Modeling & Simulation of a Cooling Tower with COMSOL Multiphysics

by

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Preface

This master thesis has been done in collaborations with the Department of Chemical Engineering at Lund University. It comprises 20 weeks of full times studies during spring 2015.

I would like to thank my supervisor, Ph. D. Anders Holmqvist for all help you provided. To my examiner Professor Bernt Nilsson, thank you for all your positive energy and your ability to always inspire me. Thanks to my friends and family for always supporting me. Last, but not least, a special thanks to Anton Löfgren, Marcus Huttunen and Fredrik Tegner for making my time in the Master Thesis room a blast.

Abstract

The aim of this project is to create a model of a Cooling Tower setup using COMSOL Multiphysics. Experiments are performed on the setup in order to provide data of the behaviour. The model is fitted to the data by estimate the models parameters. The parameter estimation is performed with MATLAB by connecting the programs using *LiveLink, COMSOL 5.0 with MATLAB*. The heat transport coefficient, h_g, is estimated from Onda´s method but to be able to adjust the coefficient it is multiplied with the term, n_{hg}.The term, n_{hg}, is estimated to 30.6 and this results in that heat transport coefficient varies between 14.5-15.7 kW/m^2°C.

The model assumes that interface temperature is the wet bulb temperature. In reality is this temperature higher increases the humidity at the interface creating a greater gradient and therefore a bigger driving force. An increased driving force means that the heat transfer coefficient decrease. By adjusting the interface temperature the mass transfer coefficient can have a more correct value.

The simulation shows that the model has a more aggressive heat removal at lower liquid flow rates compared to the data. This could be a result of uneven distribution in the experiments while the model assumes prefect distribution.

Sammanfattning

Syftet med detta projekt är att skapa en modell över en kyltornsuppställning med COMSOL Multiphysics. Experiment utförs på uppställningen för att ge uppgifter om dess beteende. Modellen anpassas mot data genom att uppskatta modellens parametrar. Parametern uppskattningen utförs med hjälp av MATLAB genom att ansluta programmen med *LiveLink, COMSOL 5.0 med MATLAB*. Värmetransportkoefficienten, h_g, beräknas från Onda's metod. För att kunna justera värmetransportkoefficienten multipliceras denna med termen n_{hg} som sedan uppskattas. När termen n_{hg} är 30,6 är modellen bäst anpassad efter data punkterna. Detta resulterar i att värmetransportkoefficienten som används varierar mellan 14.5-15.7 kW/m^2°C.

Modellen förutsätter att yttemperaturen mellan faserna är den våta termometerns temperatur. I verkligheten är denna temperatur högre vilket betyder att fuktigheten vid gränsytan är större vilket genererar en större drivkraft. Då drivkraften ökar innebär detta att värmeöverföringskoefficienten minskar. Genom att justera gränssnittstemperaturen massöverföringskoefficienten kan ha ett mer korrekt värde.

Simuleringen visar att modellen har en mer aggressiv värmeavledning vid lägre vätskeflödeshastigheter jämfört med uppgifterna. Detta kan vara ett resultat av ojämn vätskefördelning i experimenten och detta gör att den skiljer sig från modellen där fördelningen antas vara perfekt.

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1 Introduction

1.1 Background

In all processes in which heat is produced there is a need for a cooling system. Its job is to make sure that the temperature does not exceed allowed temperatures. These internal cooling systems are common in varies of chemical and heating plants. If the temperature exceeds to increase above the maximum temperature there is a danger in the construction not being able to hold, a chemical reaction can accelerate and product can be degraded. So there is a benefit both in the security and production by keeping the temperature in check.

The cooling system can consist of heat exchangers where the hot side is heat exchanged with a cooling medium. In many cases is the cooling medium water, which is cheap, not hazard and has good thermal properties. To be able to reuse the water, the temperature has to be lower to the original temperature before reenter the plant. To do that a cooling tower can be used. By evaporate a part of the liquid the temperature is lowered and can be reused. The lost liquid is replaced by fresh water. A sketch over a cooling tower can be seen in Figure 1.

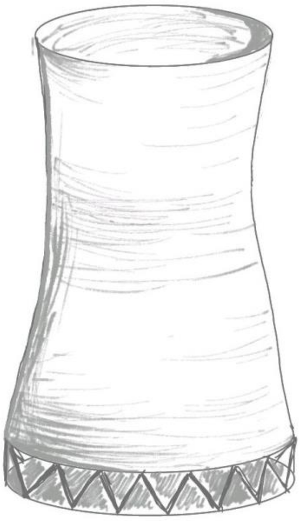

Figure 1. A sketch over a cooling tower where air enters in at the bottom and vapor saturated air leaves at the top.

A process is modulated in order to simulate and be able to predict different behavior without having to do the physical experiment. This saves time, material and energy that would have been lost in the procedure. By simulating the progression optimums can be found and control system created. The same equations can be used for an upscale system and the result from the simulations determents parameter settings.

1.2 Aim

This project is made in collaboration with the Department of Chemical Engineering at Lund University. A setup of a counter flow cooling tower is currently used in courses for demonstrating how combined heat and mass transfer works. The aim of this project is to create a model over this phenomenon using COMSOL Multiphysics. Parameters for the cooling tower are estimated in MATLAB with *LiveLink, COMSOL 5.0 with MATLAB.*

2 Literature Review and Theory

2.1 Transport phenomena

2.1.1 Mass transport

If a system can gain higher entropy it will. The system will spontaneously go towards greater disorder, which is described in the second law of thermodynamics. So if there is a concentration gradient the components tend to move in a direction which will decrease or eliminate the differences. The larger the gradient, the larger is the driving force. The general equation that describes the mass transport can be seen in Equation 1. [1], [2]

$$N = k \cdot a \cdot \Delta c \tag{1}$$

Diffusion is a movement of mass that allows the components to move in a way which increases the entropy. Molecules at temperatures above 0 Kelvin always has the ability to move around and when a concentration gradient exists the probability of the movement in a certain direction increases. In a stagnant layer of a fluid mass transfer only occurs thru diffusion. Diffusion is often much greater in gases (around 10^{-4} m^2/s) compared to liquids (around 10^{-9} m^2/s). Mass transfer also occurs when a fluid is mixed, turbulent flows create eddies and bulk flow. In the examples above larger segments of the fluid are moved in different speeds and directions causing mass to mix. In all cases diffusion still occurs but is no longer the main reason for transporting the component.[1], [2]

If a system with mass transport has a physical or a chemical equilibrium, the further from the equilibrium the greater the driving force. A chemical equilibrium is found when a chemical reaction occurs. A physical equilibrium describes phenomenon such as solvability between two fluids. There is the transport of one fluid to and from the other of equal size. When an equilibrium exist the concentration gradient, the driving force, is calculated as from the equilibrium concentrations.[1], [2]

2.1.2 Heat transport

The thermodynamic zero law says that heat is transferred from higher to lower temperatures. A temperature gradient is the driving force for heat transport. Heat transport thru thermal conductivity takes place in stagnant films, where diffusion and molecule collisions transfer the heat. When the heat is moved due to the movement of a fluid it is called convection. Natural convection takes place due to density differences when forced convection is created by for example the use of a pump. Heat can also be transfer with radiation. The general equation for heat transport can be seen in Equation 2. [1], [2]

$$Q = h \cdot a \cdot \Delta T \tag{2}$$

2.1.3 Coupled mass and heat transport

When mass is transported it leads to a transport of heat as well. But a transport in heat does not lead to a transport of mass. The change of temperature can affect physical data such as density which in turn leads to a mass transfer. Temperature difference also affects the diffusivity which can change the size of the mass transport. [3]

When a mass transfer leads to a phase transition, such as evaporation or condensation, heat is transferred as well. Evaporation requires heat and condensation releases heat. The heat loss or gain at the surface determent the direction of the heat transport from the interface to the surrounding medium. Coupled mass and heat transport are present in processes such as humidification operation and drying of solids. [2], [3]

2.2 Film theory

Film theory assumes that the mass and heat transfer between two phases, such as liquid-liquid, gas-liquid or liquid-solid, occurs through a stagnant film that exist perpendicular to the boundary surface. The stagnant films are present at both side of the interface and in that film only diffusion occurs. The velocity of the surrounding fluid does not affect what happens inside the film but it affects its thickness. At the surface there the two phases are connecting they are in equilibrium. A sketch over the film theory is shown in Figure 2 where the concentration gradient in the two phases are illustrated.[3]

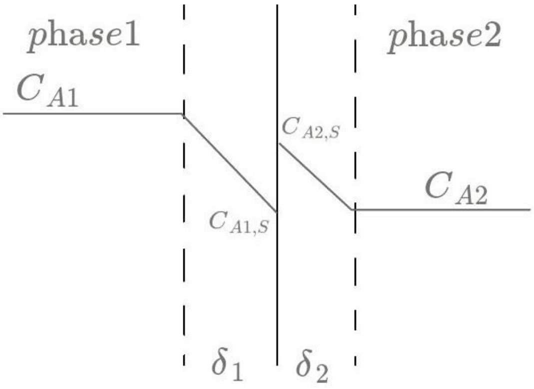

Figure 2. A schematic sketch over the film theory, C_{A1} *and* C_{A2} *represent the concentrations in phase 1 and 2. Sigma is the thickness of representative film and* $C_{A1,S}$ *and* $C_{A2,S}$ *is the concentration at the surface. The surface concentrations are in equilibrium.*

2.3 Humidification operations

Humidity is defined as a unit of mass of water per unit of mass of dry air. The humidity, X, is calculated according to Equation 3 below and a commonly used unit is kg water per kg dry air.

$$X = \frac{m_{H_2O}}{m_{air}} = \frac{M_{H_2O} p_{H_2O}}{M_{air}(P - p_{H_2O})} \tag{3}$$

The amount of water that can be carried by one kg air varies with the temperature. To calculate the vapor pressure of fully saturated air Antoine´s equation can be used, seen in Equation 4.

$$\log_{10} p_{H_2O} = A - \frac{B}{C+T} \tag{4}$$

To gain information about a water vapor in air system a Mollier chart can be studied. The diagram can be seen in Figure 3. From the chart it can be determent the humidity, wet bulb temperature, enthalpy and dry temperature for instance. If the dry temperature and the humidity is known then the wet bulb temperature can be found by following adiabatic saturation line down to 100% saturation line and there find the wet bulb temperature. [2]

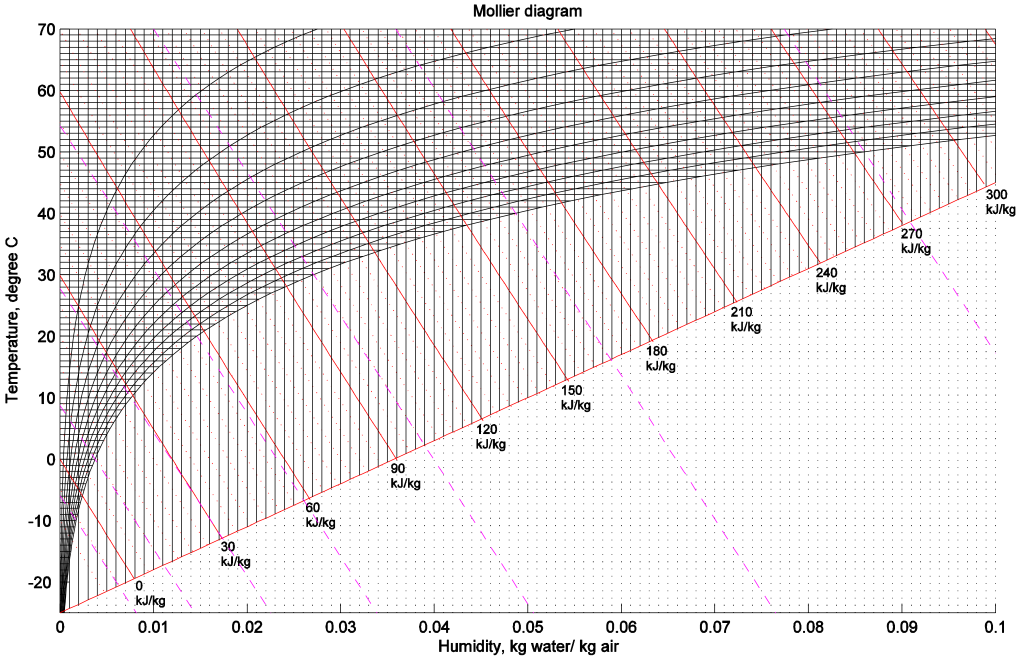

Figure 3. Mollier diagram for moist air.

The wet bulb temperature is the measured temperature when a small amount of water is exposed to a continuous flow of air and allowed to reach steady-state. Some of the liquid is evaporated lowering the temperature causing a heat is transfer from the air to the water. When the wet bulb temperature is reach are the heat transfer from the air to the surface is equal to the evaporation energy. This means that the water reaches a constant temperature, known as the wet bulb temperature. This state is illustrated in Figure 4. The air is assumed to not change in composition because the mass flow of air is much greater compare to the added vapor during the wet bulb measurements. [2]

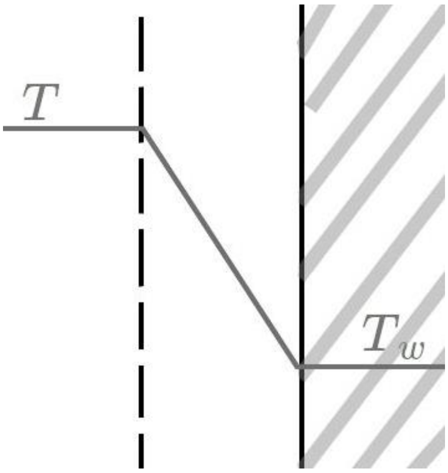

Figure 4. A schematic sketch over the temperature gradients at the boundary layer when the wet bulb temperature is reached. T is the temperature in the air and T_w is the wet bulb temperature in the water.

The mass transfer constant dependent on many variables, it will changes throughout the column because the gas temperature changes. It is estimated by equation 5 below.[4]

$$\frac{k_G}{a}\cdot\frac{RT}{D_v} = K_5\left(\frac{G^*}{a\mu_G}\right)^{0.7}\left(\frac{\mu_G}{\rho_G D_G}\right)^{\frac{1}{3}}\left(ad_p\right)^{-2} \tag{5}$$

The relationship between the mass transfer constant and the heat transfer constant can be described through Lewis equation shown in Equation 6. [2]

$$\frac{h_g}{M_{air}k_g} \cong c_S \tag{6}$$

For air-water system the humid heat c_S can be assumed to be the same as the specific heat c_P. The specific heat for the gas is calculated as a mixture of vapor and air, the adjusted Lewis equation for humid air is shown in Equation 7. [3]

$$\frac{h_g}{M_{air}k_g} = c_{p_{air}} + Xc_{p_{H_2O}} \tag{7}$$

2.4 Area

In any kind of transport phenomena the surface in which the transfer can occur is important to calculate. When water flows through a vertical pact bed the flowrate determent how much of the surface area that is covered with water. The dry surface area of the pacing will not be the same as the wet surface area. To determent the efficiency of the wetting Onda´s method is used and the equation is presented below. [4]

$$\frac{a_w}{a} = 1 - \exp\left(-1.45\cdot\left(\frac{\sigma_C}{\sigma_L}\right)^{0.75}\cdot\left(\frac{L^*}{a\mu_L}\right)^{0.1}\cdot\left(\frac{L^{*2}a}{\rho_L^2 g}\right)^{-0.05}\cdot\left(\frac{L^{*2}}{\rho_L\sigma_L a}\right)^{0.2}\right) \tag{8}$$

Where a is the dry surface area and a_w is the wet surface area.

2.5 Cooling Tower

When hot water comes in contact with a non-saturated gas a part of the water evaporates and the evaporation leads to a lowering of the waters temperature. This phenomenon is utilized in the cooling tower. A counterflow cooling tower is a vertical column with an air inlet at the bottom and an air exit at the top. An illustration can be seen in Figure 5. A fan located at the top creates the gas movement and sucks the air up thru the packing material. The water is sprinkled at the top of the filling a flows downwards and exit at the bottom. The hot water meets the heated air at the top and the cooled down water meets the cool air at the bottom and therefore the name countercurrent flow. Another used method is the crossflow cooling tower where air enters through the length of the filling, but its features will not be studied during this project. [2]

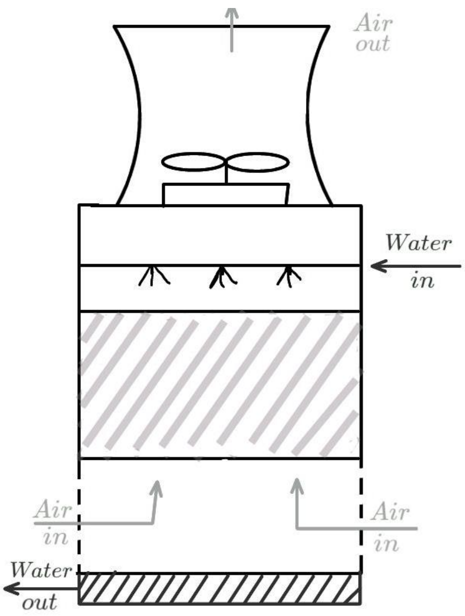

Figure 5. A sketch of a Counterflow Cooling Tower. Waters enters through the sprinklers and flows down the packing material and exit at the bottom. Air enters at the bottom and is sucked up with a fan an exit at the top.

In a cooling tower the water temperature changes as the water travels down the tower. The goal is not to reach the wet bulb temperature. As long as the interception temperature is greater than the wet bulb temperature energy is taken from the water to use in the evaporation. This causes the water temperature to decrease. The wet bulb temperature differs throughout the tower because the humidity and temperature of the air changes. As long as a there is a humidity difference at the interception and the air bulk then there is a driving force for the mass transfer in the cooling tower. If the water temperature is greater than the interception temperature the water will cool down.

In the bottom of the column the surrounding air meet the cooled down water. Two examples of temperature and humidity profile are shown in Figure 6. As long as the interception temperature is lower than the water temperature the water is cooled down. The difference in humidity will lead to evaporation of water.

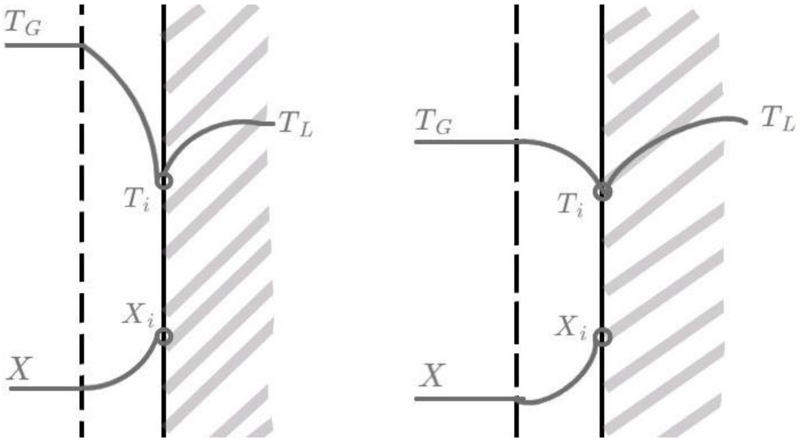

Figure 6. Two examples of possible temperature and humidity gradient profiles in the bottom of the column. Dotted area symbols the liquid phase and the blank area the gas phase.

At the top of the column the hot water meet the heated up air. An illustration of the temperature gradient is shown in Figure 7. The hot water transports heat the intercept and from the intercept heat is transported to the gas flow. The water heat up the air as well as it provides energy for the evaporation.

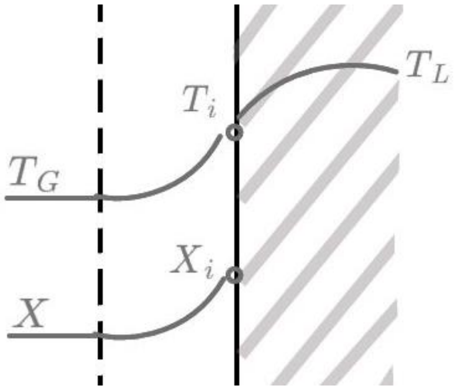

Figure 7. Possible temperature and humidity gradient at the top of the column. The dotted side represents the liquid phase and the blank side the gas phase.

2.6 COMSOL Mutiphysics

COMSOL Multiphysics is software used for model and simulate physic based problems. The graphical user interface, GUI, allow the user to navigate through many premade physical models as well as mathematical models and the simulations can be performed in 1D, 2D or 3D. COMSOL written in the programming language Java, but because of the user interface no knowledge of Java is needed. [5]

2.6.1 COMSOL 5.0 with MATLAB

The created COMSOL model can be accessed in MATLAB through *LiveLink for MATLAB*. This interfacing tool givers the program a way to communicate with each other and therefore gives the advantage access both of the programs strengths. [6], [7]

3 Existing Cooling Tower

3.1 Experimental setup

The setup used for the experiment is seen in Figure 8. A schematic sketch over the setup is presented in Figure 9. The fan is blowing air into a pipe that travels to a container and from the container the air travels into the bottom of the column. The air is pump upwards in the column and exit in the top. The water is sprinkled thru a shower head onto the top of the column and flows down on the columns packing and exit at the bottom. The inlet temperature of the water is measured in the pipe shortly before the sprinkler system and the exit temperature in measured at the beam of water leaving the column. Some of the water may exit in the opening that function as the air inlet, that water ends up in the container before the pump and can be removed from the system by opening a tap.

Figure 8. Picture of the experimental setup used.

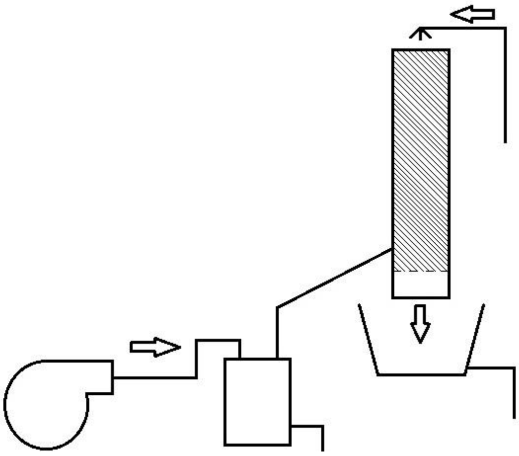

Figure 9. Schematic sketch over the experimental setup.

The packing used in the experimental setup is shown in Figure 10 and is made from a plastic pipes cut into smaller pieces.

Figure 10. Packing material used in the experiments.

3.2 Material

The materials used during the experiments are presented below and for more specific information, see appendix.

- Cooling tower setup
- Packing
- Water
- Stopwatch
- Thermometer
- HUMICAP Humidity meter, Vaisala

4 Method and Mathematical Theory

A literature study was performed in order to collect information for the experiment and the model. The experiments were made on the Cooling Tower setup and the method for the experiments is shown below. The model is constructed using COMSOL Multiphysics. The parameters used to fit the model to the experiments are estimated using *LiveLink, COMSOL 5.0 with MATLAB*. With the fitted parameters a simulation of the process is made in COMSOL Multiphysics.

4.1 Experimental method

The water source used for the experiment was tap water. The pipe leading to the shower head was attached to the faucet and the water was turned on. The tap at the container between the column and the fan was opened to avoid water reaching the fan. The fan is turned on. The attached thermometers are checked so they are turned on.

The flowrate is determined by measuring the time it takes to fill up a liter of water. The water is taken from the top of the column, after it leaves the shower head. After waiting until the temperatures are stable, steady state is obtained, the temperatures are noted. The humidity is measured by MASKIN at a sample of the different rates, focusing on the lower flow rates, to ensure that the relative humidity of the outlet air is 100 %.

The water volume inside the column at different flow rates is measured. The measurements is done by first letting the water flow in a chosen and measured flow rate and then turn the water of and at the same time collecting the water that remains in the column thru the water exit. The collected water volume is then measured.

4.2 Assumption

The model has been constructed under the assumptions listed below. Simplifications have been made and the model therefore differs from theory in aspect of:

- Interceptions temperature is calculated as the airs wet bulb temperature.
- The interception has a relative humidity of 100 %.
- Heat exchange between the water and air bulk. It is not taken into account that the interception has another temperature.
- The evaporation energy needed is provided from the water.
- The liquid has a perfect distribution on the packing material.
- Heat exchange thru the column walls to the surrounding air is neglected.

4.3 COMSOL Multiphysics model

4.3.1 Geometry

The simulation is performed at 1D and the column is simulated as an interval. The interval stretches from 0 to H_C. Boundary 1 is created at 0 and boundary 2 at H_C and a schematic picture is shown in Figure 11. Only the column is simulated in this model and it does not considerate the phenomenon that occurs at the edges of the tub.

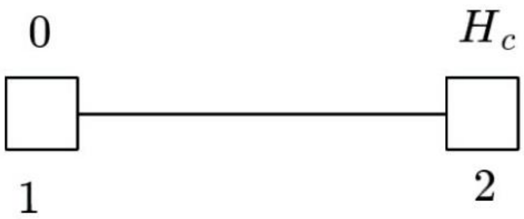

Figure 11. The interval used in COMSOL Multiphysics to describe the column. The bottom is located at boundary 1 and the top at boundary 2.

4.3.2 Gas temperature equation

The air temperature throughout the column is simulated by a Coefficient Form PDE by Equations 9. The temperature gradient used as a driving force is the temperature difference between the liquid and gas. The gas inlet is at boundary 1 and exit at boundary 2.

$$d_a \frac{\partial T_G}{\partial t} - c \frac{\partial^2 T_G}{\partial z^2} + \beta \frac{\partial T_G}{\partial z} = f \tag{9}$$

The general parameters in Equation 9 correspond to the specific parameters shown in Table 1. Parameter c is added to provide an easier system for COMSOL to solve.

Table 1. Parameters used to describe the gas temperature in the column.

General Parameter	**Specific Parameter**
$\mathbf{d_a}$	$C_{Pg}\rho_G$
c	$0.5 \cdot C_{Pg}\rho_G$
β	$C_{Pg}G/A_G$
f	$\frac{D \cdot \partial z}{A_G \cdot \partial z} \cdot h_g \cdot (T_L - T_G)$

Boundary conditions

Dirichlet Boundary Condition is used at boundary 1 where T_G is equal to T_{air}. At boundary 2 a Zero Flux is applied where $-n \cdot \left(-c\frac{\partial T_G}{\partial z} - \alpha T_G + \gamma\right) = 0$. The flow of air is described by the β-term and that will have the same value as it had before as it exits.

Initial Values

The initial temperature of the air in the column is the same as the surrounding ture, T_{air}.

4.3.3 Liquid temperature equation

The water temperature inside the column is simulated by a Coefficient Form PDE shown below in Equation 10. The cooling of water depends on the evaporation of water and the driving force is the difference between the interceptions humidity and the airs humidity. The water inlet is at boundary 2 and exit at boundary 1.

$$d_a \frac{\partial T_L}{\partial t} - c \frac{\partial^2 T_L}{\partial z^2} + \beta \frac{\partial T_L}{\partial z} = f \tag{10}$$

The general parameters in Equation 10 correspond to the specific parameters shown in Table 2. Parameter c is added to provide an easier system for COMSOL to solve.

Table 2. Parameters used to describe the gas temperature in the column.

General Parameter	**Specific Parameter**
$\mathbf{d_a}$	$C_{Pl}\rho_L$
c	$0.5 \cdot C_{Pl}\rho_L$
β	$-C_{Pl}L/A_L$
f	$-\Delta H_{vap} \cdot \frac{D \cdot \partial z}{A_L \cdot \partial z} \cdot \frac{h_g}{C_{Pg}} \cdot (X_i - X)$

Boundary conditions

Dirichlet Boundary Condition is used at boundary 1 where T_L is equal to T_{water}. At boundary 2 a Zero Flux is applied where $-n \cdot \left(-c\frac{\partial T_L}{\partial z} - \alpha T_L + \gamma\right) = 0$. The flow of air is described by the β-term and that will have the same value as it had before as it exits.

Initial values

The initial temperature of the water in the column is the same as the entering water temperature, T_{water}.

4.3.4 Gas humidity equation

The humidity changes in the column are simulated by a Coefficient Form PDE by Equation 11. The change in humidity depends on the humidity difference between the interception and the air which works as the driving force. The humidity is a property of the air and therefore enters and exit at the same boundaries.

$$d_a\frac{\partial X}{\partial t} - c\frac{\partial^2 X}{\partial z^2} + \beta\frac{\partial X}{\partial z} = f \qquad (11)$$

The general parameters in Equation 11 correspond to the specific parameters shown in Table 3. Parameter c is added to provide an easier system for COMSOL to solve.

Table 3.Parameters used to describe the humidity in the column.

General Parameter	**Specific Parameter**
$\mathbf{d_a}$	ρ_G
c	$0.5 \cdot \rho_G$
β	G/A_G
f	$\frac{D \cdot \partial z}{A_G \cdot \partial z} \cdot \frac{h_g}{C_{Pg}} \cdot (X_i - X)$

Boundary conditions

Dirichlet Boundary Condition is used at boundary 1 where X is equal to X_{air}. At boundary 2 a Zero Flux is applied where $-n \cdot \left(-c\frac{\partial X}{\partial z} - \alpha X + \gamma\right) = 0$. The humidity flow is described by the β-term and that will have the same value as it had before as it exits.

Initial values

The initial humidity in the column is the same as the surrounding airs humidity, X_{air}.

4.3.5 Interception humidity

To calculate the interceptions humidity a Domain ODEs and DAEs is used. It is assumed that the temperature at the intercept is the same as the wet bulb temperature, $T_i = T_W$, and the humidity at the interception is corresponding to 100 % humidity at that temperature. The equation used to find the humidity, X, is shown in Equation 12.

$$0 = T_{i_1}(X_i) - T_{i_2}(X_i) \tag{12}$$

The intercept of the two equations is the coordinate where the humidity is found. The first equation follows the saturated line, 100 % humidity, and is calculated using a rewriting of Antoine equation shown in Equation 13.

$$T_{i_1} = \frac{B}{A - \log_{10} p_{H_2O}} - C \tag{13}$$

Where

$$p_{H_2O} = \frac{X_i \cdot \left(\frac{M_{air}}{M_{H_2O}}\right) \cdot P}{1 + X_i \cdot \left(\frac{M_{air}}{M_{H_2O}}\right)} \tag{14}$$

The other expression follows the adiabatic saturation line and is presented in Equation 15. The slope, k, is calculated from Mollier diagram.

$$T_{i_2} = k_w \cdot X_i - k_w \cdot X + T_G \tag{15}$$

4.3.6 Variables

The mass transfer constant varies inside the column due to the variation of the gas temperature. The equation used to estimation the mass transfer coefficient is called Onda´s method and are presented in Equation 16.

$$k_G = a \cdot \frac{D_v}{RT} \cdot K_5 \left(\frac{G^*}{a\mu_G}\right)^{0.7} \left(\frac{\mu_G}{\rho_G D_G}\right)^{\frac{1}{3}} \left(ad_p\right)^{-2} \tag{16}$$

When the mass transfer coefficient change the heat transfer coefficient change through Lewis equation seen in Equation 17. The term n_{hg} is added to adjust h_g and be able to fit the model to the data. This parameter is estimated to get a good fit.

$$h_g = (C_{P_G} + XC_{P_{H_2O}}) \cdot M_{air} \cdot k_g \cdot n_{hg} \tag{17}$$

4.3.7 Parameters used

Chosen values

The parameters used and theirs value are presented in Table 4.

Table 4. Parameters used in the calculations. M stands for measured value, C for calculated value, E for estimated value.

Denotation	Value	Description	Reference
A	8.07131	Antoine equation constant, water 1-100 ℃	
A_c	0.0068 m^2	Area of the column	*C*
a	374 m^2/m^3	Surface area	[4] *E*
B	1 730.63	Antoine equation constant, water 1-100 ℃	
C	233.426	Antoine equation constant, water 1-100 ℃	
C_{P_G}	1 kJ/(kg°C)	Heat capacity at constant pressure for air	[8]
C_{P_L}	4.175 kJ/(kg°C)	Heat capacity at constant pressure for water	[8]
$C_{P_{H_2O}}$	1.86 kJ/(kg°C)	Heat capacity at constant pressure for water vapor	[8]
D_c	0.093 m	Diameter of the column	*M*
d_p	15.5 mm	Packing size	[4] *E*
G_{max}	0.119 kg/s	Maximum gas flow	[9]
g	9.81 m/s^2	Standard gravity value	[4]
H_c	0.73 m	Height of the column	*M*
ΔH_{vap}	2406 kJ/kg	Evaporation energy at 40°C	[8]
K_5	5.23	Constant	[4]
k	-2453.2 K·kg$_{air}$/kg$_{H2O}$	Slope of the adiabatic saturation line	[8] *C*
M_{air}	28. 964 g/mol	Molar mass of water	
M_{H_2O}	18.015 g/mol	Molar mass of water	
P	760 mmHg	Atmospheric pressure	
p			
R	8.3145 J/(mol·K)	Gas constant	
T_{air}1	25°C	Temperature of the surrounding air	*M*
T_{water}	52.8°C	Temperature of the incoming water	*M*
V_c	0.0050 m^3	Volume of the column	*C*
V_{P1}	2.2·10^{-6} m^3	Volume of one piece of the packing material	*C*
X_{air}	0.0055 kg$_{water}$/kg$_{air}$	Humidity in the surrounding air	*C*
μ_G	19.1 ·10^{-6} Pa·s	Dynamic viscosity of air, 40°C	[8]
μ_L	1005·10^{-6} Ns/m^2	Dynamic viscosity of water, 20℃	[8]
ρ_G	1.19 kg/m^3	Density of air, 20℃	[8]
ρ_L	998.2 kg/m^3	Density of water, 20℃	[8]
ρ_P	1.2728 10^{-5} pc/ m^3	Density of the packing material	*M*
σ_C	30 mN/m	Surface tension for the plastic packing material	[4]
σ_L	70 mN/m	Surface tension of water, 20℃	[4]

Estimated areas

The wet area is constant throughout the column for a given flow rate. It is calculated by using Ondas method.

$$a_w = a \cdot (1 - \exp\left(-1.45 \cdot \left(\frac{\sigma_C}{\sigma_L}\right)^{0.75} \cdot \left(\frac{L^*}{a\mu_L}\right)^{0.1} \cdot \left(\frac{L^{*2}a}{\rho_L^2 g}\right)^{-0.05} \cdot \left(\frac{L^{*2}}{\rho_L \sigma_L a}\right)^{0.2}\right)) \tag{18}$$

Where L^* is the liquid flow per cross-section area, calculated as $L^* = L/(A_c \cdot p)$. The total area is calculated, $a_{tot} = a_w \cdot V_c \cdot n_a$. The term n_a is added to adjust a_{tot} and be able to fit the model to the data. The "diameter" of the wet area is $D = a_{tot}/H_c$.The volume of the gas in the column is calculated from Equation 19. The liquid volume, V_L, is calculated from experimental values.

$$V_c = V_L + V_G \tag{19}$$

From the given areas the gas and liquid areas are calculated by Equation 20 and 21.

$$A_G = V_G/H_c \tag{20}$$

$$A_L = V_L/H_c \tag{21}$$

Calculated parameters

The gas flow is calculated by Equation 22. The term n_g is added to adjust G and be able to fit the model to the data points.

$$G = G_{max} \cdot n_g \tag{22}$$

The porosity of the column, p, is calculated from Equation 23.

$$p = \frac{V - \rho_P \cdot V \cdot V_{P1}}{V} \tag{23}$$

4.4 COMSOL 5.0 with MATLAB

The created COSOL model is accessed, manipulated, run and retrieved the answers through the commands in Table 5.

Table 5. Commands used in MATLAB to use the COMSOL model. The text in italic is the commands and normal text is varied to fit the purpose.

Command	**Meaning**
model= *mphload*('modelname')	Load the model into the name model
model.*param.set*('Parameter name', 'Parameter value')	Set the parameter to a new value
model.*geom*('geometric name').*run*	Run the set geometric
model.*mesh*('mesh name').*run*	Run the mesh

model.*sol*(‘solution name’).*runAll*	Run the simulation
data=*mphval*(model,’parameter name’)	Store the answers for parameter name from the model in data

When the COMSOL model is running through the MATLAB script parameters can be fitted to data using the command *lsqcurvefit*. Three parameters, n_{hg}, n_G and n_a, where investigated and estimated to fit the data points.

5 Result and Discussion

5.1 Liquid volume in the column

The volume of water inside the column varies with different flowrates and the relation was plotted in Figure 12. A linear relationship $V_L = 14.99 \cdot L_V - 18.32 \cdot 10^{-5}$ is used to determent the liquid volume in the column. The equation is put inside the parameter section in COMSOL Multiphysics.

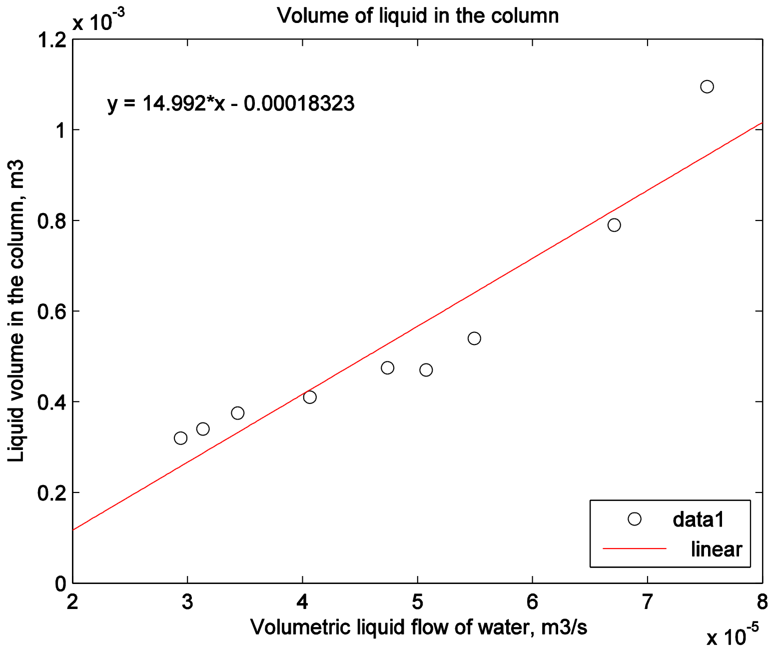

Figure 12. Liquid volume inside the column.

There is a trend showing variation in the water volume inside the column dependent in different liquid flowrate. The collected data points could be described by a cubic equation to obtain a good match, but due to the uncertainty of the experimental method this adaption is not used. The data points represent a mass flow from 0.03-0.075 kg/s, so it is uncertain what happens outside this interval. For a better approximation more data points is needed. The cubic adaption drops below the linear line after 0.015 kg/s. The linear adaption shows the behavior but more data points are necessary to determent if it is a good assumption.

5.2 Parameter Estimation

To fit the model to the data points three parameters where investigated, n_{hg}, n_G and n_a. The first term, n_{hg}, changes the heat transfer coefficient, the second, n_G, varies the gas flow and the last one, n_a, controls the wet area. The results when all three parameters where estimated are found in Table 7 as parameter set 1. Parameter set 1 gives a value of 50.5 of the squared 2-norm residual, shorten resnorm. With these parameters the gas flow exceeds the maximum flow, $n_G > 1$, which makes it unrealistic. Other combinations where investigated and are shown as parameter set 2-6 in Table 6.

Table 6. Parameter values and resnorm results after parameter estimation.

Estimation of parameter	n_{hg}	n_G	n_a	**Resnorm**	**Parameter set**
n_{hg}, n_G **and** n_a	15.15	1.54	0.76	50.5	1
n_{hg}	30.61	1	1	53.6	2
n_{hg} **and** n_a	12.21	1	2.51	53.6	3
	19.89	1	1.54	53.6	4
n_G **and** n_a	1	1.54	11.49	50.5	5
n_{hg} **and** n_G	11.46	1.54	1	50.5	6

When n_{hg} and n_a is varied different initial values results in different values but with the same resnorm. A surface plot over the relationship between n_{hg}, $n_a$and resnorm are produced and is shown in Figure 13. The optimal parameter combination is located in a valley with the resnorm of 53.6.

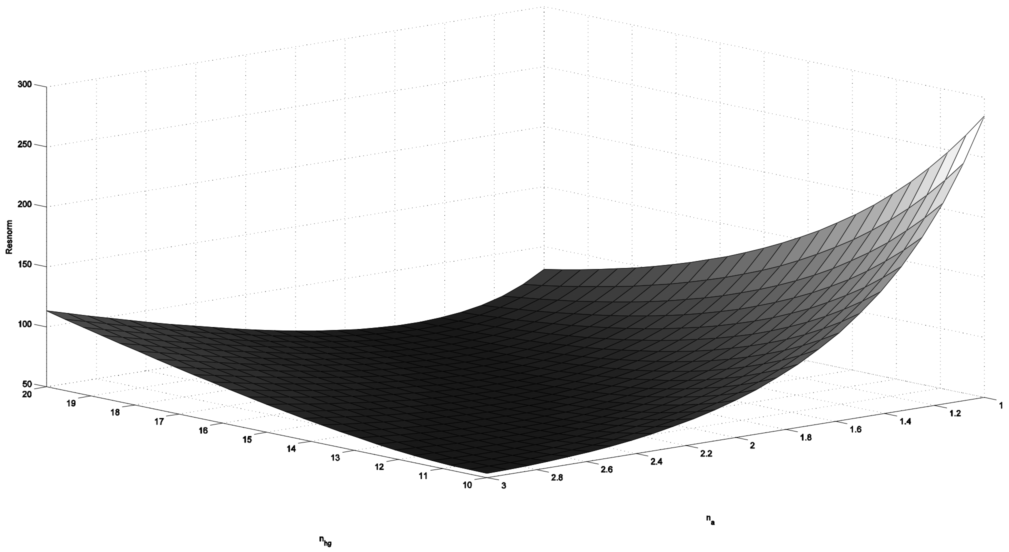

Figure 13. Surface plot over the residual, resnorm, as a function of n_{hg} *and* n_a*.*

The chosen parameter set is number 2, where n_{hg} is 30.6. Parameter set 1, 5 and 6 has a lower resnorm but parameter set 2 has a more accurate gas flow and will therefore be used.

Figure 14 shows the output liquid temperature at different liquid flowrates. The model and the data points have the same trend with lower output water temperature at low flowrates. The simulated temperatures and data are well fitted in flowrates above 0.025 kg/s but at lower flows the model has a greater slope compared to the dataset.

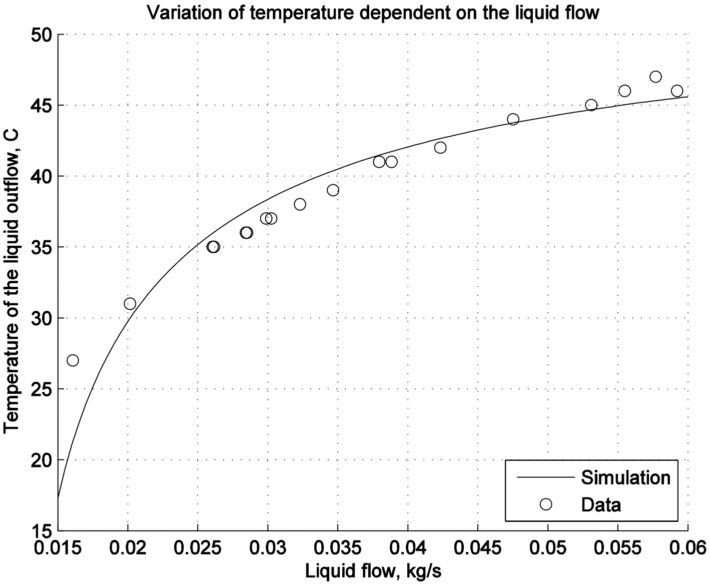

Figure 14. Simulation and data points after estimated the parameter n_{hg}. Resnorm=53.6

Figure 15 shows the heat removal per second using different flowrates. The data shows that the column has an optimal heat removal per second around a liquid flow of 0.033 kg/s. That the column is not removing heat as efficient at low flow rates could be because water is not distributed as efficiently at lower flow rates which lead to a decrease of wet area. At high flow rates is the film of water increased on the packing, which leads to that the percent of water in contact with the air in the column decrease. Because the air flow rate is not altered it is also possible that the air reach the inlet water temperature and becomes fully saturated which means it cannot take up any more water. Then it is not possible to remove any more heat. This phenomenon is not reflected in the simulation. The greater slop at lower flowrates in Figure 14 is shown as an increased heat removal per second in Figure 15. According to the model is the heat removal per second increased as the flowrate decrease.

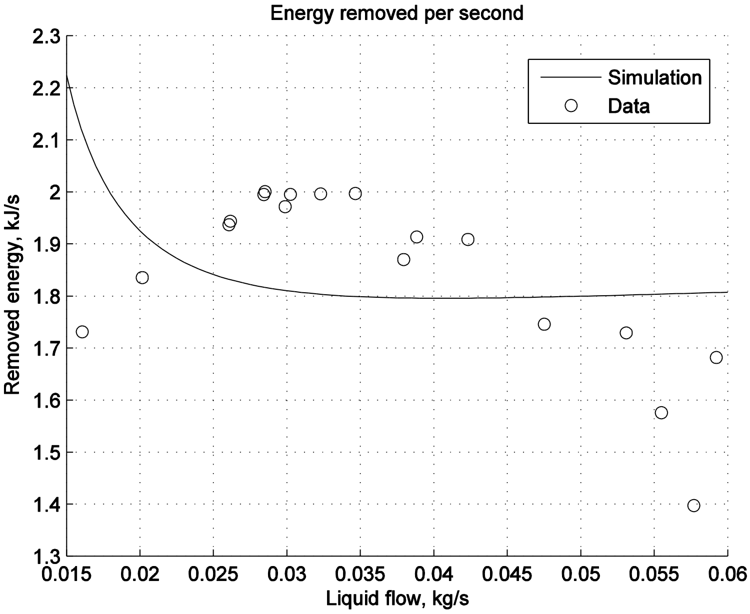

Figure 15. The columns energy removal per second dependent on the different liquid flows.

An explanation to the low liquid output temperature at flowrates below 0.025 kg/s could be that the model assumes perfect distribution of liquid. The reality could be that the liquid not sprinkled as good at the lower flowrates. The measurements where attempted to be taken with good distribution but it is possible the sprinkler system ability where gradually declined when lowering the flowrate. So when the water is not distributed correctly the wet area decline and the mass and heat transfer are lowered. To improve the model the distrusted area should grow smaller at lower flowrates or a better sprinkler system could be installed at the experimental setup.

The humidity at the interface is coupled with the temperature and the humidity of the air and represents the humidity at the wet bulb temperature. This does not represent reality. The temperature of the intercept is higher than the wet bulb temperature, which causes an increased humidity at the interception. That means that the driving force for the mass transfer increases, which lowers the mass transfer coefficient. The coupling between mass and heat transfer coefficient by Lewis relationship it also causes the heat transfer coefficient to decrease. The heat transfer coefficient, h_g, varied in the simulation between 14.5-15.7 kW/m^2°C which is 30 times greater than the estimated value. It is reasonable that the estimated value of the heat transfer constant is smaller than the used value take in consideration the actual value at the intercept. A lower interception temperature causes a smaller driving force.

5.3 COMSOL simulation

5.3.1 Stationary response

The COMSOL simulation shows behaviors inside the column. Figure 16 and 17 below shows the profile inside the column with six different water flows evenly distributed from 0.015 kg/s to 0.06 kg/s. Figure 16a shows how the waters temperature gradient in the column. The waters enters with a temperature of 52.8°C at coordinate 0.73 m and is lowered throughout the column and reaches its lowest value when it exits at 0 m. The temperature of the air throughout the column is shown in Figure 16b. The air enters at coordinate 0 m and exit at 0.73 m.

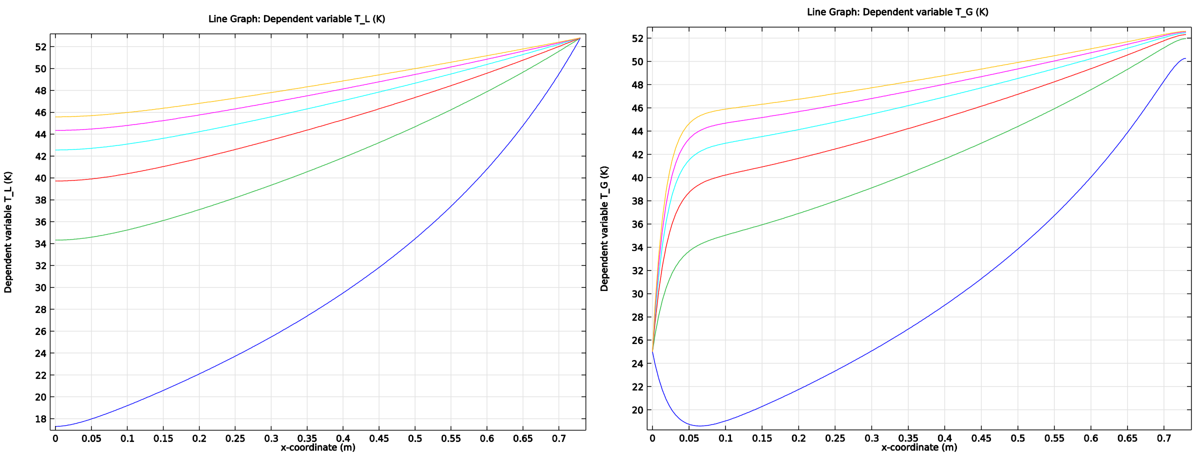

Figure 16a. Liquid temperature in the column at liquid flowrates from 0.015 kg/s to 0.06 kg/s. The lowest line represents 0.015 kg/s and the highest 0.06 kg/s. Figure 16b. Gas temperature in the column at liquid flowrates from 0.015 kg/s to 0.06 kg/s.

The temperature is changed due to heat transfer with the water. After 10 cm into the column has main heating/cooling of the air taken place and the temperature difference between the water and air is less than 1 °C. In all cases except one is the water heating the air throughout the column. At the line located closes to the bottom the water temperature has decreased under the inlet gas temperature causing heat removal from the air. The temperature profile at the interception can be expected to look like the right picture in Figure 6. The other simulated liquid flowrate always has the water as the hottest phase and will have a similar profile as the left picture at Figure 6.

Figure 17a and 17b both represent the humidity in the column, Figure 17a is the humidity in the bulk air and Figure 17b is the humidity in at the interception. Both have similar profiles, a greater slop ate the positions where the air changes a lot in temperature and then the humidity increase linear.

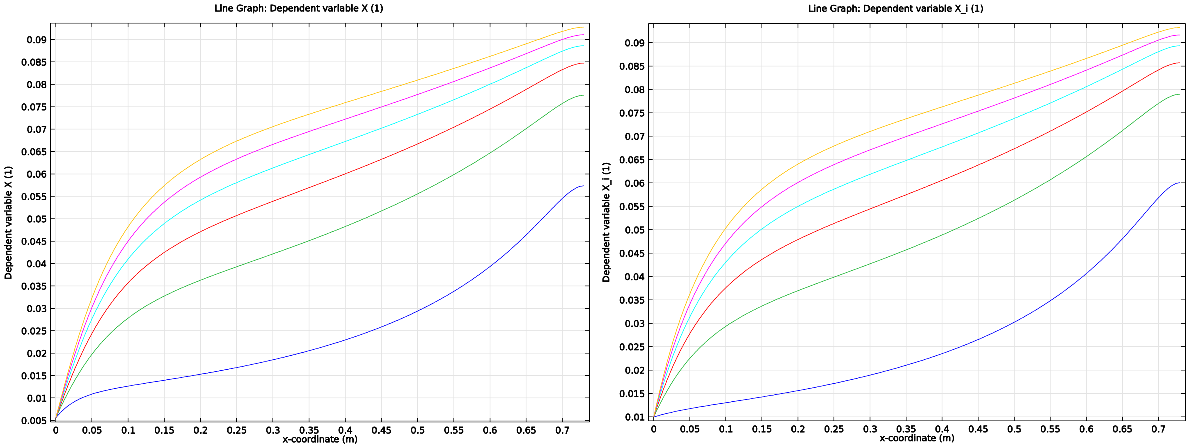

Figure 17a. Humidity of the air in the column at liquid flowrates from 0.015 kg/s to 0.06 kg/s. Figure 17b. The intercept humidity in the column at flowrates from 0.015 kg/s to 0.06 kg/s.

5.3.2 Dynamic response

A dynamic response is simulated from 0-2.5 seconds; a simulation is plotted every 0.1 seconds. Two start temperatures of the water in the column is simulated, one at a lower temperature and one at a higher temperature. The liquid flowrate is set to 0.04 kg/s.

Cold start

The dynamic response when column starts at a liquid and a gas temperature of 25°C can be seen in Figure 18. It takes less than 2 seconds to reach steady state. The temperature profiles follow each other after 10 cm into the column.

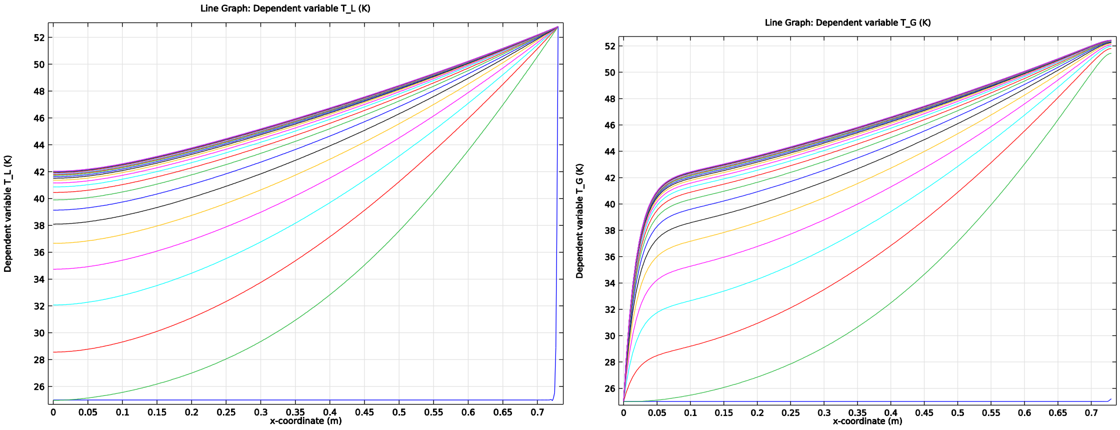

Figure 18. Liquid temperature in the column at 25 different times from 0-2.5 s. Liquid flowrate is 0.04 kg/s and the column starts at a water temperature of 25°C. Figure 18b. Gas temperature in the column at 25 different times from 0-2.5 s.

Hot start

The dynamic response when the column starts at a liquid temperature of 52.8°C and the gas at 25°C is seen in Figure 19. There is a fast heat transfer between the gas and the water which can be seen when the gas temperature increase to its highest values at the second time step. The airs temperature decrease after that before reaching steady state in less than 2 seconds.

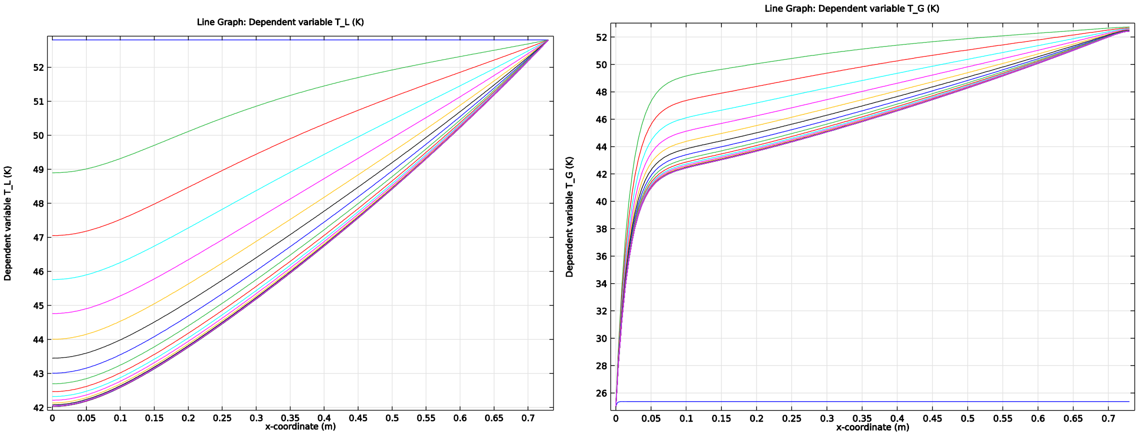

Figure 19a. Liquid temperature in the column at 25 different times from 0-2.5 s. Liquid flowrate is 0.04 kg/s and the column start with a water temperature of 52.8°C. Figure 19b. Gas temperature in the column at 25 different times from 0-2.5 s.

6 Conclusion

To fit the model to the data points the value of n_{hg} was estimated to 30.61 which leads to that the value used of the heat transport coefficient is varied between 14.5-15.7 kW/m^2°C. The model shows the same trends as the experimental values but the cooling of the water was aggressive at lower temperatures. This could be a result of uneven distribution in the experiment.

The column has an optimum for heat removal per second but it does not show in the simulation. According to the simulation is the heat removal increased by lowering the flowrate of water. That is a result of the too aggressive cooling at lower flow rates.

The interception humidity depended on the air temperature and humidity and was set to be the wet bulb temperature. It is more likely that the interception temperature where higher than the calculated value. This causes the interception humidity to increase, giving a greater driving force for the mass transfer. With a greater driving force a smaller mass, and therefore heat, transfer coefficient can be predicted. This can result that the calculated heat transfer coefficient does not need to be multiplied with the term as large as $n_{hg}$of 30.61. The estimated value then comes closer to the calculated value.

The model is created to predict the behavior at the existing cooling tower. A model over a cooling tower can be used for deciding the dimension for building a new tower or for designing a control system for an existing tower.

7 Future work

To improve the model used for this simulation it is important to investigate the interception temperature in the column. A start could be to add an arbitrarily number of degrees to the wet bulb temperature and see how the value varies.

A more complex system is to describe the heat transfer from the water to the intercept and from the intercept to the air. Then the heat transfer in the liquid h_l is added and calculated. This way both the air and the water contribute to adding energy needed for evaporation and the energy at the interception is described by Equation 24.

$$dE_{intercept} = E_{water} \pm E_{air} - E_{Evap} \tag{24}$$

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Table of abbreviations

Symbol	Unit	Description
$\boldsymbol{A}$	-	Antoine equation constant, water 1-100 ℃
$\boldsymbol{A_c}$	m^2	Area of the column
$\boldsymbol{A_G}$	m^2	Area of gas in a cross sectional area of the column
$\boldsymbol{A_L}$	m^2	Area of liquid in a cross sectional area of the column
$\boldsymbol{a}$	m^2/m^3	Surface area
$\boldsymbol{a_{tot}}$	m^2	Total wet surface area in the column
$\boldsymbol{a_w}$	m^2/m^3	Wet surface area
$\boldsymbol{B}$	-	Antoine equation constant, water 1-100 ℃
$\boldsymbol{C}$	-	Antoine equation constant, water 1-100 ℃
$\boldsymbol{C_{Pg}}$	kJ/(kg°C)	Heat capacity at constant pressure for air
$\boldsymbol{C_{Pl}}$	kJ/(kg°C)	Heat capacity at constant pressure for water
$\boldsymbol{c}$	$mole/m^3$	Concentration
$\boldsymbol{D}$	m	Diameter of the surface area in the column
$\boldsymbol{D_c}$	m	Diameter of the column
$\boldsymbol{G}$	kg/s	Gas flow, air
$\boldsymbol{G_{max}}$	kg/s	Maximum gas flow
$\boldsymbol{H_c}$	m	Height of the column
$\boldsymbol{h}$	$W/m^2{}^\circ C$	Heat transfer coefficient
$\boldsymbol{h_g}$	$W/m^2{}^\circ C$	Heat transfer coefficient on the gas side
$\boldsymbol{k}$	$mole/m^2s$	Mass transfer coefficient
$\boldsymbol{k_w}$	$K\cdot kg_{air}/kg_{H2O}$	Slope of the wet line
$\boldsymbol{L}$	kg/s	Liquid flow, water
$\boldsymbol{L^*}$	kg/sm^2	Liquid flow per cross-section area
$\boldsymbol{L_V}$	m^3/s	Volumetric liquid flow
$\boldsymbol{M_{air}}$	g/mol	Molar mass of water
$\boldsymbol{M_{H_2O}}$	g/mol	Molar mass of water
$\boldsymbol{N}$	mole/s	Mass transport
$\boldsymbol{P}$	mmHg	Pressure, atm
$\boldsymbol{p_{H_2O}}$	mmHg	Partial pressure of water
$\boldsymbol{Q}$	W	Heat transfer
$\boldsymbol{T}$	°C	Temperature
$\boldsymbol{T_{air}}$	°C	Temperature of the surrounding air
$\boldsymbol{T_G}$	°C	Temperature of the gas flow, air
$\boldsymbol{T_i}$	°C	Temperature at the interception
$\boldsymbol{T_L}$	°C	Temperature of the liquid flow, water
$\boldsymbol{T_W}$	°C	Wet bulb temperature
$\boldsymbol{T_{water}}$	°C	Temperature of the incoming water
$\boldsymbol{V_c}$	m^3	Volume of the column
$\boldsymbol{V_L}$	m^3	Liquid volume in the column
$\boldsymbol{V_G}$	m^3	Gas volume in the column
$\boldsymbol{X}$	kg_{H2O}/ kg_{air}	Humidity of the air
$\boldsymbol{X_{air}}$	kg_{H2O}/ kg_{air}	Humidity in the surrounding air
$\boldsymbol{X_i}$	kg_{H2O}/ kg_{air}	Humidity by the interception

Greek		
$\boldsymbol{\mu_L}$	Ns/m^2	Dynamic viscosity of water, 20℃
$\boldsymbol{\sigma_C}$	mN/m	Surface tension for the plastic packing material
$\boldsymbol{\sigma_L}$	mN/m	Surface tension of water, 20℃
$\boldsymbol{\rho_L}$	kg/m^3	Density of water, 20℃
$\boldsymbol{\rho_G}$	kg/m^3	Density of air, 20℃

Appendix

Detailed information about the materials used is seen in Table 6.

Table 7. Material used in the experiment.

Material	Dimension	Specifications	Capacity
Fan	-	Ventur: MPT 25S	360 m^3/h
MASKIN	-	Vaisala: HUMICAP $HMI14_A$	-
Column	Height : 0.73 m Diameter: 0.093 m	-	$4.96 \cdot 10^{-3}$ m^3
Packing	Height: $25 \cdot 10^{-3}$ m Diameter: 0.016/0.012 m	Plastic tube	-

The results from the experiment used to demonstrate the temperature difference at different flow rates is found in Table 8 and the result form the liquid volume inside the column experiment is seen in Table 9.

Table 8. Experimental result for temperature determination

Experiment number	Time to collect 1 liter water (s)	Outlet temperature of water (°C)
1	62	27
2	49	31
3	18	46
4	21	44
5	9.1	52
6	38.2	35
7	33	37
8	23.6	42

Table 9. Experimental result for volume determination.

Experiment number	Time to collect 1 liter water (s)	Water volume in the column (ml)
1	29.1	375
2	31.9	340
3	19.7	470
4	14.9	790
5	34	320
6	24.6	410
7	18.2	540
8	13.3	1095
9	21.1	475