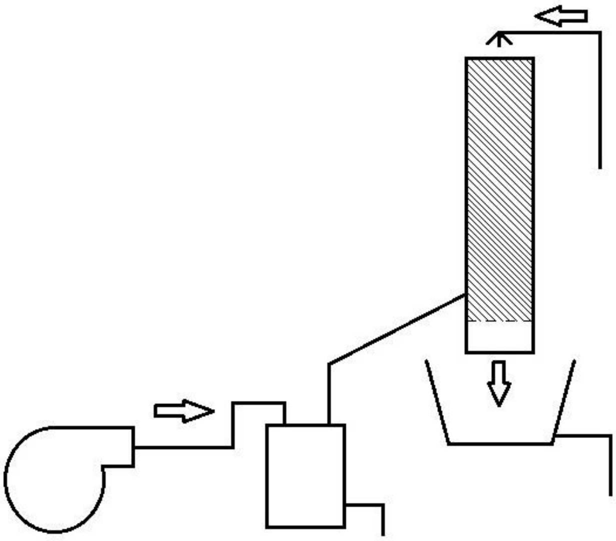
Process control is a tool for regulating and controlling a process. This is done by controlling the output of specific variable within a range or at a certain level. This is useful in plenty processes that for example want to keep a certain temperature, water level or concentration in their system. Since these variables easily can fluctuate, process control is used to stabilize them, often through another variable. Since the use of controlling processes is so great, it’s important to implement and study this technique. [12]

3 Experimental setup

The experimental set up can be seen in figure 3.1. The water is distributed on the top and collected in a box on the bottom. Air is pushed through from the bottom. The packing consists of parts of plastic tubes.

Figure 3.1. The equipment that's used in the experimental part. At the top, water is sprayed out and distributed into the column. The fan, seen on the lower level, blows air through the tank and up into the column where it's pushed through and out on the top.

Both figure 3.1 and 3.2 show the experimental setup. The purpose of the tank between the fan and the column is to prevent water from dripping into the fan directly. The water is instead collected in the box just below the column and let out to the drain.



Figur 3.2. A schematic picture of the equipment. The air comes from the fan on the left and goes up the column. The water comes from the right and goes down through the column.

The height of the filled part of the column is 0.73 m. The inner diameter is 0.093 m. The plastic tubes average height is 0.025 m and the inner diameter is 0.014 m and the outer is 0.016 mm. The estimated dry area is 350 m2/m3.

The fan is of a model MPT 25S with a Q_{max} of 360 m^3/h.

The surrounding air temperature and relative humidity are at all experimental times 26 °C and about 34 %. This was measured with a dry thermometer and a wet thermometer that was waived to create air movement around the thermometer.

Figure 3.3. This is what the packing looks like. The distribution of the water phase can also be seen since the column is active. Note that a lot of the water is located at the edges of the column.

A complementary list of parameters is seen in table 3.1 below.

Table 3.1. Parameters used in the calculations.

Denotation	Value	Description
H_c	0.73 m	Height of the column
D_c	0.093 m	Diameter of the column
V_c	0.0050 m^3	Volume of the column
a	374 m^2/m^3	Surface area, [8]
σ_C	30 mN/m	Surface tension for the plastic packing material, [8]
σ_L	70 mN/m	Surface tension of water, 20℃
μ_L	$1005*10^{-6}$ Ns/m^2	Dynamic viscosity of water, 20℃, [7]
ρ_L	998.2 kg/m^3	Density of water, 20℃
ρ_G	1.19 kg/m^3	Density of air, 20℃, [7]
g	9.81 m/s^2	Standard gravity value, [8]
A	8.07131	Antoine equation constant, water 1-100 ℃
B	1730.63	Antoine equation constant, water 1-100 ℃
C	233.426	Antoine equation constant, water 1-100 ℃
P	760 mmHg	Pressure, atm
k	-2500 Kkg_{air}/kg_{H2O}	Slope of the wet line, [7]
M_{H_2O}	18.015 g/mol	Molar mass of water
M_{air}	28. 964 g/mol	Molar mass of water
C_{Pg}	1 kJ/(kg°C)	Heat capacity at constant pressure for air

4 Mathematical theory and method

The column was discretized in one dimension to be able to describe it mathematically in a simpler way. By height the column is divided into different segments, or tanks, where they are handled each by their own with regards to the transport phenomena that occurs. This could be viewed as a tank series, one for the liquid phase and one for the gas phase. Across the phases the exchange of mass and heat occurs in every segment. This can be seen in figure 4.1 below.

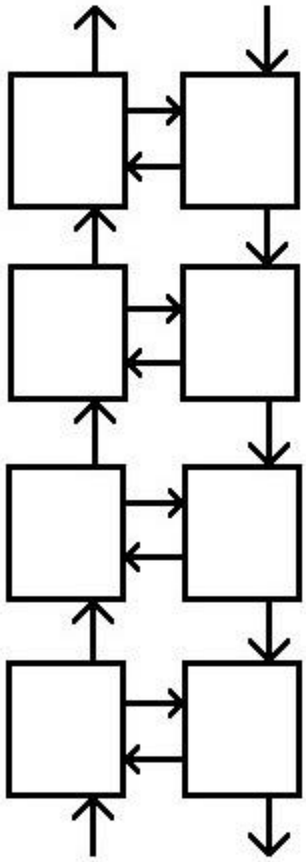


Figure 4.1. A model of a tank series where in this case N=4. Every tank consists of either air or water but the tanks in the same level contain the same fluid. An exchange of mass and heat happens in every tank with the corresponding tank in the other level.

The mass balances and energy balances have to be found for the model to work properly and give satisfactory results. The balances that were found are described below, starting with a mass balance. In the equations, *i* refer to the level or the tank starting from the bottom. The rest of the parameters can be explained in appendix A

$$\frac{dy_i}{dt} = \frac{G_y}{V_{N,v}}(y_{i-1} - y_i) + \frac{m_{evap,i}}{\rho\, V_N} \tag{4}$$

The energy balance for air

$$\frac{dT_i}{dt} = \frac{G_y}{V_{N,v}}(T_{i-1} - T_i) + \frac{e_{vvx,i}}{\rho\, V_N} \tag{5}$$

The energy balance for water

$$\frac{dT_i}{dt} = \frac{G_x}{V_{N,L}}(T_{i+1} - T_i) - \frac{e_{evap,i}}{\rho\, V_N} \tag{6}$$

The rate of evaporation is calculated with the following equation [7]

$$m_{evap} = \frac{A_N h_y}{c_{p,v}}(y'' - y) \tag{7}$$

The heat exchange is described by

$$e_{vvx} = \frac{A_N h_y}{c_{p,v}}(T_{water} - T_{air}) \tag{8}$$

The enthalpy of evaporation is calculated by [13]

$$e_{evap} = \frac{\Delta H_{vap} m_{evap}}{c_{p,L}} \tag{9}$$

The water volume in the column is measured with the water flow range that was used. It's measured by a measuring jug that collects all water in the column after the faucet is turned off. This is used to create a simple function that calculates the percentage of water and of air for each G_x.

4.1 Absorption

For this and the following part, another upscaled and fictive column was simulated. The used height is 2 meters and the diameter was 1 meter.

The absorption that was used in a later part of the work is described by the following equations. The mass balance for the amount of substance in the gas phase is described by

$$\frac{dd_i}{dt} = \frac{G_y}{V_{N,v}}(d_{i-1} - d_i) + N_A a_{wet} \tag{10}$$

Mass balance for the amount of liquid phase is described by

$$\frac{dc_i}{dt} = \frac{G_x}{V_{N,L}}(c_{i+1} - c_i) - N_A a_{wet} \tag{11}$$

N_A from the above equations is the rate of transfer between the phases. It's built from the ideal gas law and Henry's law and calculated as follows

$$N_A = K_{tot}\left(\frac{He \cdot c_i}{V_{N,L}} - \frac{d_i RT}{V_{N,v}}\right) \quad (12)$$

The substance that this model used as a base for calculations was carbon dioxide.

4.2 Process control

A PI-regulator is also implemented to test the model and is described below. The error is defined in equation 13.

$$e = T_{out,max} - T_{w,out} \quad (12)$$

The sum of the control is described by

$$G_y = k_p e + k_I \int e(t)dt \quad (14)$$

Where the first part is the P-part and the latter is the I-part. The closed loop system can be seen in figure 4.2. The temperature of water out of the column is the measured variable and the set point is the desired level.

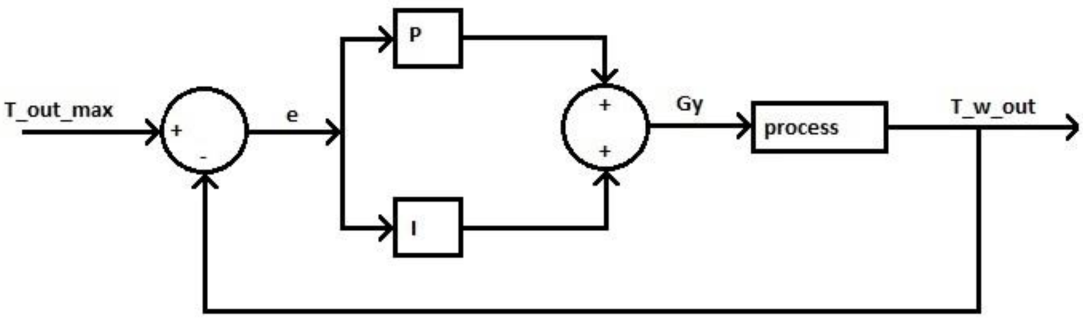


Figure 4.2. Schematic picture of how the process is controlled in a closed loop using a PI-controller.

4.3 Correlation of variables

The Matlab command *corr* uses Pearson's linear correlation coefficient. The results are two matrices. The first matrix shows the correlation between all variables and the second matrix shows how significant the values are compared to an alternative that has nonzero correlation. The location of the correlations and the significance are same in both matrices. If a value is small in the second matrix, the corresponding value in the first matrix is more significant. [14]

Performing the analysis in the upscaled tower, five different variables were randomized when analyzing the output temperature. The water temperature was randomized from 40 to 70, the air temperature from -10 to 35 degrees celcius, the humidity from 0.001 to 100 percent, water flow from 0.001 to 0.010 m^3/s and finally air flow from 1 to 20 m^3/s.

4.4 Programming theory

Matlab provides many useful functions for simulations and modelling. Among them are several differential solvers where one of them, ode15s, was used in this project. In an ordinary differential equation solver, the mass matrix is non-singular. [14] Since the problem includes determining the wet temperature at every time step and in every "tank", the Jacobian becomes singular. This means that the equation for the wet temperature is algebraic and not differential, which is why a DAE (differential algebraic equation) is used to solve both the differential and algebraic equations.

The built-in function *lsqcurvefit* will be used to evaluate the parameters, such as the mass transfer coefficient and the efficiency of the fan. The structure for using *lsqcurvefit* is seen in figure 4.3.

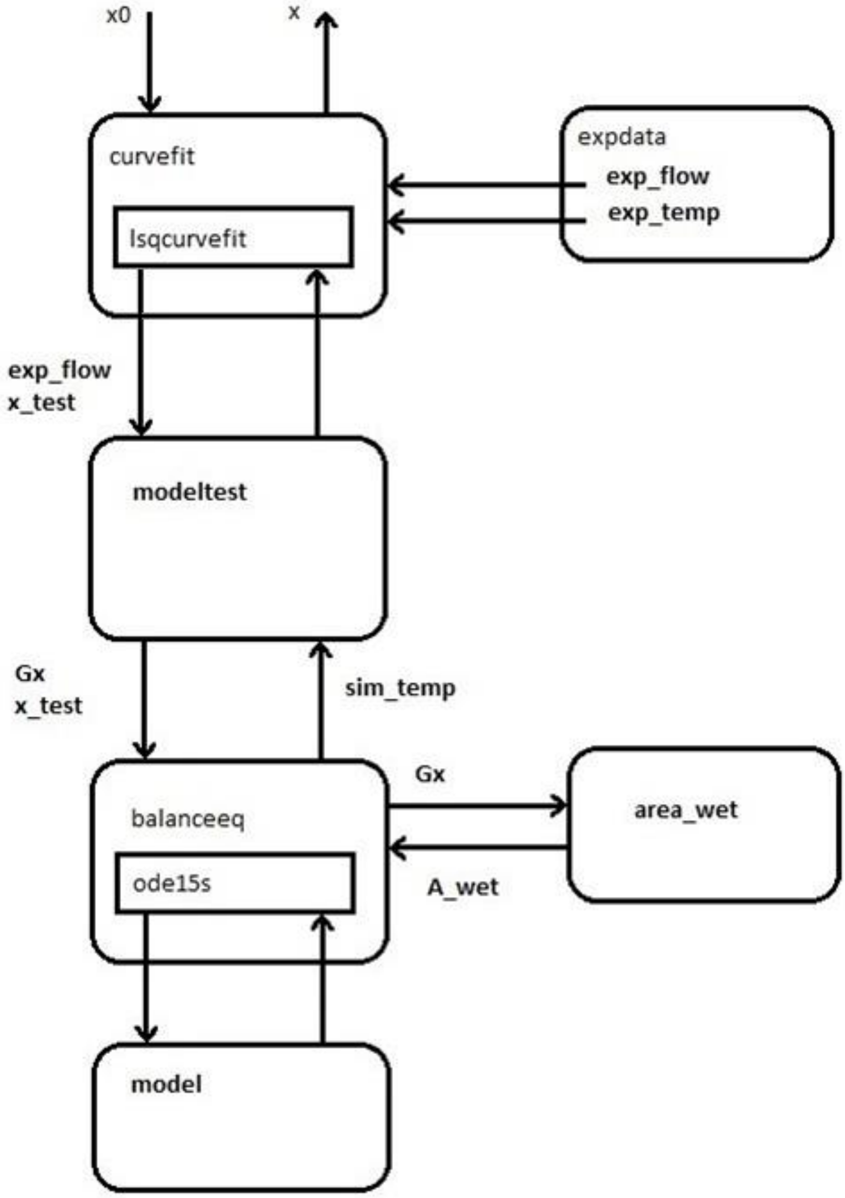


Figure 4.3. The structure used to estimate the parameters of the model. The function modeltest *is used to find all different simulated temperatures for each experimental flow speed. The model function only provides one final simulated temperature which is why* modeltest *is necessary to calculate, through* balanceeq, *the total span.* Lsqcurvefit *finds the most appropriate x-values (the parameters) after several iterations.* Area_wet *is an example of a function that the model function uses, there are others such as the function for calculating the holding volume of liquid.*

The other simulations (process control and absorption) only use the lower half of figure 4.3. Some other implementations are incorporated. In the absorption simulation, the mass balances in chapter 4.1 are included. In the process control, equation in 4.2 is included. Some parts of the code itself can be seen in appendix C.

5 Results and discussion

In this part, all results are shown and discussed before going to the conclusion of the project. Firstly, the results from original cooling tower will be presented and discussed. Following that, the upscaled model is used for evaluating both absorption and process control with regards to the original model.

5.1 Cooling tower

The result from *lsqcurvefit* shows that the efficiency of the fan (how much air passes through the column versus the maximum of the fan) is at 7.74 %, which corresponds to 7.7 liters/s, and the heat transfer coefficient in the gas phase is 13.8 kW m^{-2}. These results can be considered to be high but might show that there are many factors that are not taken into consideration and would influence the results in another direction.

The results from both the experiments and the simulation are shown and compared in pictures 5.1 and 5.2 below. Both plots were created in Matlab, with the calculated coefficients, in the function *modeltest* as seen in figure 4.3.

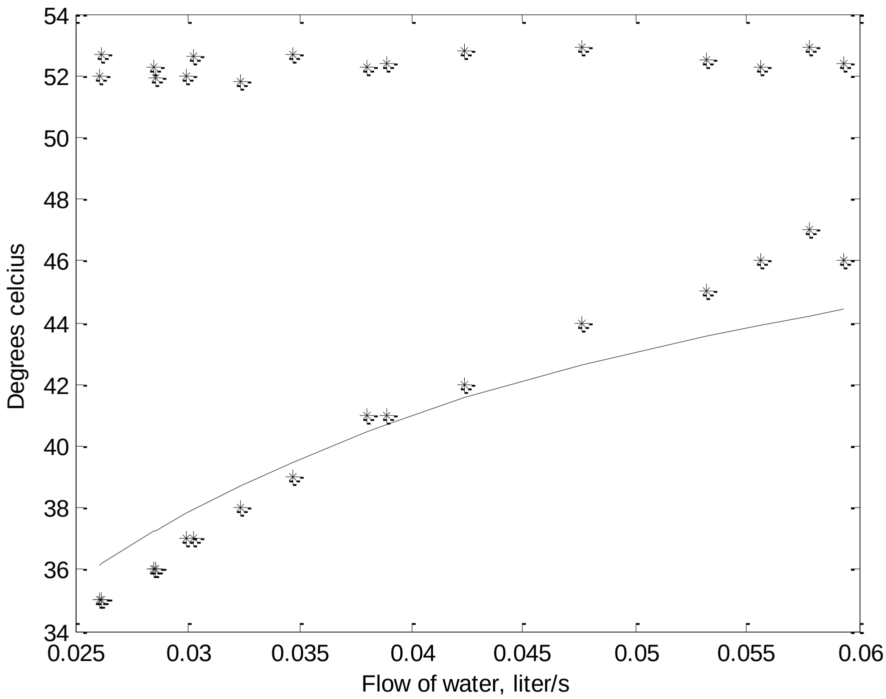


Figure 5.1. The temperature of water in (the upper stars) and out from the cooling tower (lower stars). The simulation is the line that crosses the lower stars and this line represents the temperature out. All temperatures are plotted against the water flow.

The experiments were successful though there was a slight variation in the spray pattern that occurred below 0.04 liter/s. The water looked more like it was poured from one side of the shower head than sprayed. How this affected the wet area is unclear. From figure 5.1 it seems that there is no significant effect, the cooling tower rather looks like it’s more effective at ranges lower than 0.04 liter/s, foremost in figure 5.2.

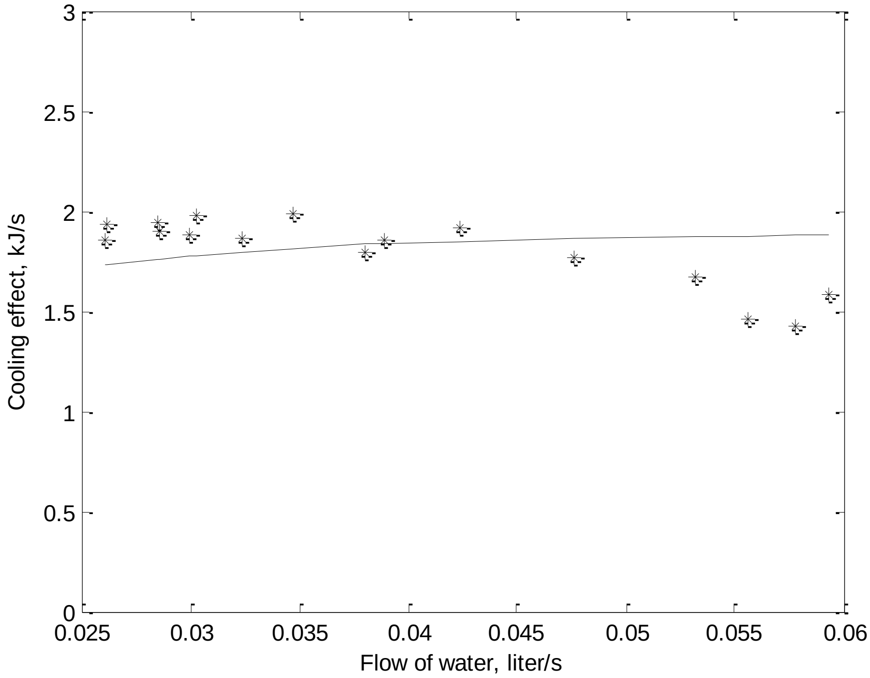


Figure 5.2. The cooling effect of the water versus the water flow. The stars represent the experimental data and the line is the simulation. The cooling effect was calculated by taking the temperature difference and multiplying it with the water flow and the heat capacity.

The experimental data shows that the tower is actually performing worse when the flow is higher. The experimental values in figure 5.2 show that the cooling effect is declining with increased water flow. The simulation on the other hand shows increased efficiency with the flow. There are probably several practical explanations for this.

An explanation for the decline in the experimental data could be that the effectivity of the fan is declining as more water is flowing against it and creates more pressure drop. Another explanation may be that the excess water in higher flow rates is flowing along the column wall instead of being distributed across the cross-section. It's possible that a larger diameter would diminish these effects and reduce the decline.

The packing in the tower is also a factor that there are no data for and the effects are uncontrollable and hard to verify. AnoxKaldnes were kind to let us test one of their plastic materials that they use for other purposes. Unfortunately the pressure drop increased too much in the tall tower.

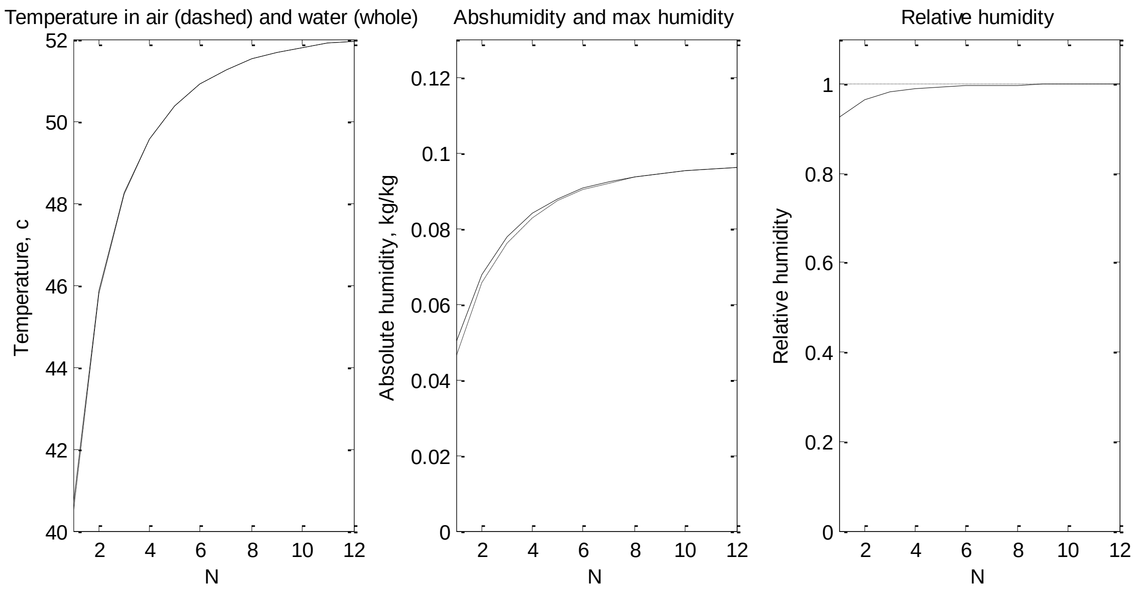


Figure 5.3. The temperatures and humidity at steady state with flow speed 0.04 liters/s. Left figure (a) shows the temperature of water and air being the same over the whole column. Middle figure (b) shows how the absolute humidity is changing in the column and the right figure (c) shows the relative humidity.

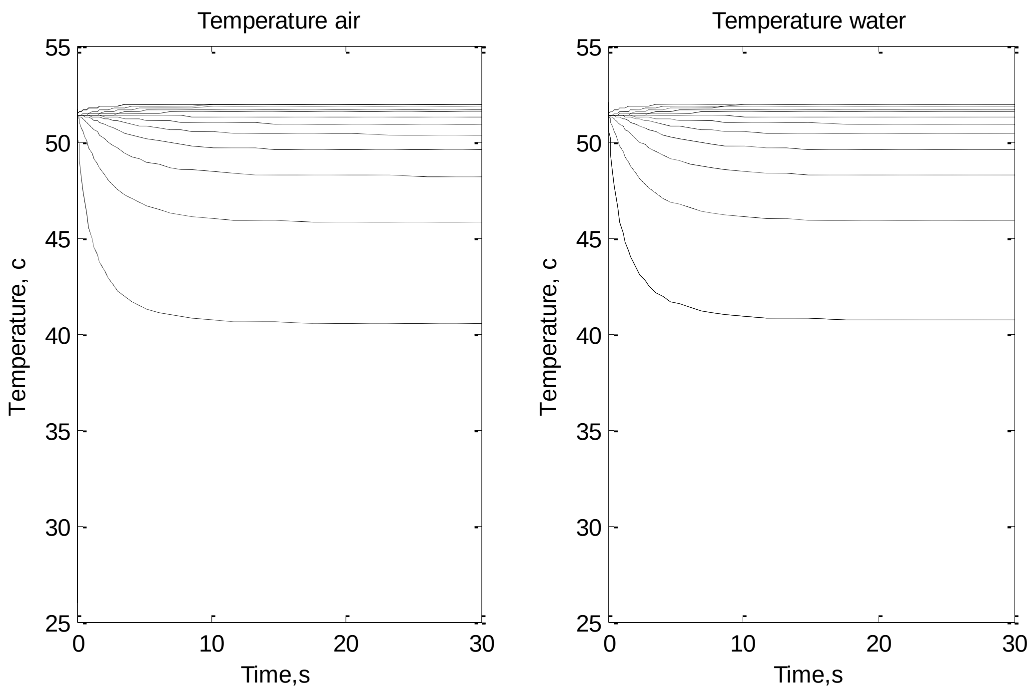


Figure 5.4. The temperature plotted against the time for both air (a) and water (b). The temperatures in all "tanks" are showed. *This is a dynamic simulation with flow speed 0.04 liter/s. The non-dashed lines are the temperatures that air and water have when they leave the column, air top and water at the bottom.*

Even though the surrounding air temperature is 26 degrees Celsius, it's quickly heated to the same level as the water. This can be seen in both the static and the dynamic conditions in figure 5.4. The relative humidity is soon up to maximum, see figure 5.3c. Since the temperature of the air increases with the height of the column, the maximum absolute humidity increases. This implies that the absolute humidity will increase even though the relative humidity is at 100 percent.

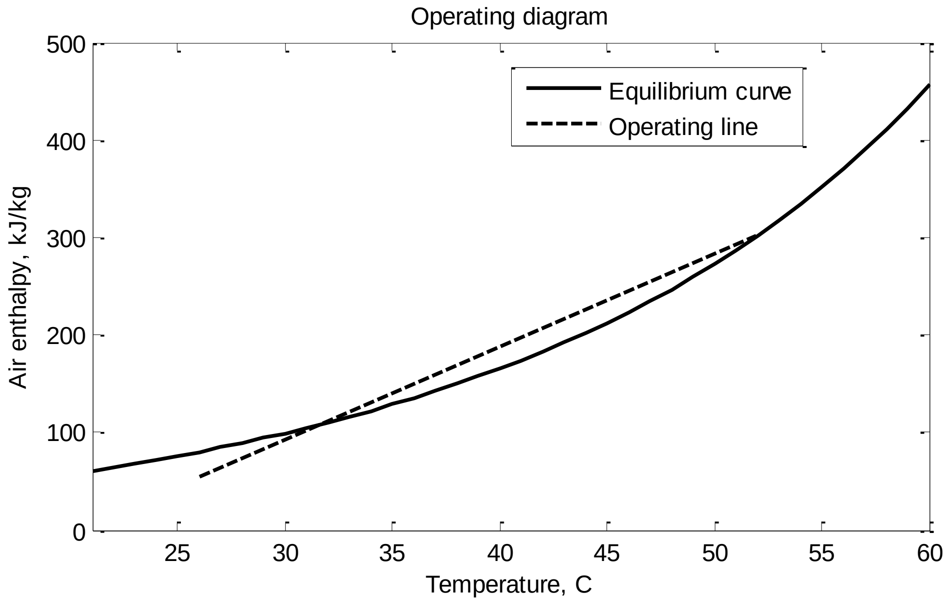


Figure 5.5. Operating diagram for cooling tower. The enthalpy of the air is plotted against the temperature. The dashed line represents the cooling towers operational status with only two data points being used, which is why the line is straight. Water flow is 0.04 l/s.

The operating diagram for the tower is seen in figure 5.5. The operating line meets the equilibrium line at the end which shows that all cooling capacity of the air is used and there is no additional space for more water which of course could be concluded already in figure 5.2. The reason might be that the use of the fan is rather inefficient and that the air flow probably is negatively correlated to the water flow.

5.1.1 How efficient is the tower?

Using the created model, the simulated efficiency could be found for different water flows, see figure 5.6

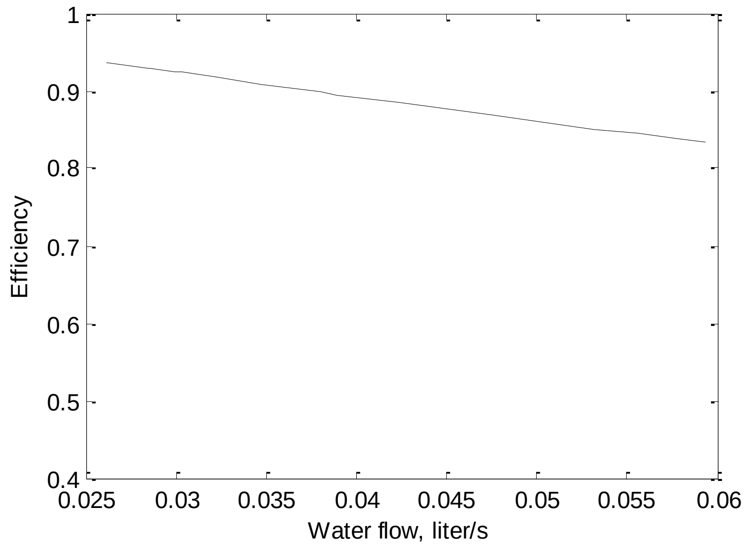


Figure 5.6. The simulated efficiency of the cooling tower, plotted against different flow rates.

The simulated cooling tower seems to have a decent efficiency over the used range but declines with increased water flow. When the wet bulb temperature is close to the temperature of water going out, the efficiency goes up. It also goes up when the output and wet bulb temperature is lower which probably the case in this project is. The purpose of a good cooling tower is to be both efficient and to cool the water to a certain level. Therefore, a consideration has to be done in regards to both having spare capacity and being efficient.

Looking at figure 3.3 it can be seen how the water is distributed. It might be hard to see without a video, but a big portion of the water is poured along the walls and the middle of the column is quite unused. This is quite inefficient.

5.2 Absorption

The upscaled model was also used when simulating absorption. The results are seen below.

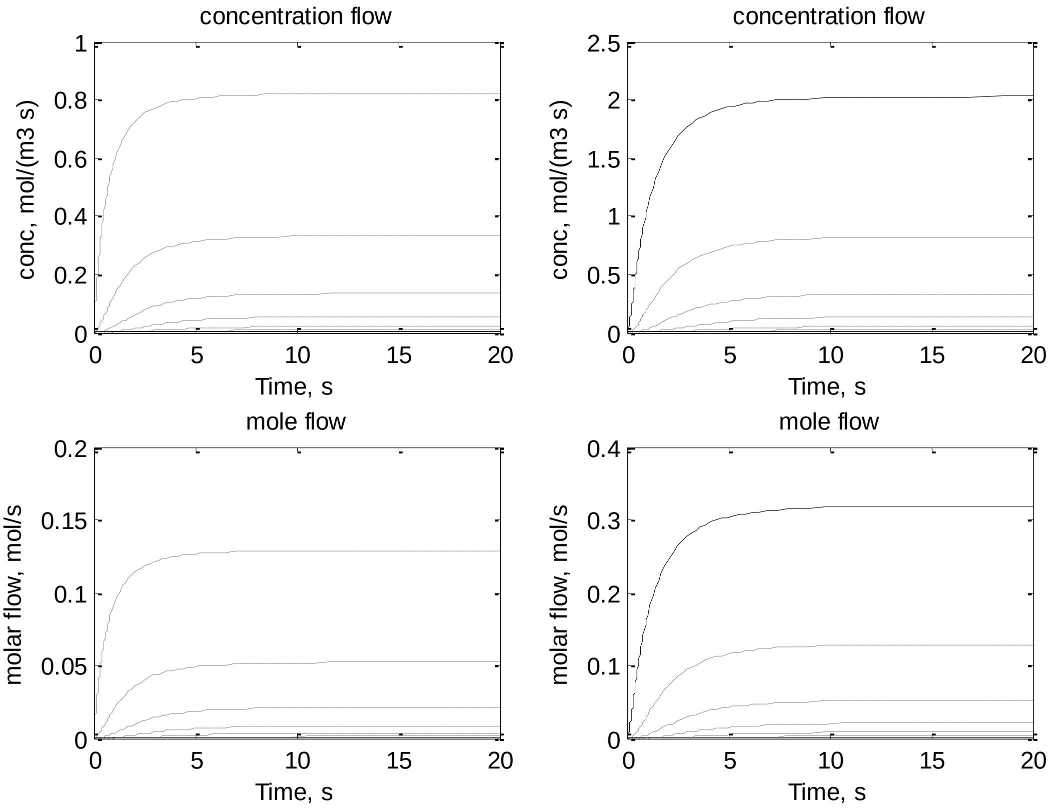


Figure 3.7. The concentration flow and the mole flow are plotted dynamically. Every line represents a tank. Seen both in air (left side) and in water (right side). The full lines are the outputs from the column. There is full absorption in the water phase which is why the output on the air side is a flat line. N=15.

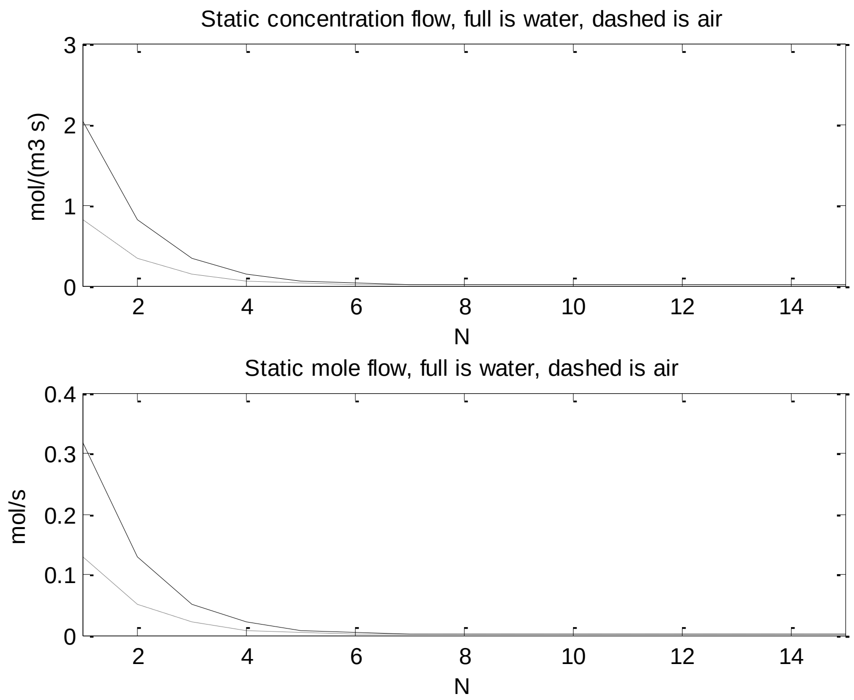


Figure 5.8. The static mole concentration in every tank. Both in concentration flow and mole flow. The dashed lines are in the air phase.

How the mole flow varies in different sites in the column can be seen in figure 5.7 and 5.8.. At a first glance the mole flow isn't correct; the output should be equal to the input. This is however correct and the misleading plot is a consequence of the model. The input into the next tank is the result of what happened in the former tank. The output in the water phase is from the first tank but the input in the air phase is not in the first tank as seen in figure 4.1. This was verified with an increase of tanks, as the same effect is seen.

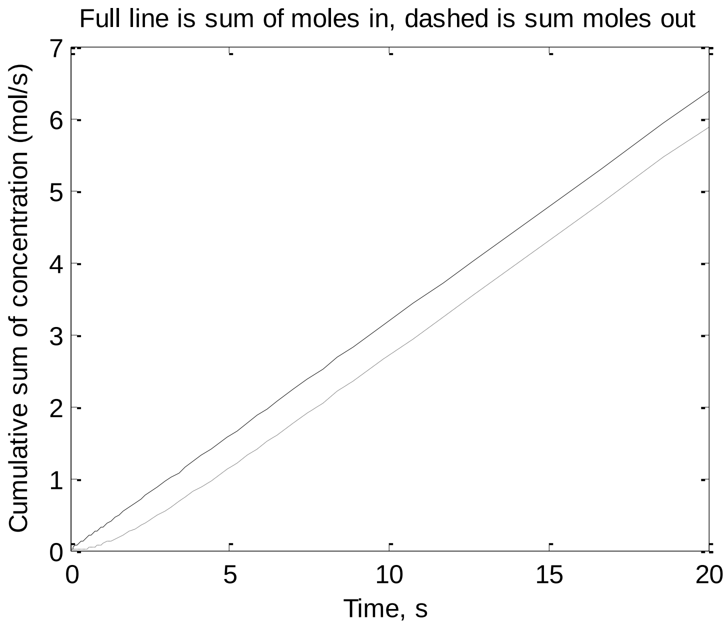


Figure 5.9. The cumulative sum of the concentration versus time. The full line is concentration of the air into the column and the dashed is the output. N=15.

In figure 5.9 there is a slight time delay before the output catches up. This shows that no material is lost in the column and that the model is working satisfactorily.

5.3 Process control

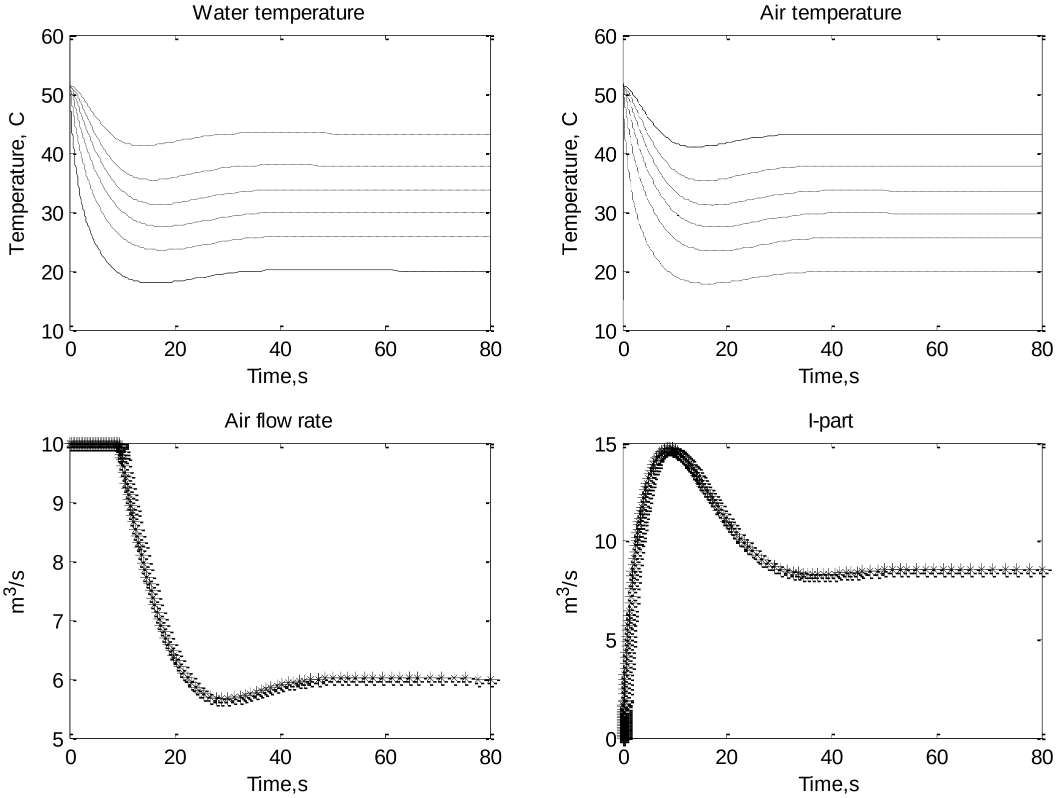


Figure 5.10. How the dynamic relation between the water temperature and the controller can look like at start up. The upper left figure (a) shows water temperature at all different tanks where the full line is the output, the upper right (b) is the corresponding for the air phase. The lower left figure (c) shows how the controller behaves. The I-part of the controller is shown in the lower right (d). N=6.

As seen in figure 16.2c the controller has a maximum limit set at 10 m^3/s. After a while the output temperature was lowered and the controller stabilized itself with a slight overshoot. The I-part was also stabilized after a while at a level that eliminated the static error. The constants of the PI-control can of course easily be changed for the type if system it's intended. After the static error is eliminated, the control signal only consists of the I-part.

5.4 Correlation between variables

Table 5.1 is the result of the correlation analysis and table 5.2 is the significance of the values in the first table.

Table 5.1. The table shows how different variables are correlated to each other. Higher absolute value shows a higher correlation. The numbers are based on 500 runs where the parameters were randomized. This was performed on the upscaled column.

	G_x	T_x	T_y	y_b	G_y	$T_{x,out}$
G_x	1	-0,078	-0,006	-0,065	0,045	0,310
T_x	-0,078	1	0,027	0,029	-0,083	0,106
T_y	-0,006	0,027	1	0,696	-0,029	0,367
y_b	-0,065	0,029	0,696	1	-0,030	0,477
G_y	0,045	-0,083	-0,029	-0,030	1	-0,698
$T_{x,out}$	0,310	0,106	0,367	0,477	-0,698	1

The results show that the factors that most affect the temperature out of the column are the air flow and its humidity, thirdly the air temperature. The values are also highly significant, seen in table 5.2. However, the temperature and the absolute humidity are coupled which is logical when looking at Mollier's diagram because the temperature limits the absolute humidity.

Table 5.2. This table shows the significance of the values in table 5.1, where the value is compared to a nonzero correlation alternative. Small values show that the values are significant.

	G_x	T_x	T_y	y_b	G_y	$T_{x,out}$
G_x	1	0,160	0,925	0,843	0,872	0,000
T_x	0,160	1	0,247	0,710	0,068	0,007
T_y	0,925	0,247	1	0,000	0,159	0,000
y_b	0,843	0,710	0,000	1	0,212	0,000
G_y	0,872	0,068	0,159	0,212	1	0,000
$T_{x,out}$	0,000	0,007	0,000	0,000	0,000	1

The correlation between the temperature in and the temperature out is low which might be surprising. Some additional studies were performed and it was found that the range of the randomized variables had a great impact on the data and what the correlations were showing.

In figure 5.11, another way to visualize the correlation between the parameters is shown. It is a principal component analysis, PCA. There is a difference in this study and it is that the process control is used to capture the air flow as a parameter as well. This has of course an impact on the results.

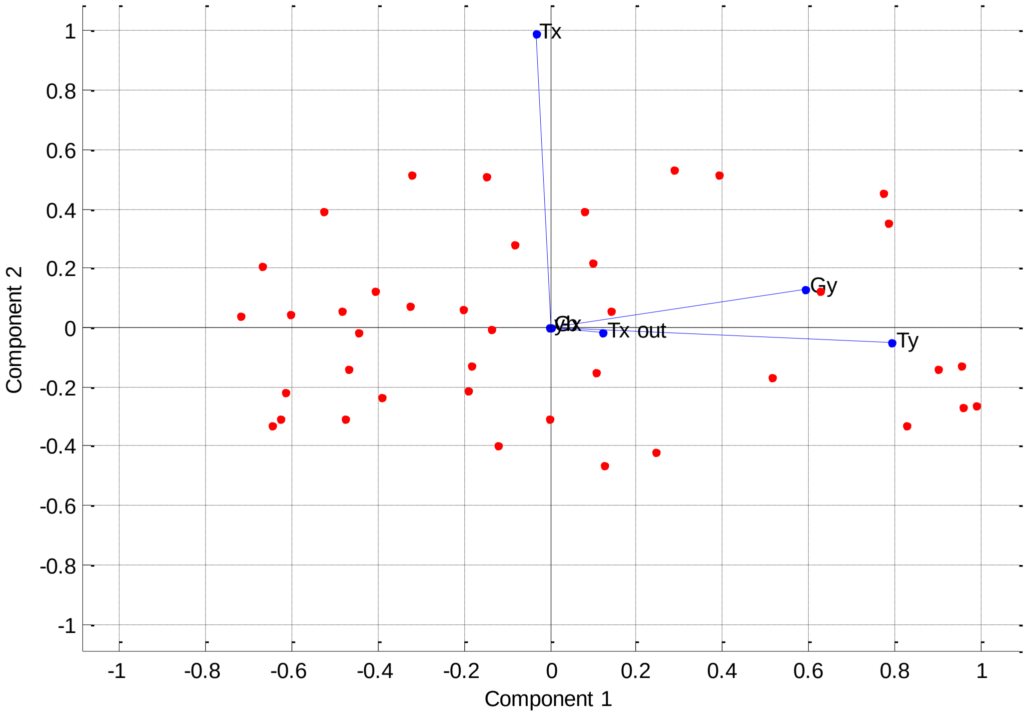


Figure 5.11. A Principal Component Analysis performed on parameters that were randomized, 40 times. Every dot represents a simulation and every line represents a parameter. If the angles are right, there is no correlation and if the line is long the parameter is significant.

In figure 5.11, only two components are shown, but it was calculated that they contain 98.49 % of the information together. It can be concluded that the parameters were randomized since the dots are evenly spread out. Regarding the parameters, there is no correlation between the temperature of the water into the column and the temperature out from it. There is a correlation between the temperature of air out, T_y, the fan speed, G_y, and to a lesser extent the water temperature out, $T_{x,out}$. The rest of the parameters have little significance in this study.

For designers of cooling towers it might be useful to look at what range all the variables can change over when optimizing the performance. The lesson from this would be that it’s important to know how weather and other characteristics change when designing a cooling tower, since they impact the performance directly.

6 Conclusions

The model seemed to work properly for the original cooling tower except for uncontrollable effects, probably due to the small diameter. The decline in efficiency at the higher flow rates was the result of this and the simulation did not capture these effects.

The dynamic model was tested for different purposes which overall gave satisfying results. The absorption part worked like it was supposed to but was harder to visualize. Process control was also incorporated in the model successfully, being more accessible and easier to visualize.

An analysis of the effectivity and the correlation of variables were done with more or less meaningful results.

Since most studies in this work are based on the simulations, *in silico*, there is a probability that the results would vary if they would've been performed on a real large scale cooling tower. Since the model is still meaningful and the parameters easily changed, it can be considered to be useful.

7 Future work

For future work it would be interesting to see comparisons to real cooling towers that are used in the industry. This would probably lead to many new insights on how this model works and both what its weaknesses and strengths are.

The absorption could be more in depth, comparing with experimental data as well as adding a reaction in the water phase.

It would be interesting to further evaluate the basic model and making it even more advanced. This model is quite basic and uses relatively basic expressions for the transfer rates. To further investigate alternatives for these would make an even more exciting project.

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9 Appendix

9.1 Appendix A

Table 9.1. Table of abbreviations.

Symbol	Units	Parameter
A	m^2	interfacial area
a	m^2/m^3	area
c	mole	moles of substance in liquid phase
c_p	kJ/kg K	heat capacity
d	mole	moles of substance in gas phase
D	m^2/s	diffusivity
d_p	m	packing size
e		error of output in process control
e_{vvx}	kW	rate of heat transfer
g	m/s^2	gravitational acceleration
G	m^3/s	mass velocity
He	$Pa*m^3/mol$	Henry's constant
h_y	kW/m^2 K	heat transfer coefficient
K_5	2.0	constant, applied below 15 mm packing size
k_G	mol/(m^2 s atm)	mass transfer coefficient, gas phase
k_i		I-part constant
k_p		P-part constant in
K_{tot}	mol/(m^2 s atm)	overall mass transfer coefficient
L	kg/m^2 s	liquid mass flow rate
m_{evap}	kg/s	rate of evaporation
N_A	mol/m^2 s	rate of mass transfer
Q_{max}	m^3/h	maximum fan speed
R	8.3145 Pa m^3/K mol	gas constant
T	K	temperature
V	m^3	Volume
V*	kg/m^2 s	cross-sectional gas mass flow
y	kg/kg	absolute humidity
ΔH_{vap}	kJ/kg	

Table 9.2. Table of abbreviations - greek letters.

Symbol	Units	Parameter
μ	Pa s	dynamic viscosity
σ	N/m	surface tension
ρ	kg/m^3	density

Table 9.3. Table of abbreviations – Suffixes.

Symbol	Parameter
L	liquid
N	segmental part
wb	wet bulb
x	Liquid phase
y	gas phase
v	vapour

9.2 Appendix B, wet bulb temperature

The wet bulb temperature is calculated by finding where the Antoine equation crosses the lines for constant wet temperatures.

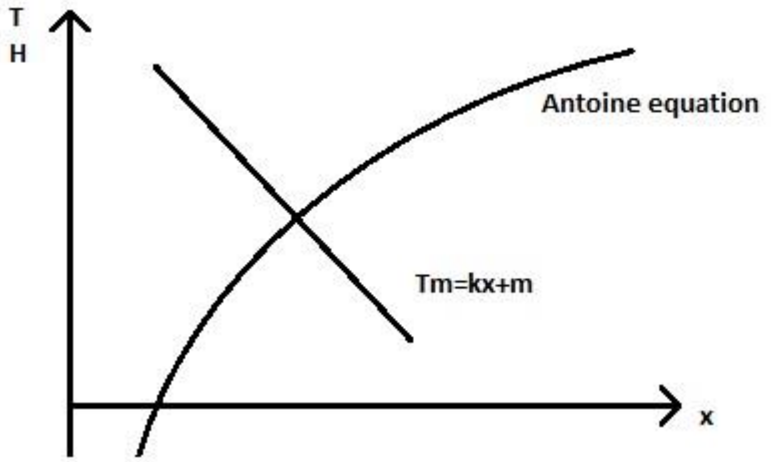

Figure A.1. Parts of a Mollier diagram. The wet bulb temperature is the temperature at which these two curves cross each other.

The Antoine equation

$$p = 10^{\left(A - \frac{B}{C + T_{wb}}\right)} \tag{15}$$

x is described by the following expression from the partial pressure

$$x = 0.622 \frac{p_w}{p - p_w} \tag{16}$$

The constant wet temperature line

$$T_{wb} = kx + m \tag{17}$$

These expressions results in the following combined equation (18) which is solved for T_{wb} in a solver for DAEs. $\frac{P_{tot}}{760}$ is added to correct the units to Pa from mm Hg.

$$0 = \frac{P_{tot}}{760} 10^{\left(A - \frac{B}{C + T_{wb}}\right)} - \frac{T_{wb} - T_y + x * k}{k} * \frac{P_{tot}}{0.622 + \frac{T_{wb} - T_y + x * k}{k}} \tag{18}$$

9.3 Appendix C, Matlab code

This appendix shows the important Matlab functions used in this project

9.3.1 The original cooling tower

The following equation was used for the testing the original cooling tower. All the parameters are not written since they are not important for a general model.

```
% ode-solver with DAE
M=[eye(3*N,3*N) zeros(3*N,N);zeros(N,4*N)];
options=odeset('Mass',M);
init=[d.yb.*ones(1,N) d.Ty.*ones(1,N) d.Tx.*ones(1,N) d.Tx.*ones(1,N)];

[T,Y]=ode15s(@(t,z) model(t,z,d,N),[0 tslut], init, options);



function out=model(t,z,d,N)
yb=d.yb/d.skalningsf;
y(1:N,1)=z(1:N)./d.skalningsf;
Ty(1:N,1)=z((N+1):(2*N));
Tx(1:N,1)=z((2*N+1):(3*N));
Tywet(1:N,1)=z((3*N+1):(4*N));

ybissl=ymax(Tywet); % ymax for wet temperature

h_air=d.h_air; % heat coeff - kW/(m2 K)
h_vvx=1/(1/h_air + 1/d.h_water);

dHvap=deltaHvap(Tx); % kj/kg
mevap=d.AN.*h_air./d.cpa.*(ybissl-y); % kg/s


% massbalances water in air
y_before=[yb;y(1:N-1)];
dydt=d.Gy./d.VairN.*(y_before-y)+mevap./(d.rhoair*d.VairN);

% energybalance air
Ty_before=[d.Ty;Ty(1:N-1)];
dTydt=(d.Gy./d.VairN).*(Ty_before-
Ty)+h_vvx.*d.AN/(d.rhoair.*d.cpa.*d.VairN).*(Tx-Ty); % vvx

% energybalance water
Tx_before=[Tx(2:N);d.Tx];
dTxadt=(d.Gx./d.VwaterN).*(Tx_before-Tx)-
dHvap.*mevap./(d.VwaterN.*d.cpl.*d.rhowater); % dhvap

% Solves for Tywet
Tyta=(Tx+Ty)./2;
res=d.P/760.*10.^(d.A-d.B./(d.C+Tywet))-(Tywet-Tyta-y.*2338.3)./(-
2338.3).*d.P./(0.622+(Tywet-Tyta-y.*2338.3)./(-2338.3));


out=[dydt.*d.skalningsf;dTydt;dTxadt;res];
end
```

9.3.2 Absorption

For the absorption, the following was added in the model function

```
%-------------------------------------------------------
dCO2(1:N,1)=z((3*N+1):(4*N)); % moles in air
cCO2(1:N,1)=z((4*N+1):(5*N)); % moles in water

% absorption
pd=dCO2.*8.3145.*(Ty+273.15)./d.VairN;
NA=d.Ktot.*(pd - d.He.*cCO2./d.VwaterN); % mol/m2 s


% amount of substance air
dCO2_before=[d.dCO2in;dCO2(1:N-1)];
dddt=(d.Gy./d.VairN).*(dCO2_before-dCO2)-NA.*d.AN; % mol/s

% amount of substance water
cCO2_before=[cCO2(2:N);d.cCO2in];
dcdt=(d.Gx./d.VwaterN).*(cCO2_before-cCO2)+NA.*d.AN; % mol/s
%-------------------------------------------------------
```

9.3.3 Process control

The following part was added instead for process control in the balanceeq function

```
% process control
d.kp=1; d.ki=0.2;
d.Gy_max = 10;
d.Tout_max=20;
```

And this part in the model function

```
%  reglering
I=z(4*N+1);

err=Tx(1)-d.Tout_max;              % target temperature 20 degrees

P=d.kp*err;                        % P-part
dIdt=d.ki*err;                     % I-part

Gy=min(P+I,d.Gy_max);
```

9.3.4 The wet area function

```
function Awetkvot = areawet(Lin,a,diam)
%AREAKVOT Beräknar effektiva arean, [m2/m3]
% L in är i enhet kg/s. a in är i enhet m2/m3

L=Lin/((diam/2)^2*pi); % kg/(m2 s)
```

```
muL=1004*10^-6; % dynamisk visk m2/s (20 grader)
g=9.81;
rho=998.2; % kg/m3 (20 grader)
sigmaL=0.0728; % liquid surface tension, N/m
http://www.engineeringtoolbox.com/water-surface-tension-d_597.html
sigmaC=0.033; % critical surface tension for particular packing, N/m

term1=L/(a*muL);
term2=L^2*a/(rho^2*g);
term3=L^2/(rho*sigmaL*a);


konstant=1.45; % 1.45 från början
Awetkvot=(1-exp(-konstant*(sigmaC/sigmaL)^0.75*term1^0.1*term2^(-
0.05)*term3^0.2))*a;

end
```

9.3.5 Enthalpy in gas phase

This function is one of many to calculate characteristics of the phases and is just an example of how the bi-functions are constructed.

```
function [ h_air ] = enthalpyair( T,x )
% ENTHALPYAIR Calculates enthalpy of air
%   In goes T (celcius), x (kg water/kg air)
%   Out goes enthalpy of the air

enthalpydryair=1.004.*T;
deltaHvap=-2.3943.*T+2501.4;
enthalpywater=4.1833.*T+0.161;

h_air=enthalpydryair+x.*(deltaHvap+enthalpywater);

end
```