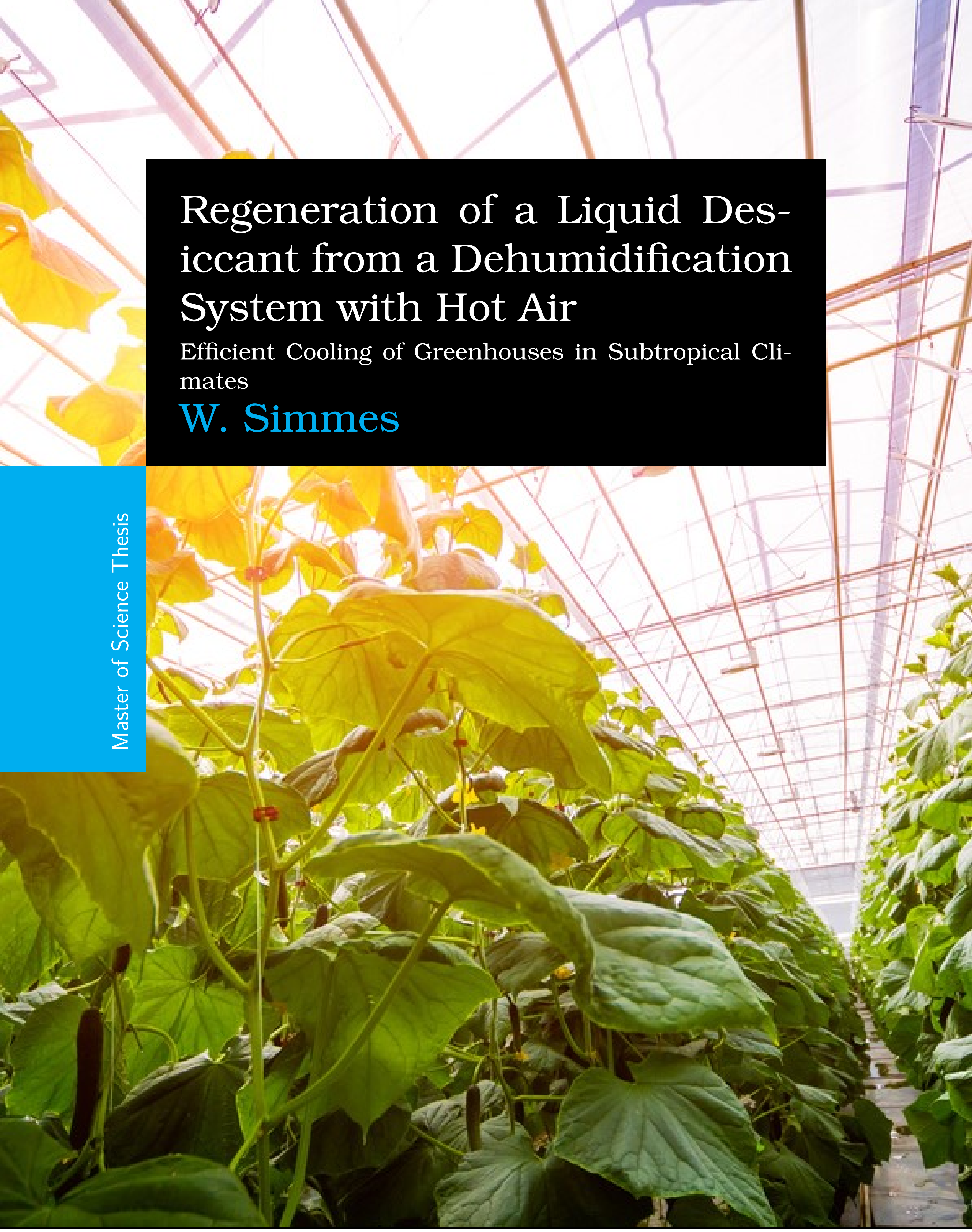
Regeneration of a Liquid Desiccant from a Dehumidification System with Hot Air

Efficient Cooling of Greenhouses in Subtropical Climates

W. Simmes

Master of Science Thesis



Delft University of Technology

VAN DER HOEVEN Horticultural projects

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For the degree of Master of Science in Process & Energy at Delft University of Technology

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The undersigned hereby certify that they have read and recommend to the Faculty of Mechanical, Maritime and Materials Engineering (3mE) for acceptance a thesis entitled

Regeneration of a Liquid Desiccant from a Dehumidification System with Hot Air

by

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in partial fulfillment of the requirements for the degree of

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Abstract

As the world population is increasing and cities grow faster than before, food scarcity becomes a bigger issue. To depend less on import and decrease CO_2 footprint, food should be produced nearby its consumers. A good solution for food production is a greenhouse which provides a steady high yield throughout the year. Some of the world's fastest growing cities are in Subtropical climates. Subtropical climates are characterized by high temperatures, abundance of sun and high humidity. Due to the high temperatures, cooling in greenhouses in subtropical climates is necessary, but evaporative cooling is not sufficient due to the high humidity. Outside air can be dehumidified by a liquid desiccant to cool the air further with an extra evaporative cooling step. After dehumidifying the air, the absorbed moisture from the air in the desiccant must be removed from the desiccant solution for re-use. This requires a lot of energy, which makes this cooling technique for greenhouses in subtropical climates not economically feasible. The proposed solution is to remove moisture from the desiccant by making use of the hot air that can be collected in the top of the greenhouse. The potential of this solution is assessed in this study. To predict the transfer of mass and heat between air and a calcium chloride solution as desiccant, a mathematical model of the process of mass and heat transfer over a structured cardboard pad is made. An experiment is conducted to validate the mass and heat transfer coefficients of the model. The model is used to evaluate the workings of the proposed system of regeneration. Results show that dehumidification can significantly lower the inlet temperature of the air in the greenhouse, provided that the inlet temperature of the desiccant is low. Regeneration of the desiccant solution with hot air is also possible, provided that the air in the greenhouse is significantly heated by the sun and pre-heating of the desiccant before regeneration is beneficial. The direct coupling of these two systems is not sufficient due to the big difference in temperature of the desiccant that is required at the inlet of the dehumidifier and regenerator. In future work attention should be paid to this temperature difference which is currently limiting the performance of the system. Then it's possible for the concentration of the desiccant to be brought back to the starting conditions for the dehumidifier.

Table of Contents

List of Figures

List of Tables

Nomenclature

Symbol	Description	Units
A	Specific surface area of the pad	$[m^2/m^3]$
α	Mass transfer coefficient	$[kg/m^2s]$
Cp	Specific heat capacity	$[kJ/kgK]$
ϵ	Effectiveness	$[\%]$
h	Enthalpy	$[kJ/kg]$
h_{fg}	Latent heat of vaporization	2450 $[kJ/kg]$
I	Irradiance	$[W/m^2]$
$\dot{m}$	Mass flow rate	$[kg/s]$
N	Number of elements	$[-]$
NTU	Number of transfer units	$[-]$
P	Pressure	$[Pa]$
Q	Energy	$[Watt]$
RH	Relative humidity	$[\%]$
ρ	Density	$[kg/m^3]$
T	Temperature	$[°C]$
τ	Transmission factor	$[\%]$
V	Volume	$[m^3]$
X	Solution concentration	$[kg/kg]$
y	Absolute humidity	$[kg/kg]$

Subscripts	Description	
a	Air	
atm	Atmosphere	
avg	Average	
d	Dilution	
eff	Effective	
eq	Equilibrium	
in	Inlet	
m	Moist air	
out	Outlet	
s	Solution	
sat	Saturated	
top	Top of the greenhouse	
vap	Vapor	

Chapter 1

Introduction

1-1 Motivation

The world population is increasing and cities are fast growing. A result of an increase in the population, is an increase in food demand which is even higher if the population is becoming wealthier over time and can afford to eat healthier and more diverse. Rapid economic and population growth are a cause for food scarcity and increases the demand on import. A few examples of regions like this are: Singapore, Oman, The United Arab Emirates and the South-East of China. Figure (1-1) and (1-2) show the increasing population and vegetable import respectively for three of these regions.What is striking in these figures is that the import of vegetables is increasing two times as fast as the increase in population, which shows that vegetable demand is fast growing.

Moving food to other regions is expensive, not only in terms of money but it also leaves a big CO_2 footprint due to transportation. Import of food to the aforementioned countries comes from all over the world and the ecological footprint of these vegetables on the environment is big, which does not fit in our modern sustainability goals. Aforementioned countries have to produce more food on their own to reduce dependence on import. Regular agriculture is sometimes not possible or very hard due to challenging climates or policy. A solution for an all-year-round production of vegetables is a greenhouse which provides a steady high yield.

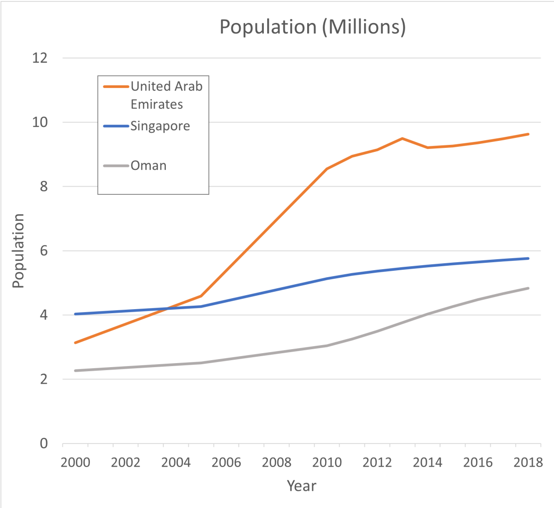


Figure 1-1: Population growth in three countries with a subtropical climate [1].

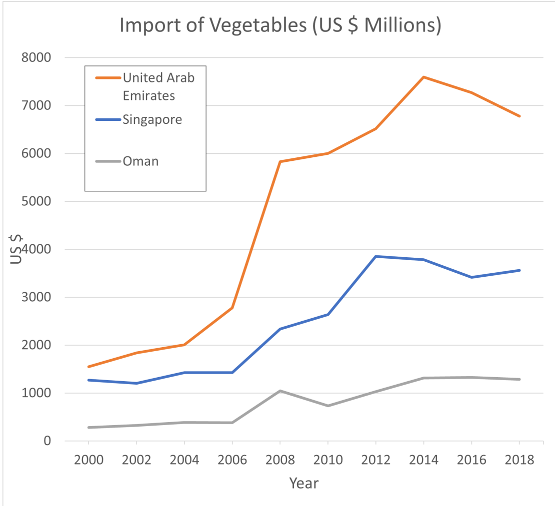


Figure 1-2: Import of vegetables in three countries with a subtropical climate [2].

The climates of the mentioned countries resemble with a subtropical climate. Subtropical climates are characterized by high temperature and high humidity throughout the year. Figure (1-3) and (1-4) show the temperature and relative humidity for the city Singapore.

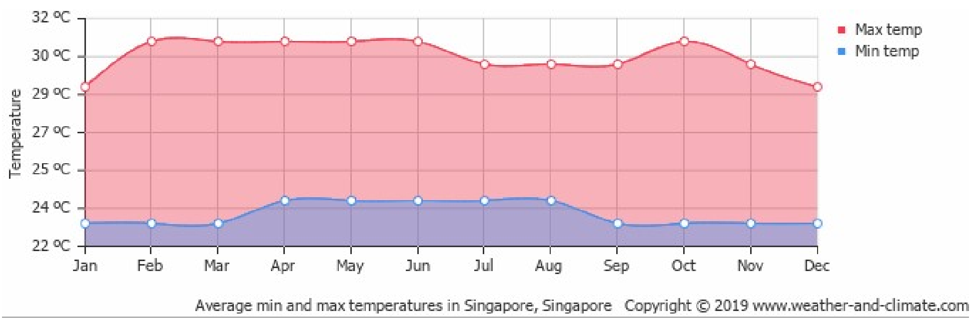


Figure 1-3: Average temperature in Singapore over one year [3].

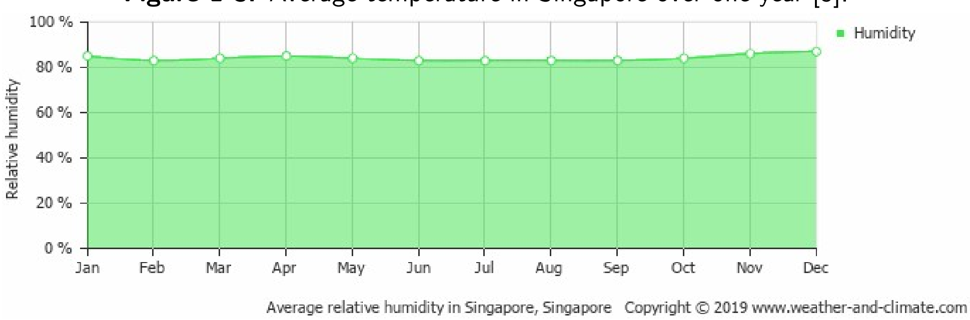


Figure 1-4: Average relative humidity in Singapore over one year [3].

The temperature reaches on average from 23°C to 31°C throughout the year. The relative humidity is on average above 80 % throughout the year. This kind of climate is not ideal for current greenhouse climate management, [13]. This forces us to look at climate management for food production in greenhouses in a different way. Greenhouses are made to provide a steady environment to grow crops. Different crops like lettuce, tomato and peppers need different temperatures, humidity's and lighting for growing. The work that is required to meet these different indoor characteristics, is different for all climates over the world. Greenhouses in subtropical climates need cooling because of the high temperatures. Innovative technology on cooling greenhouses in subtropical climates is new and immature. Regular cooling systems require a lot of energy, which does not fit the modern sustainability goals.

1-2 Van der Hoeven, Horticultural Projects B.V

This thesis is done in collaboration with Van der Hoeven Horticultural Projects B.V. Van der Hoeven provides custom made solutions for turnkey horticultural projects worldwide. Van der Hoeven is a company located in Den Hoorn in the province South-Holland of the Netherlands. Since 1953, Van der Hoeven is a world leading company on the ecological and technological progressive design of innovative and energy efficient greenhouses with over hundreds of projects completed. Van der Hoeven does not only design the greenhouse but also does the construction and helps to manage crop growth.

1-3 Evaporative Cooling

To provide a high quality, consistent and well-regulated indoor climate for crop growth, it is preferred to use a (semi)-closed greenhouse structure in which almost no direct ventilation with the outside air is provided. The CO_2 levels in the greenhouse can be maintained high, a small over pressure can be applied and a fully closed environment will eventually be more constant and therefore energy efficient. There are different possibilities for cooling greenhouses from which evaporative cooling is the most effective, [13]. This technology is already commonly used in not only greenhouses but also in consumer goods, for example home coolers. In greenhouses these systems are mostly equipped with packed pads with corrugated cardboard sheets as can be seen in figure (1-5).

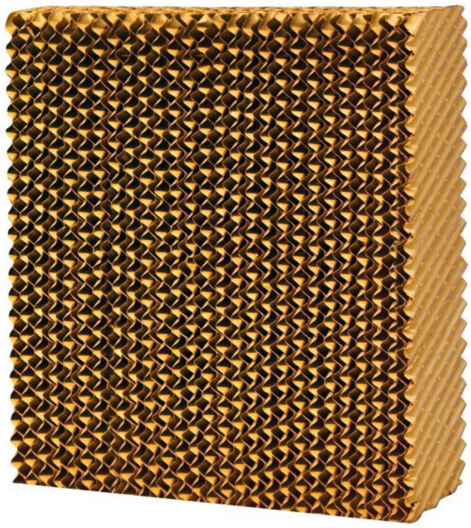


Figure 1-5: Commonly used packed pad with corrugated cardboard sheets for evaporative cooling [4].

Evaporative cooling uses the fact that water will absorb a relatively large amount of heat in order to evaporate. When warm, dry and unsaturated air is pulled through the packed pad that is soaked with water, the water evaporates from the medium to vapor in the air. Sensible heat is thereby removed from the air and is converted into latent heat of vaporization. The evaporation energy comes from the air and water which are cooled down. Evaporative cooling is only possible until saturation of moisture in the air is achieved, or in other words, a relative humidity of 100 % in the outlet air. The next chapter will go into more detail on the physics behind heat and mass transfer in a packed pad.

1-4 Dehumidification

The relative humidity in subtropical climates is on average high and evaporatice cooling is only possible if the inlet air humidity is low. If the air needs to be cooled down further after one evaporative cooling pad, which is necessary in these not only humid but also hot regions, dehumidification, or drying, of the air is necessary to add another evaporative cooling step. Dehumidification is commonly done with a hygroscopic medium. Hygroscopy is the phenomenon of attracting and holding water molecules via either absorption or adsorption from the surrounding environment. The hygroscopic medium, from now on called the desiccant, attracts water molecules and holds them until they're actively removed.

Dehumidification can be done in a likewise manner as evaporative cooling with a packed pad, but instead of pure water, a liquid desiccant is used. For re-use of this desiccant, the water molecules must be actively removed from the desiccant solution, this is called regeneration and is done with heat, and/or lowering of pressure. These methods of regeneration are energy consuming at the size of greenhouse structures. It's preferably done with residual heat from factories or energy plants nearby, but these are not always available and constricts the building of these greenhouses to a very limited number of regions. A more efficient method of regeneration is needed to make the technology of dehumidification with a liquid desiccant for further cooling of the greenhouse air more applicable and economically feasible.

1-5 Research Proposal

Greenhouses in subtropical climates are hard to cool sufficient due to high temperatures and high humidity. Dehumidification of the air with a liquid desiccant is necessary to cool down the entering greemhouse air sufficient with evaporative cooling. The current way of regenerating the desiccant in a desiccant dehumidification system, consumes high amounts of energy and is bound to certain regions. Due to the high temperatures and high irradiance in subtropical climates, the temperature, in specifically the top of the greenhouse, can rise significantly, for the calculation see Appendix [B-5]. Instead of trying to lose this heat in the greenhouse, what is currently done, it's also possible to try to locally increase the temperature in the top of the greenhouse and use this energy in the form of heat for regeneration of the liquid desiccant. An advantage of this system, besides the savings in energy use for regeneration, in this form is the simplicity of the design, which makes it favorable over current rather complex regeneration systems. The proposed system uses a packed pad that is also used in evaporative cooling and dehumidification to regenerate the desiccant. A schematic overview of the proposed system can be seen in figure (1-6).

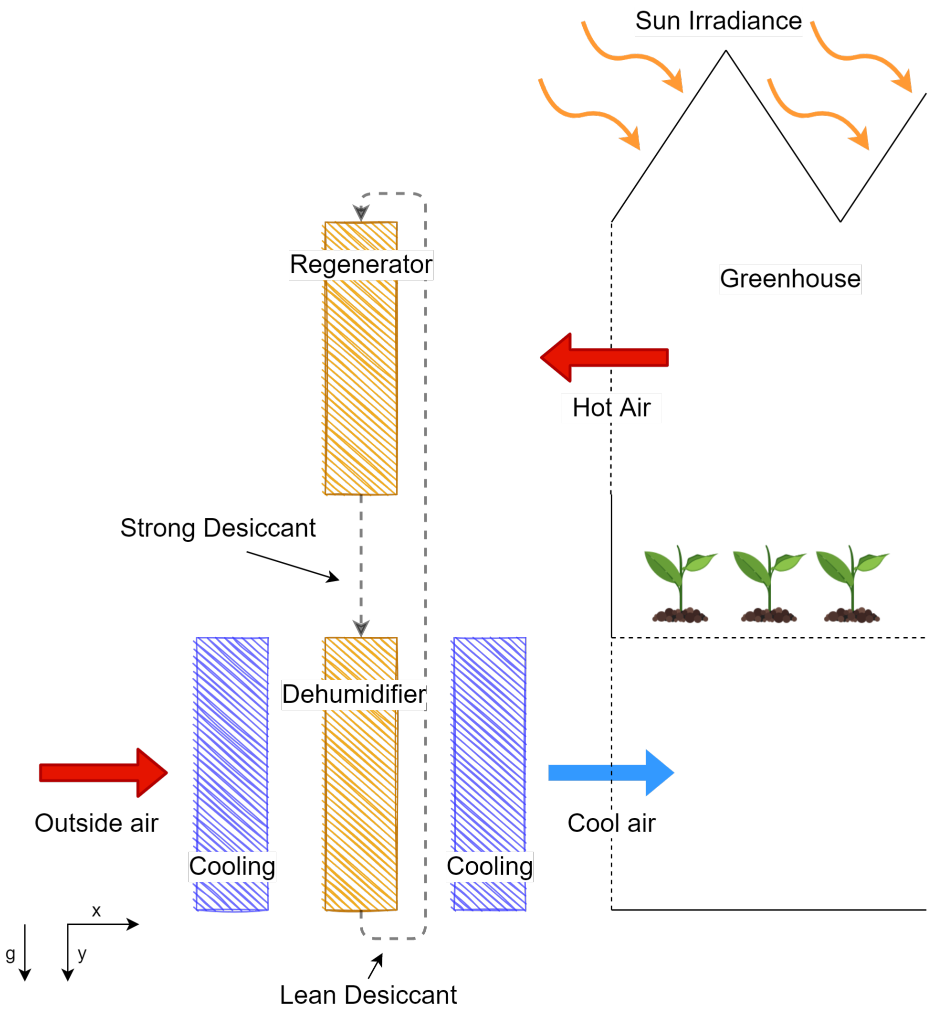


Figure 1-6: Proposed Liquid Desiccant Dehumidification System with regeneration of the desiccant by hot air from the top of the greenhouse.

The outside air is first pulled through a cooling pad before it enters the dehumidifier. The dehumidification pad lowers the humidity, so the next evaporative cooling pad can cool the air further before the air enters the greenhouse. The hot air that is collected in the top of the greenhouse can be used for regeneration. The aim of this thesis is to investigate this new method of regeneration of the liquid desiccant. By making a model that predicts the performance of heat and mass transfer in a packed pad, the total system can be evaluated. The overall research question for this thesis can be formulated as follows:

Is the proposed liquid desiccant regeneration system, that works with hot air from the top of the greenhouse, able to regenerate the liquid desiccant sufficient for re-use in dehumidification?

Chapter 2

Heat and Mass Transfer in a Packed Pad

The physics behind heat and mass transfer in a packed pad is within the field of psychrometrics. This field of engineering is concerned with the physical and thermodynamic properties of gas-vapor mixtures.

2-1 Psychrometrics

A few definitions are important for the study of gas-vapor mixtures. When addressing the temperature of any medium, the **dry bulb** temperature is meant. The dry bulb temperature is the temperature that can be read from a thermometer that has no water on it [14], [15]. The **wet bulb** temperature is the temperature that can be read from a wet thermometer and is the lowest temperature that can be reached under current ambient conditions by the evaporation of water only. **Relative humidity**, RH, gives the moisture content of air as a percentage of what it can hold when the air is saturated. Like the name suggests, it is not a measure of the absolute amount of moisture in the air; it measures the moisture contained in the air relative to the maximum value at the dry bulb temperature of this air sample. To define the absolute amount of moisture in the air, the weight of moisture is compared to the weight of the air. This is known as the **absolute humidity**, y and is given in units kg/kg.

2-1-1 Vapor Pressure

Saturated air refers to the point where the air at that temperature and pressure is saturated with moisture, which means a relative humidity of 100 %. In a two-phase closed system, this means that there are as many molecules returning to the liquid as there are escaping the liquid phase. At such a saturated state, the vapor in the air-vapor mixture, exerts a certain pressure which is called the **saturated vapor pressure**. Saturated vapor pressure, at ambient pressure, graphs for water and a 40% mass calcium chloride solution can be seen in figure (2-1), note the fast increasing saturated vapor pressure with increasing temperature [5],[7],[6].

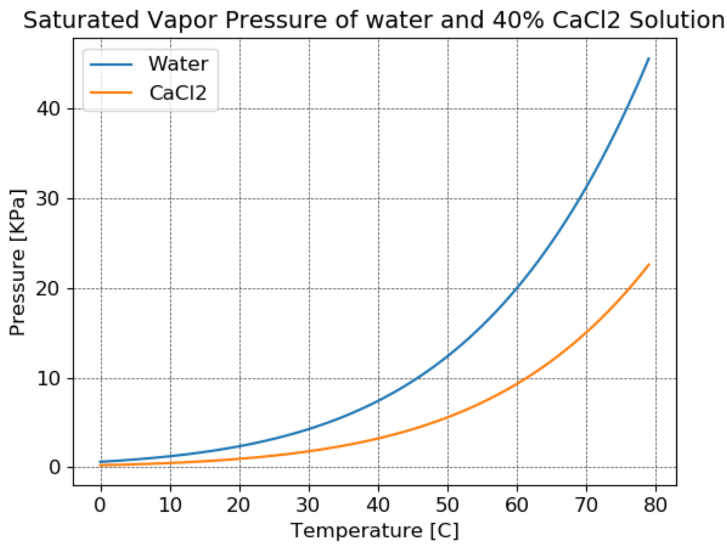


Figure 2-1: Saturated vapor pressure of water and a 40% $CaCl_2$ solution [5], [6], [7].

An approximation of the saturated vapor pressure-temperature relation can be described with a fitted Antoine equation, which is derived from the Clausius-Clapeyron equation. see Appendix [B-2], [16]. For simplicity, moist air is considered a mixture of independent perfect gasses, so every partial gas and the total mixture suffices the perfect gas equation of state. Dalton's law states that the individual components of the mixture exert a partial pressure, which contributes to the total pressures of all the partial pressures combined. The term moist air, which in fact is nearly all air around us, can be treated as a mixture of dry air and water vapor in which the dry air is treated as if it were a pure component. The partial pressure of the water vapor component is the **vapor pressure**. The vapor pressure is the partial pressure of water in a mixture. As explained earlier, relative humidity is the moisture content of air as a percentage of what it can hold when the air is saturated. If there's a relative humidity of 70 %. The vapor pressure is 70 % of the saturated vapor pressure and the absolute humidity is 70 % of what it maximal can be at that temperature. Equation (2-1) shows the pressure of water vapor in the air, $P_{vap,a}$, in Pa, by multiplying the saturated vapor pressure, P_{sat}, at the given temperature, with the relative humidity, RH, which is a percentage. ASHRAE [15] and Moran and Shapiro [16] provide more insight in the field of psychrometrics.

$$P_{a,vap} = P_{a,sat} \cdot RH \tag{2-1}$$

2-1-2 Driving Pressure

In the case of mass transfer of water, the driving force is a concentration difference; diffusion takes place in the direction of decreasing concentration. In this case the driving force is a pressure: the vapor pressure difference, see equation (2-2). This driving pressure determines the direction of the mass transfer and the extent of this transfer is limited by a thermodynamic equilibrium, [17].

$$\Delta P_{vap} = P_{a,vap} - P_{s,vap} \tag{2-2}$$

The vapor pressure of a mixture like an aqueous salt solution can be derived with Raoult's law. Raoult's law states that in an ideal mixture, the partial vapor pressure of a component is equal to the vapor pressure of the pure component multiplied by the mole fraction in the mixture. Or the vapor pressure can be found in literature with equations determined by experiments like the Antoine equation, [18]. If the vapor pressure of the air vapor mixture is higher than the vapor pressure of the solution, the driving pressure is towards the solution and condensation takes place. If the vapor pressure of the solution is higher, the vapor tends to evaporate into the air. This condensation and evaporation is the same principle as moisture transfer in a packed pad, this will be discussed further in section (2-3).

2-2 Liquid Desiccant Choice

In the introduction, dehumidification is discussed for further cooling of the inlet air in greenhouses. The Liquid Desiccant Dehumidification System, or LDDS, is the complete system that is concerned with the dehumidification of the processed air. Dehumidification in the proposed system is done with the same packed pads as shown in figure (1-5).

A hygroscopic solution, coming in from the top of the pad, has a certain vapor pressure, $P_{s,vap}$, and can exchange mass in the form of moisture with the processed air. For dehumidification, a strong driving force for mass transfer is desired from the air to the desiccant. This means a low vapor pressure of the desiccant so the moisture from the air will transfer to the desiccant. As the desiccant flows downwards along the pad, the desiccant becomes more saturated with water and its vapor pressure starts to increase and thus decrease the driving force from air to desiccant. A desiccant solution which has absorbed water and thus having a higher vapor pressure, is called a lean solution. The Mollier diagram in Appendix [A-2] shows the process of evaporative cooling, dehumidification and again evaporative cooling with the blue, orange and again a blue line respectively.

The new proposed system consists not only of a dehumidifier but must also regenerate the desiccant for re-use. After the first cooling pad, the inlet air is sucked through a dehumidification pad after which a second cooling pad will produce lower outlet temperatures. The desiccant that absorbed moisture from the processed air in dehumidification is regenerated in the top of the greenhouse with the use of hot air. For regeneration, a strong driving pressure is desired from the desiccant to the air. This means a high vapor pressure of the desiccant or/and a low vapor pressure of the air so the moisture from the desiccant transfers to the air and thus make the desiccant a strong solution again.

The desiccant that is used is an important factor on the performance of the LDDS. The performance of the system doesn't only depend on the lowest vapor pressure for the solution to ensure good dehumidification. For regeneration, a desiccant is needed with fast increasing vapor pressure with increasing temperature. Besides the performance measure, there are more factors that must be considered such as the costs of the desiccant, corrosion risks, availability and air quality. In the following subsection, different desiccant will be compared and a substantiated choice will be made for this thesis.

2-2-1 Comparing Desiccants

Multiple studies have been performed to compare desiccants and the way they influence heat and mass transfer [19],[20],[21]. Commonly used desiccants are aqueous salt solutions like $LiBr$, $CaCl_2$, $LiCl$ and aqueous solutions of organic compounds. Mujahid et al. [10] made a list of good and desired qualities of a desiccant, see table (2-1). Some more important for functioning in a greenhouse than others.

1. Large saturation absorption capacity	7. High heat transfer
2. Low regeneration temperature	8. Non-volatile
3. Low Viscosity	9. Non-corrosive
4. Odorless	10. Non-toxic
5. Non-flammable	11. Stable
6. Inexpensive	

Table 2-1: Good and desired qualities of a desiccant [10].

A previously used desiccant for dehumidification by Van der Hoeven is propylene glycol, which is an aqueous solution of an organic compound. Propylene glycol is a strong desiccant with a low vapor pressure and is relatively cheap, [22]. Due to yet unknown reasons it's damaging the crops in the greenhouse. Until the cause is found, propylene glycol is ruled out for desiccant use in greenhouses. The use of a hygroscopic salt solution or a glycol solution has important effects on the characteristics of the liquid desiccant system. Glycols work well as desiccants and are less corrosive than hygroscopic salt solutions. However, glycols have a relative high vapor pressure compared to salts and might evaporate and thereby be contaminating both process and regeneration air streams, whereas hygroscopic salts have essentially zero vapor pressure and therefore almost cannot evaporate into the air streams. Evaporation losses are undesired because this means contamination in the air stream of the controlled climate of the greenhouse. Therefore hygroscopic salt solutions dominate liquid desiccants commercial applications, [23]. Table (2-2) shows characteristics of $CaCl_2$, $LiBr$, $LiCl$ as desiccants.

Property	Unit	Aqueous solution		
		$CaCl_2$	$LiBr$	$LiCl$
Concentration (mass solute/mass solution)	-	0.36	0.39	0.26
Hygroscopicity (equilibrium RH)	[%]	50	50	50
Cost	$[US\$/m^3]$	560	7300	4600
Density	$[kg/m^3]$	1.35	1.38	1.4
Specific heat capacity	$[kJ/kgK]$	2.6	2.6	3
Thermal conductivity	$[W/mK]$	0.56	0.48	0.56
Viscosity	$[MPa/s]$	4.6	1.8	2.5

Table 2-2: Characteristics of different desiccants [11].

A drawback for salt solutions is the corrosion risk. Greenhouse structures are mainly made of steel and aluminium which can be corrosion sensitive. In the Lans experiment done by Wageningen University in 2013, a $CaCl_2$ solution is used as desiccant on dehumidification pads and the Ca^{2+} and Cl^- ions in the air are measured after the pad. Ca^{2+} and Cl^- ions can speed up the corrosion process of iron by increasing the flow of electrons from iron to oxygen. However, there was almost no difference measured in the ion values before and after the pad, [24]. Which shows that the greenhouse structure is safe of severe corrosion risk due to use of a $CaCl_2$ solution as desiccant.

Table (2-2) shows that the price of $CaCl_2$ is significantly lower than other common used desiccants LiBr and $LiCl$. Greenhouses are often big structures and dehumidifying pad walls stretch over the entire width of the structure so large amounts of desiccant solution are needed. Therefore cheap desiccants are preferred.

Taking the factors of costs, performance, availability and crop health into account. The choice for a solution of $CaCl_2$ is made for this study. Appendix [A-1] shows a solubility diagram of $CaCl_2$. To use $CaCl_2$ as liquid desiccant, it is necessary to stay in the solution region, which means above the blue line to prevent crystallization of the salt particles and clogging in the system.

2-3 Heat and Mass Transfer Analysis

This section provides background in heat and mass transfer on a packed pad with references to literature. A pad as explained before that is used for evaporative cooling and the new proposed system, can be modelled as a control volume seen in figure (2-2). A solution comes in from the top and flows down the packed pad structure due to gravity to exit the pad at the bottom. The packed pad structure ensures a large area, A, for contact between the air and the liquid medium. The air comes in horizontally and flows, in a relative cross flow direction to the fluid, through the pad. The following symbols are used for describing the flows: T in $°C$, h in kJ/kg, $\dot{m}$ in kg/s, X as a mass fraction and y in kg/kg.

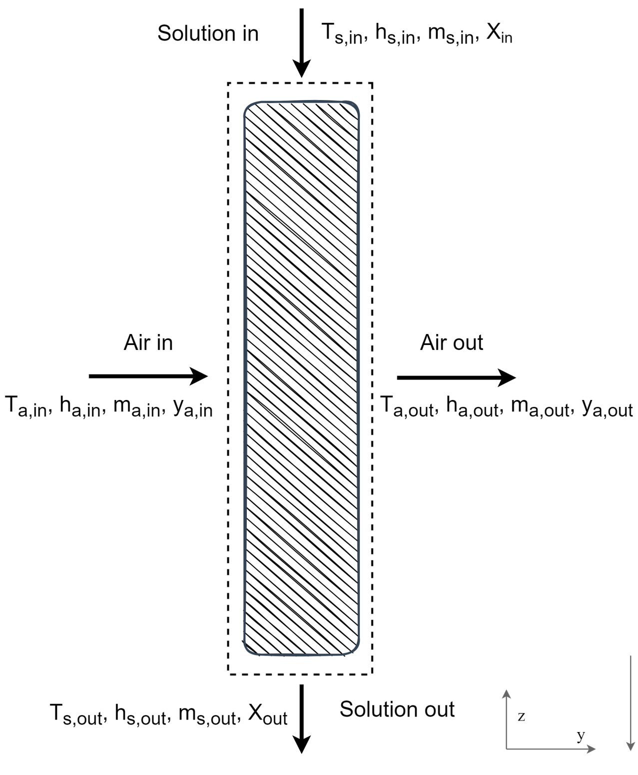


Figure 2-2: Control volume, indicated with the dotted line, of a cross flow packed pad.

2-3-1 Basic Equations across the Pad Control Volume

Over the process of evaporative cooling with a packed pad, the enthalpy of the in- and outlet air remains constant. The process of evaporative cooling can be seen as the blue lines in figure (A-2) in Appendix [A-2]. The enthalpy value of moist air can be calculated if the absolute humidity and temperature at the concerned state are known with equation (2-3), [16].

$$h_a = Cp_a \cdot T_a + y_a \cdot (h_{fg}) \tag{2-3}$$

Where Cp_a is the specific heat capacity of dry air in kJ/kgK, T_a the temperature of air in $°C$, y_a the absolute humidity of the air in kg/kg and h_{fg} the latent heat of vaporization in kJ/kg. For water to evaporate in the air, heating of the solution is needed. Latent heat of vaporization is the energy required to vaporize water and is assumed constant at 2450 kJ/kg which corresponds to a temperature of 20$°C$. However, the thermal energy required or liberated in a calcium chloride solution due to the vaporization or condensation of pure water is bigger than the latent heat of vaporization and this difference is called the differential enthalpy of dilution, Δh_d. Details on the equations for the differential enthalpy of dilution for a calcium chloride solution can be found in Appendix (B-1), [18]. The energy transferred to ($Q > 0$) or from ($Q < 0$) the system due to evaporation or condensation of moisture before and after the pad in $Watt$, is seen in equation (2-4).

$$Q = (y_{a,in} - y_{a,out}) \cdot (h_{fg} + \Delta h_d) \tag{2-4}$$

The enthalpy of the solution, h_s, coming in vertically can be described with equation (2-5), with Cp_s the specific heat capacity of the solution in kJ/kgK and T_s the temperature of the solution in $°C$. The specific heat capacity of a solution can be calculated by the fractions of the molar masses of the components times their own specific heat capacity.

$$h_s = Cp_s \cdot T_s \tag{2-5}$$

A mass and energy balance can be set up on the control volume from figure (2-2). Mass balance over the pad is given by equation (2-6) with $\dot{m}$ the mass flow in kg/s. where the outlet mass flows equal the inlet mass flows.

$$\dot{m}_{s,out} + \dot{m}_{a,out} = \dot{m}_{s,in} + \dot{m}_{a,in} \tag{2-6}$$

A complete energy balance over the pad can be formulated as equation (2-7), [7].

$$\dot{m}_{s,in}h_{s,in} + \dot{m}_{a,in}h_{a,in} = \dot{m}_{s,out}h_{s,out} + \dot{m}_{a,out}h_{a,out} \tag{2-7}$$

2-3-2 Performance Evaluation of Heat and Mass Transfer

To make a well substantiated decision whether the performance of the new system is satisfactory, the performance must be measured. This can be done from several levels, for example the total performance of the system in terms of energy use, but also on the dehumidifier or regenerator performance itself. On the level of the pads, a few common measures for the performance of heat and mass transfer are given in literature. These are the humidity effectiveness, ϵ_y in %, the temperature effectiveness, ϵ_T, in % and the moisture removal rate. The humidity effectiveness is based on change in the ratio of the humidity of the air compared to what the maximal change can be, [7],[17]. A high humidity effectiveness is desired because this means that the biggest possible change in humidity is achieved. Humidity effectiveness is given by:

$$\epsilon_y = \frac{y_{a,in} - y_{a,out}}{y_{a,in} - y_{eq}} \times 100\% \tag{2-8}$$

Where $y_{a,in}$ and $y_{a,out}$ are the absolute humidity at the air in-, outlet respectively and y_{eq} is the humidity ratio of air in equilibrium with the solution at the inter facial area and is given by equation (2-9), [16].

$$y_{eq} = \frac{0.622 \cdot P_{vap}}{P_{atm} - P_{vap}} \tag{2-9}$$

P_{vap} is the partial vapor pressure on the desiccant solution surface in Pascal and P_{atm} the atmospheric pressure also in Pa. The number 0.622 corresponds to the ratio of the molecular weight of water to that of dry air, [15]. Temperature effectiveness, ϵ_T, in %, is the ratio between the difference of the temperature of the inlet, $T_{a,in}$, and outlet, $T_{a,out}$, air flow and the difference of the inlet and equilibrium temperature, T_{eq}. The equilibrium temperature is the temperature of air in thermal equilibrium with the solution at the inter facial area [7],[17]. Temperature effectiveness is given by:

$$\epsilon_T = \frac{T_{a,in} - T_{a,out}}{T_{a,in} - T_{eq}} \times 100\% \tag{2-10}$$

If the pad concerned is a dehumidification pad, a moisture removel rate or MRR can be calculated, see equation (2-11), [7]. The moisture removal rate gives the rate at which water vapor is condensed from the air and absorbed by the desiccant in kg/s. The moisture removal rate can also be used for regeneration of the desiccant over the pad and can generally be seen as a moisture transfer rate in a certain direction. A more general coefficient is the overall mass-transfer coefficient, K, in kg/m^2s, which is defined as the moisture flux transferred from a square meter area of pad per unit time, [23].

$$MRR = \dot{m}_a \left(y_{a,in} - y_{a,out} \right) \tag{2-11}$$

The next section shows a comparison of different methods of modelling a heat and mass transfer pad as found in literature.

2-4 Mathematical Modelling of Heat and Mass Transfer in a Packed Pad

To perform research on the proposed liquid desiccant dehumidification system with hot air regeneration, it's necessary to model the performance of heat and mass transfer in the pads. The basic equations that are formulated in section (2-3) on a control volume, form the basis of the models. A mathematical model is meant to give an estimation of the output parameters if the input values are given. With the most accurate method, the best simulation can be done to estimate the performance of the new proposed liquid dehumidification and hot air regeneration system.

2-4-1 Comparison of Different Models from Literature

Previous studies have already proposed different mathematical models to predict the cross-flow heat and mass transfer on a packed pad. The mathematical models can mainly be classified into three types of models which can be seen in table (2-3) [12].

Method	Assumption	Iteration	Accuracy
Finite difference model	Least	Extensive	High
ϵ-NTU model	More	Less	Medium
Simplified model	Most	None	Low

Table 2-3: Comparison of different mathematical modelling methods of heat and mass transfer in a packed pad, [12].

The finite difference model is the most accurate of the three, but also the most computational demanding. The finite difference model is based on a finite element as can be seen in figure (2-3), which can represent element (1,1) from figure (2-4).

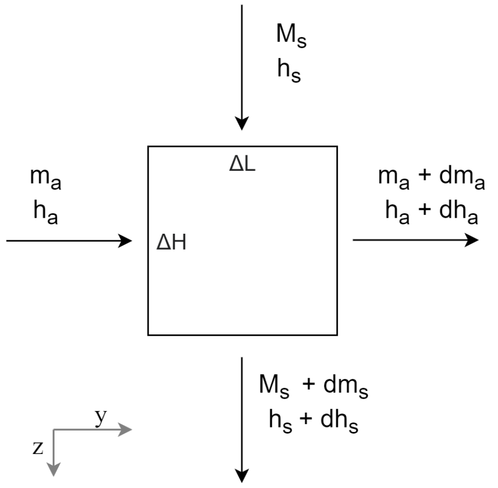


Figure 2-3: In- and outlet parameters of a control volume element [8].

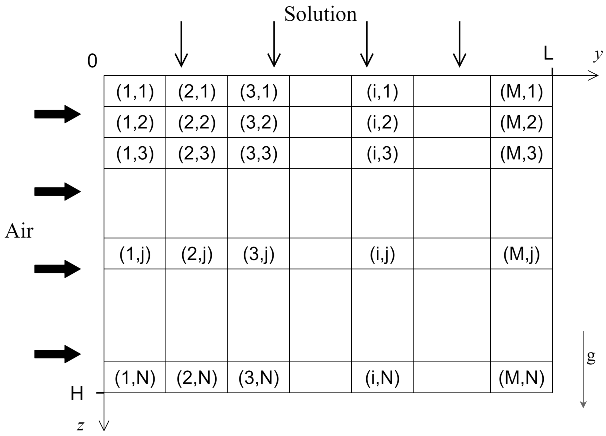


Figure 2-4: Schematic in 2D of a cross flow packed pad with (M,N) control volume elements.

This figure shows a packed pad with solution coming in from the top and air coming in horizontally and is divided in M by N elements. A packed pad can be divided in as many elements as desired. Examples of previous studies with finite difference models are Niu, Liu and Chen [8], [25], [26]. Governing equations and boundary conditions for the finite difference model can be found in Appendix [B-3].

The second method is the Effectiveness NTU method or the ϵ-NTU model. This model comes with more assumptions but needs less iteration and thus results in a lower accuracy than the finite difference models. The main equations and calculation process of the ϵ-NTU model are summarized in Appendix [B-4]. The last category of modelling are the simplified models. The finite difference model and the ϵ-NTU model both require iteration procedures and are meant for a qualitative evaluation of the heat and mass transfer performance. Simplified models are good for fast performance evaluation. Simplified empirical models have been formulated based on experimental data, but they are limited to the equipment and range of conditions for which the data was taken and therefore a lot of assumptions are made [17], [27].

2-4-2 Modelling a Heat and Mass Transfer Packed Pad

The previous section showed that modelling of a packed pad can be done in different ways. The most accurate method is a finite difference model, which needs extensive iteration, but has the least assumptions. The simplified models are the simplest but are only valid for certain experiment ranges. The model that is made in this thesis is based on a 1D finite difference model with small control volume elements that are formed by dividing the cross flow packed pad in N elements in vertical direction. A few assumptions have been made in modelling the heat and mass transfer in a packed pad, namely:

1. Mass flow of air is constant over the depth of the pad.
2. Surface of the pad is fully wetted; the area of heat and mass transfer is equal to the specific surface area of the pad.
3. There is no heat and mass transfer with the surroundings.
4. Heat and mass transfer coefficients are uniform throughout the pad.
5. There are steady state conditions over a differential element.

Table 2-4: Assumptions in modelling the heat and mass transfer pad.

The structure of the model is shown in figure (2-5).

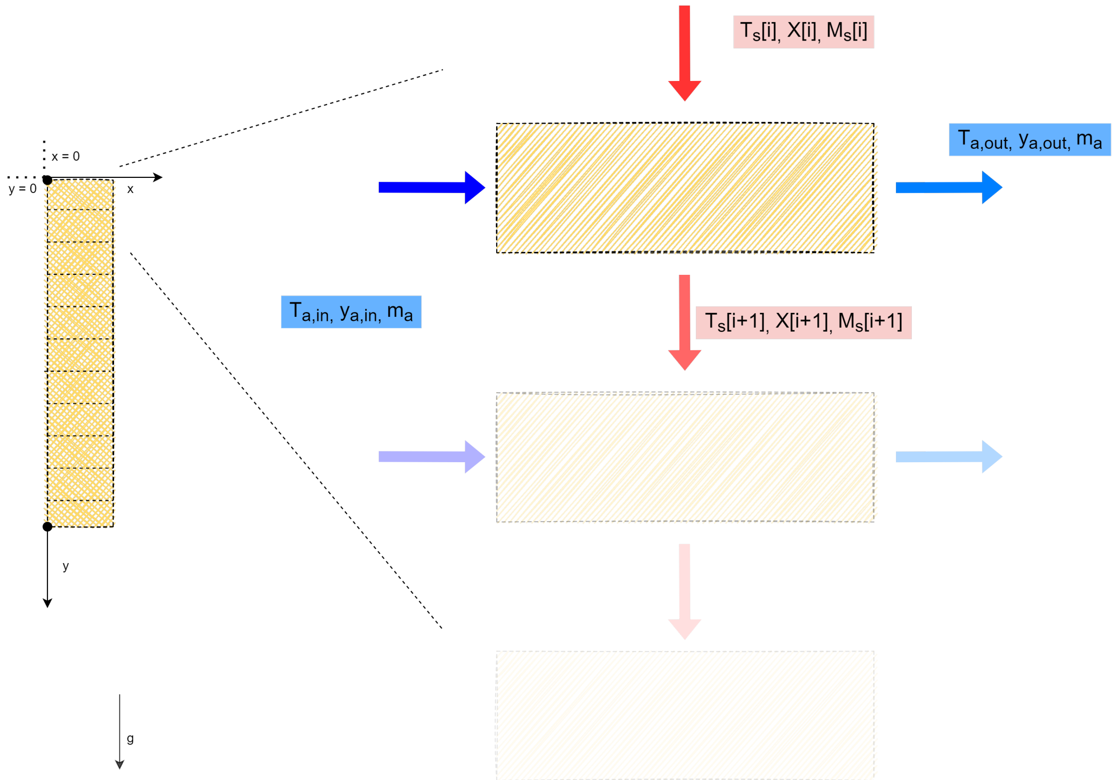


Figure 2-5: Structure of the model of the pad with a zoomed in section on how the pad is divided in multiple elements, N.

On the left, the complete pad can be seen and how it's divided in multiple smaller elements, or nodes, that are taken as separate control volumes. The right side of the figure shows these elements. Heat and mass transfer in the packed pad, and so thus our model, consists of two flows. One being the horizontal air flow.

The air flow has a constant mass flow, $\dot{m}_a$, temperature, $T_{a,in}$, and humidity, $y_{a,in}$, along the height and width of the pad. The vertical flow from top down is the desiccant flow. The whole pad can be seen as one 'node' like in figure (2-2), where the output can be predicted by the inputs. This does however not include the change in desiccant concentration, temperature and therefore vapor pressure over the height of the pad. This is why the nodes are introduced over the height of the pad, which are shown in figure (2-5).

The boundary conditions for the model are as follows:

$$T_s = T_{s,in}, \;\; X = X_{s,in}, \;\; \dot{m}_s = \dot{m}_{s,in} \;\; at \;\; y = 0 \tag{2-12}$$

$$T_a = T_{a,in}, \;\; y_a = y_{a,in}, \;\; \dot{m}_a = \dot{m}_{a,in} \;\; at \;\; x = 0 \tag{2-13}$$

A step by step description of the model of the pad will be given: The inlet conditions for the model are for the air: mass flow, $\dot{m}_a$, temperature, $T_{a,in}$, and humidity, $y_{a,in}$, which are decided by the user and will be the same at all the elements, N, along the height of the pad. For the desiccant: mass flow, $\dot{m}_s$, temperature, $T_{s,in}$, and concentration, $X_{s,in}$, which are decided by the user for only the first element. Starting point is calculating the vapor pressures for both the air and the calcium chloride solution of the first element. These vapor pressures are calculated with relations from Conde [18] for calcium chloride and for air with the Arden buck equation, [28]. The difference between these vapor pressures is the driving force for the moisture transfer between the two mediums. This driving pressure difference is a measure of the extent of the mass transfer and can be linked to the absolute humidity with equation (2-14). The outlet air humidity is given by $y_{a,out}$ in kg/kg_{dryair} and α is a mass transfer coefficient with units ms^2/kg_{dryair}.

$$y_{a,out} = y_{a,in} - \Delta P_{vap} \cdot \alpha \tag{2-14}$$

In section (2-3-1), the mass balance over the pad is explained and this can also be applied on an element in the model with the known in and outlet absolute humidity of air and the mass flow of the air and the desiccant. The difference between the outlet and inlet air absolute humidity times the mass flow of air in this element, is the amount of moisture that is transferred between the solution and the air. The new mass flow of the desiccant for the next node can be calculated with equation (2-15). where the current element is indicated by i and the next element with $i+1$.

$$\dot{m}_s[i+1] = \dot{m}_s[i] + (y_{a,in} - y_{a,out}) \cdot \frac{\dot{m}_a}{N} \tag{2-15}$$

The only mass that is transferred between the air and the desiccant is water. With the mass flow of the desiccant known on in- and outlet of the element and the inlet concentration known, the outlet concentration of the desiccant solution can be calculated with equation (2-16).

$$X[i+1] = \frac{X[i] \cdot \dot{m}_s[i]}{\dot{m}_s[i+1]} \tag{2-16}$$

The next step is concerned with the heat transfer and consists of the latent heat part due to evaporation or condensation and the transfer of heat due to the temperature difference between the two mediums. Latent heat, as already explained in chapter 2 is given by equation (2-17) and its units are in Watts. This is the latent energy that is associated with evaporation or condensation in this element.

$$Q_{latent} = (y_{a,in} - y_{a,out}) \cdot h_{fg} \tag{2-17}$$

The energy required for absorption or desorption is larger than that corresponding to the evaporation or condensation of pure water alone. This difference constitutes the energy of dilution and when referred to the unit mass of water is named the differential enthalpy of dilution, h_d, with units kJ/kg, [18]. Which for calcium chloride is around $60 - 100\ kJ/kg$ and dependent on concentration and temperature of the solution. Further details can be found in Appendix [B-1]. Total energy transferred to ($Q > 0$) or from ($Q < 0$) the system due to evaporation or condensation of moisture is given by equation (2-18) and called Q_{latent} in $Watt$.

$$Q_{latent} = (y_{a,in} - y_{a,out}) \cdot (h_{fg} + h_d) \tag{2-18}$$

The heat transfer due to the temperature difference is given by equation (2-19) and called $Q_{\Delta T}$, which is also in $Watts$. The heat transfer is dependent on the temperature difference between the inlet air temperature, $T_{a,in}$ and the inlet desiccant temperature of his particular element, $T_s[i]$. A is the total area of the packed pad in m^2/m^3, V is the volume of the pad in m^3 and $h_{transfer}$ is a heat transfer coefficient with units W/m^2K.

$$Q_{\Delta T} = (T_s[i] - T_{a,in}) \cdot A \cdot V \cdot h_{transfer} \tag{2-19}$$

The outlet temperatures of the air and desiccant for this element can be given by equation (2-20) and (2-21) respectively.

$$T_{a,out} = T_{a,in} + \frac{Q_{\Delta T}}{Cp_{a,out} \cdot \dot{m}_a} \tag{2-20}$$

$$T_{s,out} = T_{s,in} - \frac{Q_{\Delta T} + Q_{latent}}{Cp_{s,out} \cdot \dot{m}_s[i+1]} \tag{2-21}$$

With the equations above, all the unknown outlet values are known. The outlet desiccant mass flow, $\dot{m}_s$, temperature, $T_{s,out}$, and concentration, $X_{s,out}$ are the new inlet conditions of the next element. This process is done for the chosen number of elements in the pad, N, until the last outlet flow of the desiccant are the final conditions of the desiccant. Assuming that the mass flow over the height of the pad is constant and there's full mixing behind the pad, the average of the outlet air flows' temperature and humidity are the final outlet air characteristics.

2-5 Experimental Data

In all the modelling methods that are presented in section (2-4), assumptions are present for transfer coefficients for heat and mass. Experimental data can be used to provide these models with in- and outlet values to find the coefficients. Mass transfer coefficient, α, from equation (2-14) and heat transfer coefficient, $h_{transfer}$, from equation (2-19) are currently unknown and making an assumption on these coefficients reduces the accuracy of the model. An experiment must be performed to gather data on in- and outlet characteristics of the air and desiccant over a packed pad. With this data, the unknown coefficients α and $h_{transfer}$ from the model that is made in section (2-4-2) can be determined and thereby validate the model with a calcium chloride solution as desiccant. If the coefficients α and $h_{transfer}$ are known, the model can be used to predict the outlet characteristics of different inlet characteristics to investigate the performance of the proposed system of regeneration.

Chapter 3

Experimental Study

3-1 Experiment Motivation

The previous chapter showed that for the model in this thesis, heat and mass transfer coefficients are yet unknown. These coefficients are difficult to obtain with theoretical and literature analysis alone. For validation of the model that is made in the previous chapter, the values of the mass transfer coefficient, α, from equation (2-14) and heat transfer coefficient, $h_{transfer}$, from equation (2-19) have to be found. This chapter describes the experiment that is executed to provide in- and outlet values for the model to find these transfer coefficients. The results from the experiment can be matched with the predicted results from the model, so the transfer coefficients can be found. The calibrated model can predict the performance of the new proposed desiccant dehumidification regeneration system better. The experiments will also give some general insight if regeneration and dehumidification is easily achievable with calcium chloride.

3-2 Setup

Two schematics of the setup can be seen in figure (3-1) and figure (3-2) on the next page.

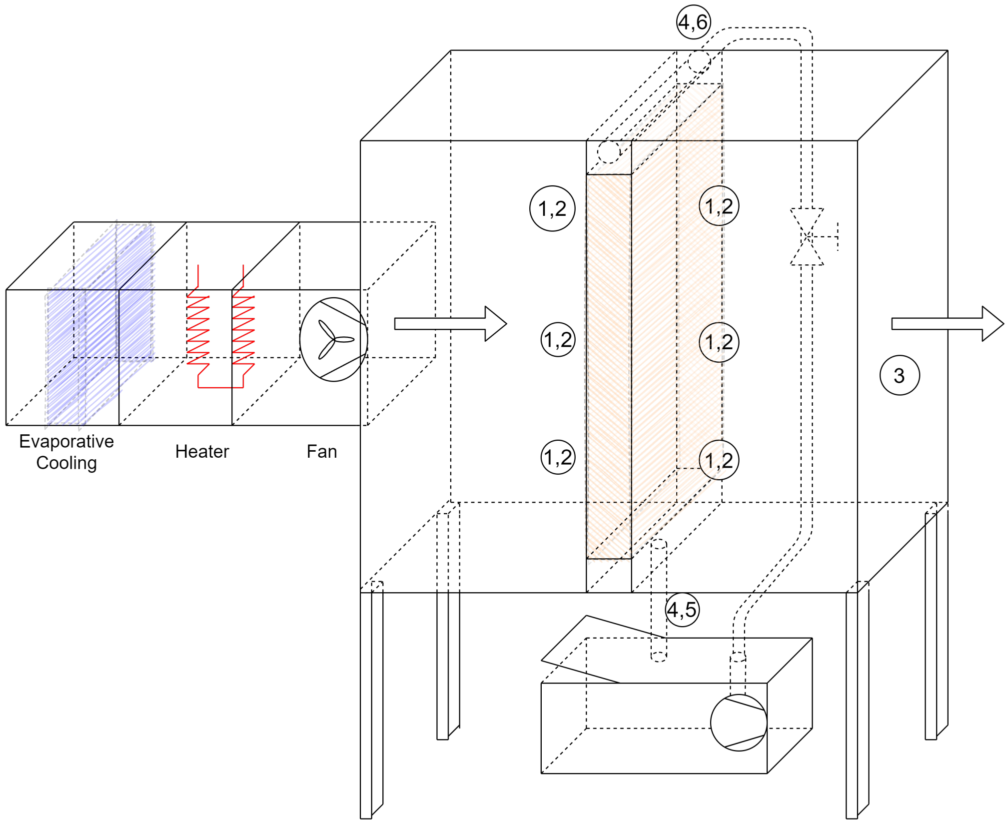


Figure 3-1: Setup drawing with on the left side the humidifier, heater and fan before to the inlet of the pad box. The packed pad is indicated with orange. The desiccant container and pump system are shown around the pad. Locations of the sensors are indicated.

The aim for the experiment is to perform dehumidification and regeneration experiments. In this way, transfer coefficients for both processes that will be used in the model can be validated more accurately. The setup is used for dehumidification and regeneration measurements depending on the conditions of inlet air and desiccant. Inlet air can be heated as desired by the heater and humidity can be added with an evaporative cooling system and thereafter is blown into our pad chamber by a fan.

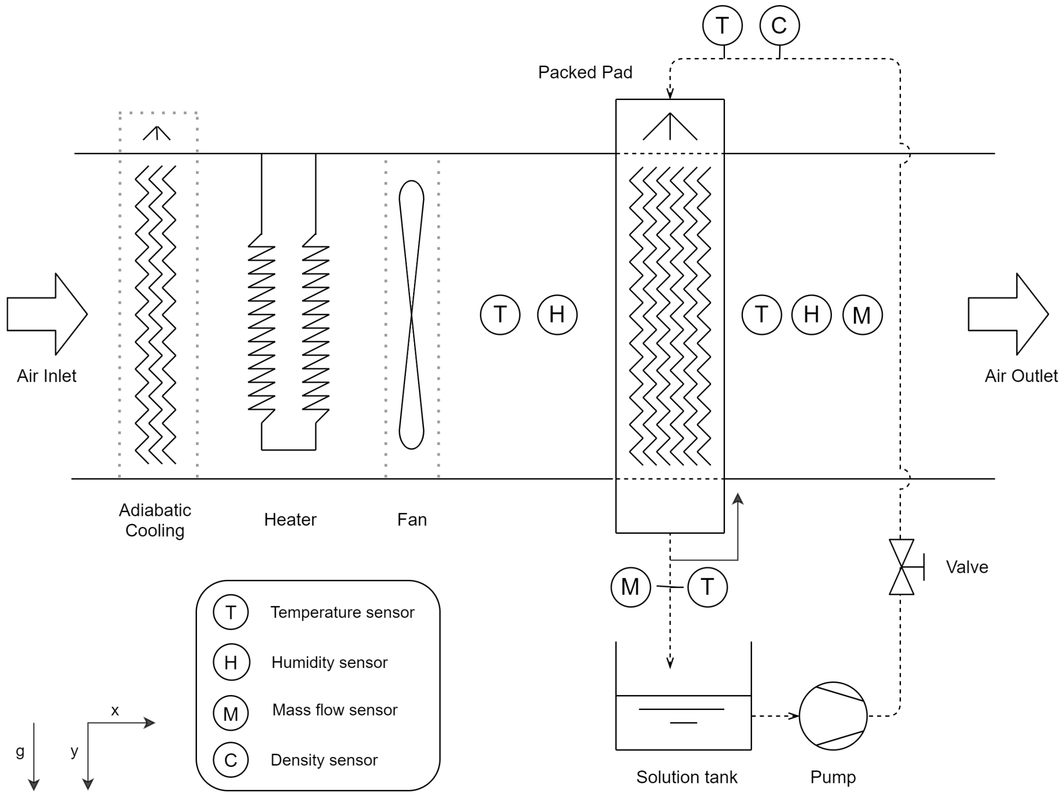


Figure 3-2: Schematic of the complete experimental setup.

3-2-1 Measuring Equipment

The measured quantities in this experiment are listed below and the locations of the sensors can be seen in figure (3-2) and (3-2):

1. Air temperature before and after the pad. (T)
2. Air humidity before and after the pad. (H)
3. Air mass flow at the air outlet of the pad. (M)
4. Desiccant temperature upon entry and exit of the pad. (T)
5. Desiccant mass flow after leaving the pad. (M)
6. Desiccant density upon entry of the pad. (C)

The air properties are measured before and after the pad by AgriSensys temperature and humidity sensors, details on the sensors can be found in table (3-1). Inside

Parameter	Device	Operational Range	Accuracy
Air Temperature	AgriSensys AS-DLTc	-40.0°C - 150.0°C	± 0.1°C
Air Humidity	AgriSensys AS-DLTc	0 - 100 %	± 1.5 %
Desiccant Temperature	Thermocouple Thermometer	0°C - 40°C	± 1.5 %
Air Mass Flow	Testo Air speed 405-V1	0 -10 m/s	± 5%
Desiccant Weight	Kern, EMS6KO 1	0.0-6000.0 gram	± 0.3 gram

Table 3-1: Specification of the different measuring devices.

the pad, the air comes in contact with the desiccant solution on the large surface of the CELdek® packed pad from Munters, which characteristics can be found in table (3-2). The desiccant is pumped from the solution tank on the bottom to the

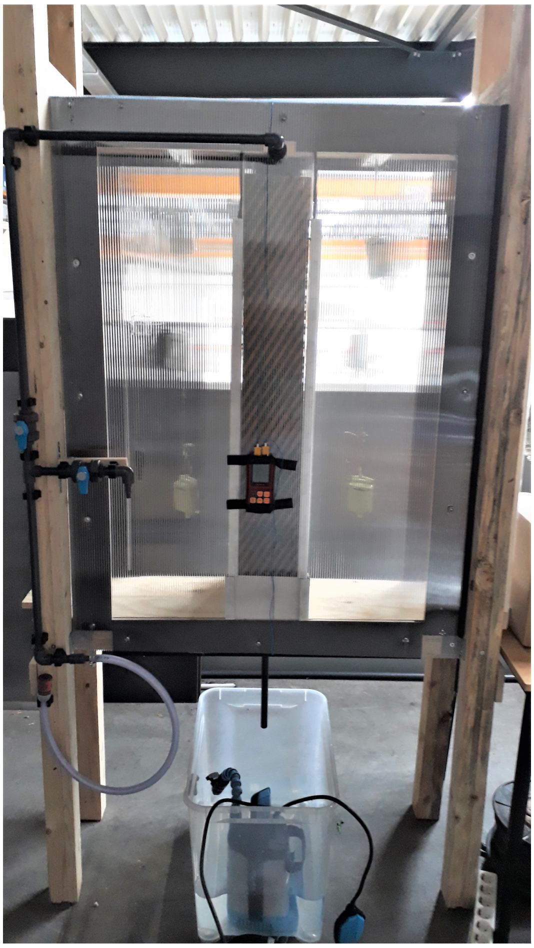
Material	Paper
Height, H (cm)	88
Width, W (cm)	24
Depth, D (cm)	15
Channel angle from horizontal, layer 1, (°)	60
Channel angle from horizontal, layer 2, (°)	30
Specific surface area of the pad, (m^2/m^3)	360

Table 3-2: Characteristics of the packed pad as used in the experiment[4].

top of the pad where it is distributed over the pad. Before entering the pad, the temperature of the desiccant is measured by a thermocouple thermometer. After running over the pad, the desiccant temperature is measured right below the outlet of the pad. from there it enters the solution tank from which it's pumped to the top of the pad again. The density of the desiccant can be measured before entering the pad with a 500 ml flask and a Kern scale. In this way it's possible the measure the complete in- and outputs of the control volume as introduced in figure (2-2). The calcium chloride used are $CaCl2$ tech prills with a 94-97 % calcium chloride concentration. Further used equipment is listed in table (3-3). Four pictures of the setup are shown in figure (3-3) on the next page.

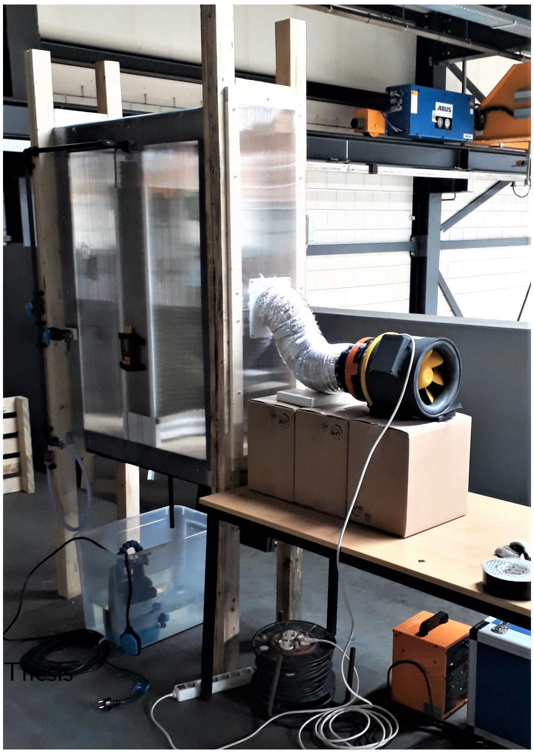
Device	Type	Operational Range
Heater	Eurom EK 2000	2000 $Watt$
Pump	FQ-RP 3.400	3400 $liter/hour$
Fan	Ruck EM 200 E2M 01	0,272 m^3/s

Table 3-3: Overview of other equipment used in the experiment.



(a) Closed box with packed pad inside.

(b) Packed pad inside the box, with open right side.



(c) Setup with inlet fan.

(d) Complete setup with fan, evaporator and heater.

Figure 3-3: Pictures of the experimental Setup

3-3 Methodology

There are different variables in the experiment that influence the effect of heat and mass transfer between the air and the calcium chloride desiccant solution. These variables are:

1. Inlet air temperature	4. Desiccant mass flow
2. Inlet air mass flow	5. Desiccant solution concentration
3. inlet air humidity	6. Desiccant temperature

Table 3-4: Variables that influence heat & mass transfer in the packed pad experiment.

In this experiment, the desiccant mass flow and the air mass flow are held constant at $\dot{m}_a = 0.127kg/s$ and $\dot{m}_s = 0.05kg/s$ respectively, in all the experiments.

Before the start of an experiment, a calcium chloride solution is made and the starting concentration is measured. The air inlet conditions are adjusted to the desired humidity and temperature by making use of the evaporation pad and a heater. For regeneration experiments, a higher air temperature is needed. For dehumidification experiments a strong desiccant and a high humidity in the inlet air is needed. The temperature of the desiccant at start of the experiment is not actively chosen at each experiment but differs due to differences in the ambient.

The inlet air is pushed in the closed box by the fan, as seen in figure (3-3a) and (3-3c). The air temperature and humidity are measured before the pad to know the inlet conditions before contact with the desiccant on the pad surface. The desiccant solution with a certain start concentration in the solution tank is pumped to the top of the pad and the temperature is measured before entering the pad on the top. On the pad's surface, transfer of heat and mass takes place between the air and the desiccant. The characteristics of the outlet air are measured right after the pad as the outlet conditions of the air. The desiccant outlet temperature is measured at the outlet of the pad. The density and thus the concentration of the desiccant upon inlet is measured just before it reaches the top of the pad. This density corresponds with the inlet density of the desiccant.

The experiment is executed like this: The desired inlet air conditions are set up with the heater and the water evaporation unit. The desiccant is added to the tank and when the pump is turned on, the experiment starts. The experiment will run for a certain amount of time and measurement points of the air humidity and temperature, desiccant temperature and desiccant concentration are taken at equal time intervals. Eventually if the experiment is run long enough, the desiccant and air will reach an equilibrium where no transfer of heat and mass is taking place anymore. The experiment is stopped by the user if decided to.

For both dehumidification and regeneration multiple experiments are done and the variable parameters that can be changed are adjusted at the start of the experiment.

3-4 Experiment Results

This section shows the resulting graphs and the observations of the experiments. The next chapter continues on finding the mass transfer coefficient, α, and heat transfer coefficient, $h_{transfer}$ for the model by making use of these results of the performance evaluation of the new proposed regeneration system.

3-4-1 Regeneration Results

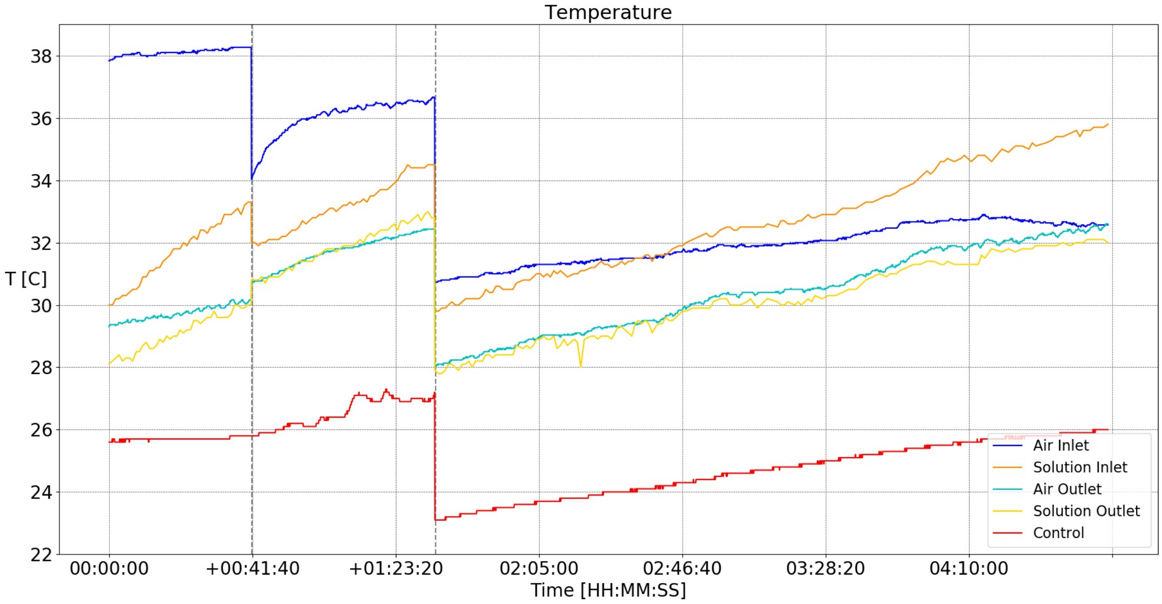
Three regeneration experiments have been conducted. A list of the complete ranges of the inlet parameters for the three regeneration experiments is presented in table (3-5). The regeneration experiments are characterized by the evaporation of moisture from the desiccant to the air and thus making the solution stronger. This can be seen in figure (3-4). Figure (3-4a) shows the temperature for three experiments added together in one plot. The two dotted vertical lines mark the beginning of new experiments, the horizontal axis shows the time in hours : minutes : seconds and the vertical axis shows the temperature. The dark blue line indicates the inlet air temperature, the sudden changes at the dotted lines correspond with the beginning of another experiment.

Variable	T_a ($°C$)	T_s ($°C$)	$y_a(kg/kg_{dryair})$	$X(\%)$
Parameter value	$30.5 - 38.0$	$29.8 - 35.8$	$0.0117 - 0.0155$	$22.9 - 40.5$

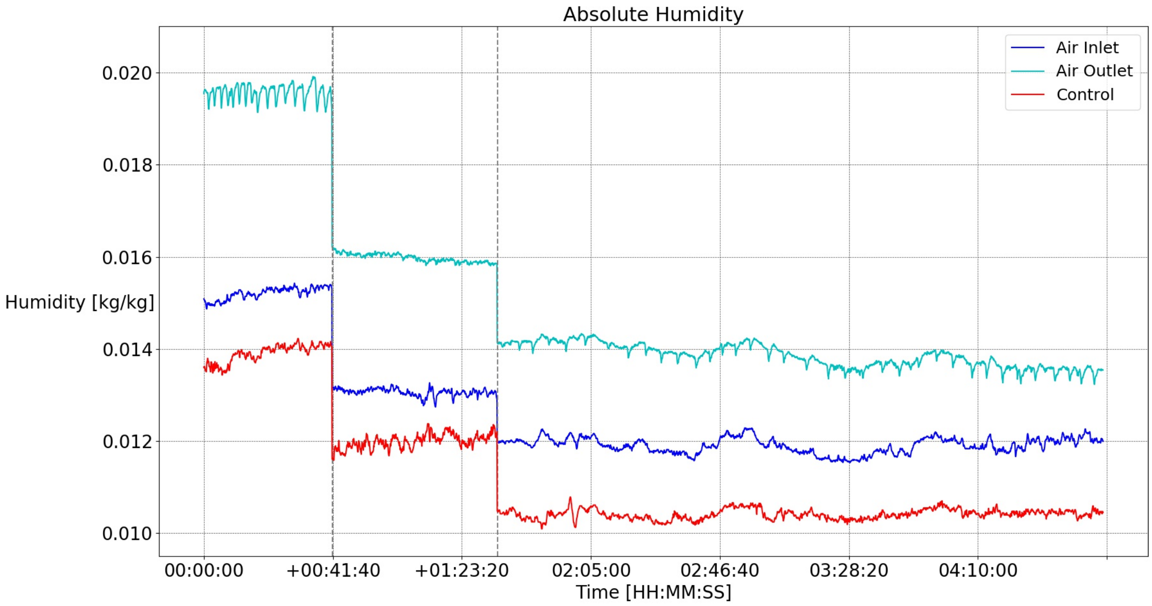
Table 3-5: Inlet ranges of air and desiccant parameters during the regeneration experiment.

3-4-2 Regeneration Observations

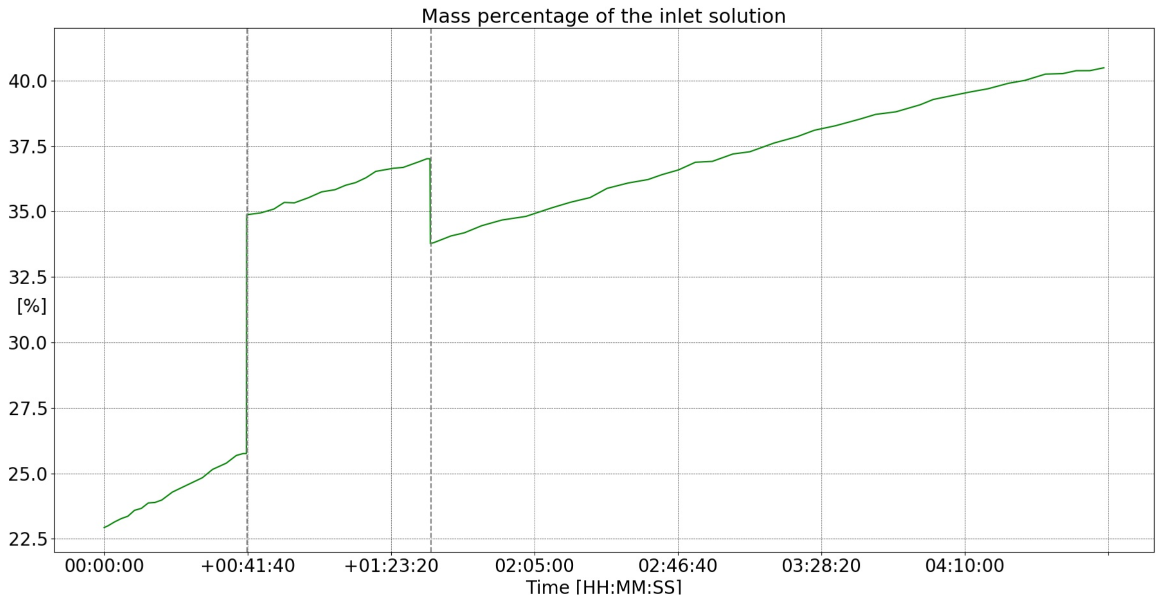
Figure (3-4a) shows the temperature development of the air and desiccant at the in- and outlet of the pad. The red line corresponds with the air temperature in the ambient. Remarkable in the temperature graph is the nearly constant difference between the desiccant inlet and outlet temperature. We can also see that the outlet air and desiccant temperatures are close. This is in line with the expectations. Figure (3-4b) shows the absolute humidity of the in- and outlet air and in red the absolute humidity in the ambient. The difference between the in- and outlet humidity corresponds with the amount of moisture transferred, this corresponds with the steepness of the slope of the concentration graph that can be seen in figure (3-4c). This graph shows the change in the mass percentage of calcium chloride in the solution. For regenerating, this means that we are removing moisture from the solution, thus the solution is getting stronger, this corresponds with what we see in the graph for all three of the experiments. In the first experiment, the moisture removal is high, shown by the big difference between the in- and outlet humidity and the steepness of the concentration line. This can be explained by the low percentage of calcium chloride and the high temperature of the entering air. As explained earlier, vapor pressure difference here is high.



(a) Air and desiccant in- and outlet temperatures in the regeneration experiments



(b) Absolute humidity of the in- and outlet air in the regeneration experiments



(c) Concentration of the desiccant solution in the regeneration experiments

Figure 3-4: Temperature, absolute humidity and concentration graphs of the regeneration experiments

3-4-3 Dehumidification Results

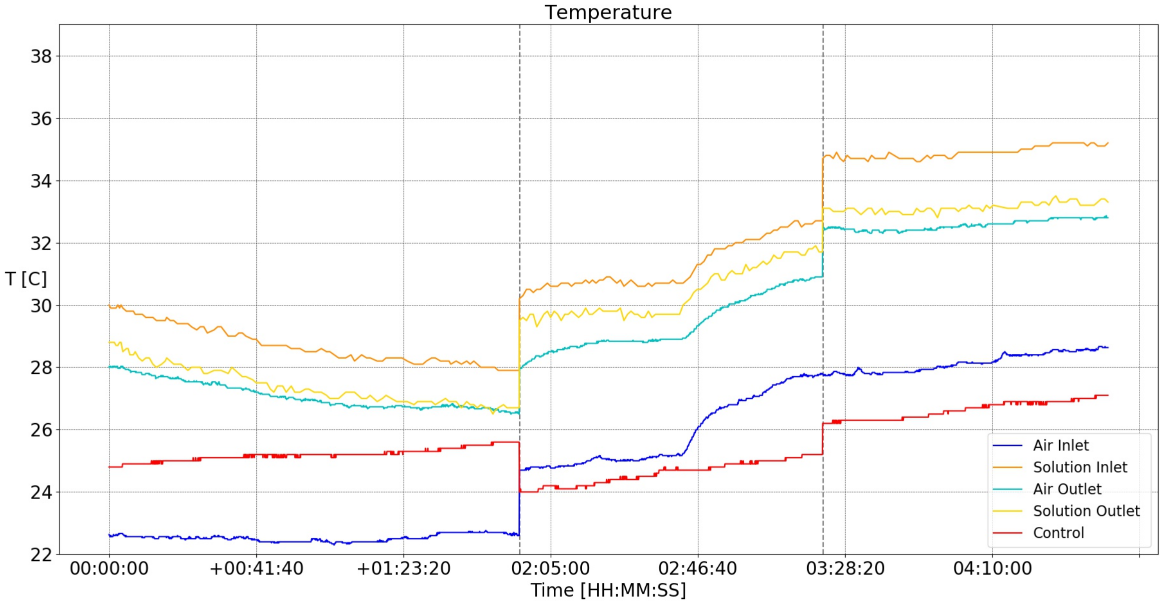
Three dehumidification experiments have been conducted. A list of the complete ranges of the inlet parameters for the three dehumidification experiments is presented in table (3-6). The dehumidification experiments are characterized by the condensation of moisture from the air to the desiccant and thus making the solution weaker. Figure (3-5) shows the three experiments added in one plot. The dotted line marks the beginning of a new experiment.

Variable	T_a ($°C$)	T_s ($°C$)	$y_a(kg/kg_{dryair})$	$X(\%)$
Parameter value	$22.4 - 28.6$	$27.9 - 35.2$	$0.0155 - 0.0205$	$30.5 - 35.9$

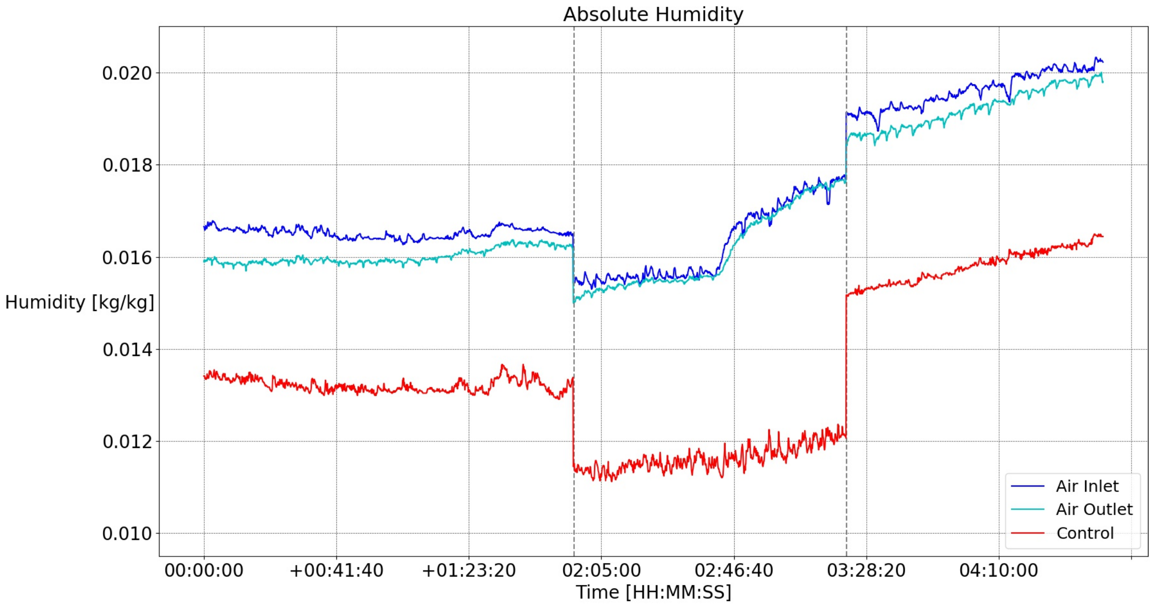
Table 3-6: Inlet ranges of air and desiccant parameters during the dehumidification experiment.

3-4-4 Dehumidification Observations

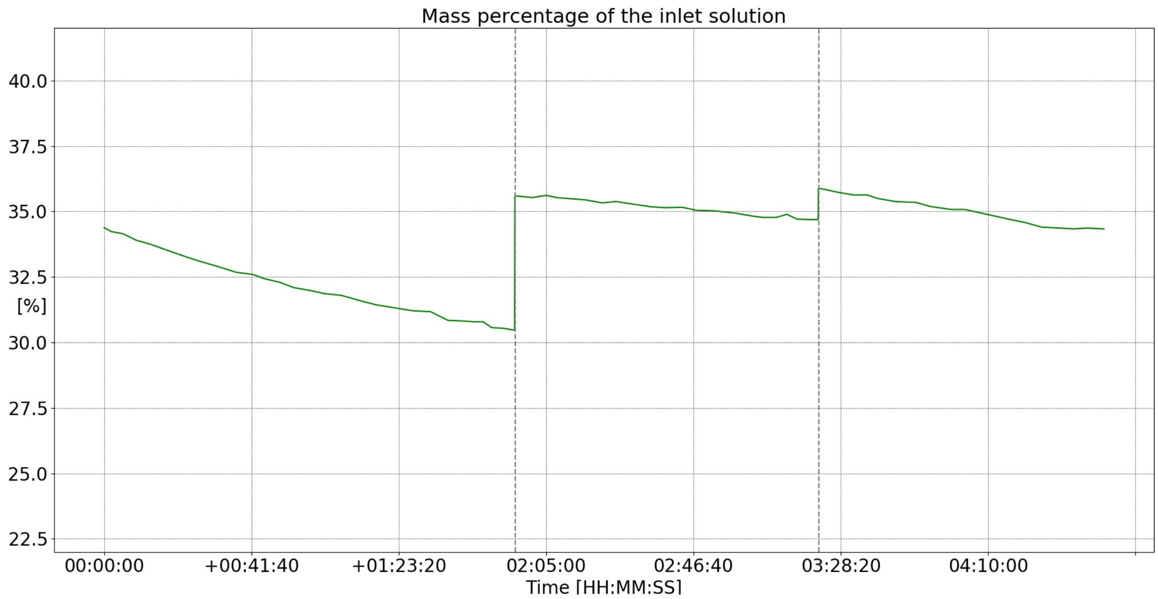
The temperature development of the air and desiccant at the in- and outlet of the pad are shown in figure (3-5a). Three experiments are conducted which are separated by the dotted grey vertical lines and the red line corresponds with the ambient. Just as in the regeneration experiments, the outlet temperatures of the desiccant and the air are close together. Again, a desiccant temperature of one to two degrees higher upon inlet than outlet is measured. As dehumidification happens, moisture is transferred from the air to the desiccant. The second graph shows the absolute humidity of the in- and outlet air. In contrast to the regeneration experiments, the absolute humidity of the in- and outlet air are almost the same in dehumidification. This means that the difference in absolute humidity is small between the in- and outlet and the driving pressure is not big. Dehumidification is confirmed by the decreasing concentration of the desiccant solution shown in the graph. The steepness of the slope shows the rate at which air is dehumidified and this is backed by the difference between the in- and outlet air absolute humidity in the second graph.



(a) Air and desiccant in- and outlet temperatures in the dehumidification experiments



(b) Absolute humidity of the in- and outlet air in the dehumidification experiments



(c) Concentration of the desiccant solution in the dehumidification experiments

Figure 3-5: Temperature, absolute humidity and concentration graphs of the dehumidification experiments

3-5 Discussion

This section provides an analysis on the calibration of the AgriSensys sensors. Chapter 6 gives a further discussion on the executed experiments.

By comparing the weight of the moisture that is removed from the air in time of one experiment with the changing concentration of the desiccant in that same time, the calibration of the sensors can be checked. Although the exact total volume of desiccant solution in the system was not measured, an estimation of 15 liters is given based on photos and the dimensions of the tank. The amount of moisture added to the air in one of the regeneration experiments is the moisture removal rate as in section (2-3-2):

$$\dot{m}_a \cdot (y_{a,out} - y_{a,in}) = 0.127 \cdot 0.0019 = 0.0002413\, kg/s \tag{3-1}$$

The length of this experiment is 11700 seconds, so the total amount of moisture added to the air is 2.82 kg. The density of the solution at the start of the experiment was measured at 1.338 kg/l. Which gives a total weight of 20 kg for 15 liters of desiccant. With 2.82 kg of moisture being removed, the new weight of the solution is 17.18 kg and the new volume, assuming density of water, $\rho = 1000\, kg/m^3$, is 12.18 liters. Calculating the final density to be 1.411 kg/l. Comparing this with the measured density at the end of the experiment of 1.418 kg/l, this matches well. From this the assumption is made that the AgriSensys sensors are correctly calibrated.

Chapter 4

Model Validation with Experiment

In the previous chapter, the results of the experiment are presented. The gathered experimental data on in- and outlet values for the air and the desiccant can now act as input for the mathematical model to find the two transfer coefficients α and $h_{transfer}$ for the mass and heat respectively.

4-1 Error Minimization

Every measurement point in the experimental data represents a control volume as presented in figure (2-2) with all in- and outlet values. All these different in- and outlet values are fed to the model. By minimizing the error of the relative difference between the measured and the model predicted values of the air outlet temperature, $T_{a,out}$, the desiccant outlet temperature, $T_{s,out}$, and the outlet air humidity, $y_{a,out}$, the transfer coefficients for which the outlets of the model match the experiments the best can be found. Chapter 3 showed that the experiment considers a closed system in time with changing input values in time. The fit however is not done in time, but on each measurement point. Table (4-1) shows the number of measurements and time of the regeneration and dehumidification experiments.

	Number of Measurement Points	Total Time of Experiments
Regeneration	3486	04:50:25
Dehumidification	3394	04:42:45

Table 4-1: Details on the number of measurement points and the length of the measurements.

Equation (4-1) shows an example of how the temperature error that must be minimized is calculated. The difference between the measured value and the predicted value by the model is normalized by a reference value. In this case $T_{reference} = 20°C$ for air and desiccant temperature and $y_{reference} = 0.015\, kg/kg$ for the absolute humidity. The errors are squared to avoid negative values. The total error is given by equation (4-2), which is the sum of the errors, ϵ, of every measurement point, M. This is minimized by a build in numerical method in Python for finding the minimum of an objective function, called the Nelder-mead method.

$$\epsilon = \left(\frac{T_{measured} - T_{modelled}}{T_{reference}}\right)^2 \tag{4-1}$$

$$min\left(\sum_{1}^{M} {\epsilon_{T_a}}^2(\alpha, h) + {\epsilon_{T_s}}^2(\alpha, h) + {\epsilon_{y_a}}^2(\alpha, h)\right) \tag{4-2}$$

Figure (4-1) and (4-2) show the best fit of the model with the smallest error and thus the optimized mass and heat transfer coefficients, α and $h_{transfer}$, for the regeneration and dehumidification experiments respectively. Figure (4-1) shows the fit of the regeneration experiments. The upper graph shows the absolute humidity development. The dark blue line corresponds with the inlet air and the lighter blue line with the outlet air measured as in the experiments. The two sudden drops in the graphs correspond with the start of another experiment. The red line is the output of the model after error minimization with the found transfer coefficients for heat and mass. The goal is to match the red line with the outlet line of the experiments. The closer the red line is to the light blue line, the better the fit is. From top to bottom can be seen the: absolute humidity, y_a, the air temperature, T_a and the desiccant temperature, T_s.

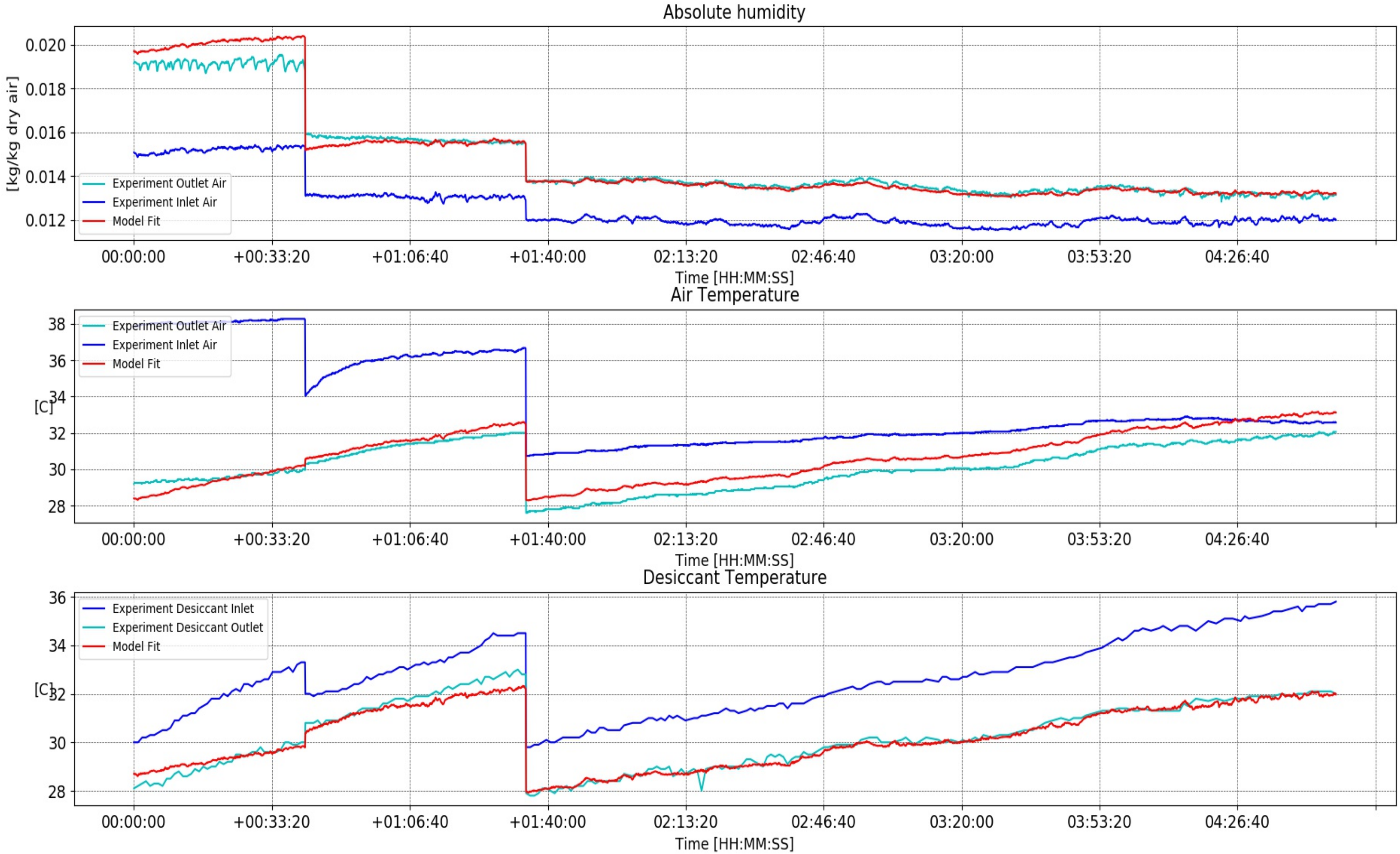


Figure 4-1: Graph of the measured in- and outlet values and the predicted outlet values of the model for the regeneration experiments.

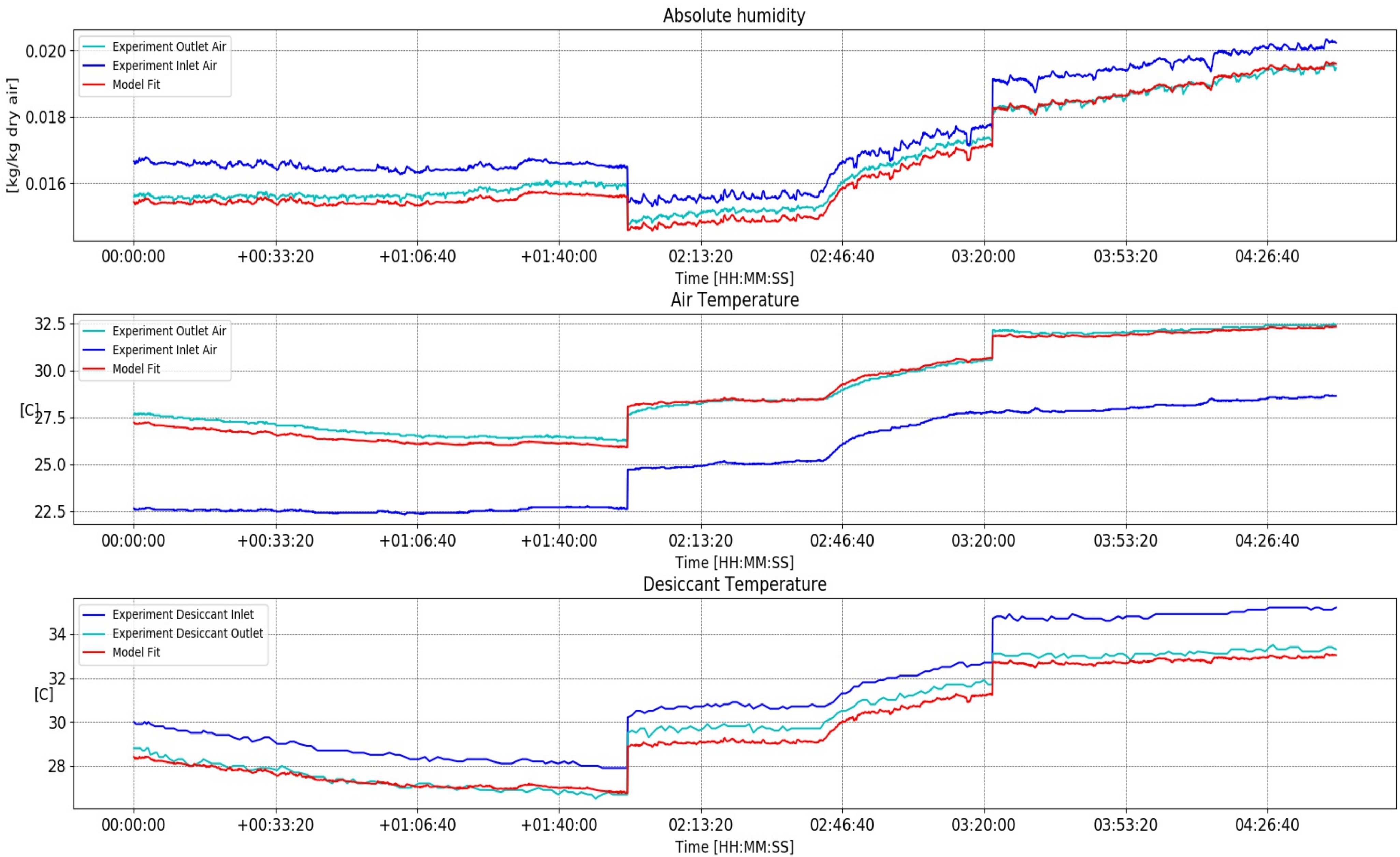


Figure 4-2: Graph of the measured in- and outlet values and the predicted outlet values of the model for the dehumidification experiments.

4-2 Improved Model

4-2-1 Transfer Coefficients

The transfer coefficients for mass, α, and heat, $h_{transfer}$, found after minimizing the error between the predicted value by the model and the measured value for the outlet temperature, $T_{a,out}$, the air outlet humidity, $y_{a,out}$ and the desiccant outlet temperature, $T_{s,out}$ for the regeneration experiment were:

α	0.00547	ms^2/kg
$h_{transfer}$	12.6	W/m^2K

Table 4-2: Mass and heat transfer coefficients for the regeneration process.

The same coefficients for the dehumidification experiments were found to be:

α	0.00317	ms^2/kg
$h_{transfer}$	8.3	W/m^2K

Table 4-3: Mass and heat transfer coefficients for the dehumidification process.

What is striking, is that the coefficients are different for the two processes. A discussion on the differences between the transfer coefficients and the values itself is given in chapter 6. Due to the design of the model, it's possible that at the top of the pad for example dehumidification of the desiccant is happening, but over the pad it changes to regeneration. The outlet air temperatures and humidity's of all the elements in the model are averaged. It depends on this average of the air outlet humidity if dehumidification or regeneration is taking place.

4-2-2 Comparison of the Model with Experiments

The model that is made in section (2-4-2) is validated with the new mass and heat transfer coefficients, α, and $h_{transfer}$, found in the experiments. Table (4-4) and (4-5) below show three measuring points along the dehumidification and regeneration experiments in comparison with the value of the model. In this way the differences between the measured and predicted values can be compared better than in the graphs of figure (4-1) and (4-2). The concentration of the desiccant at the outlet of the pad is not measured in the experiment so this box is empty in the table. The smaller the difference between the measured experiment outlet value and the predicted outlet value by the model, the better the fit corresponds with the real case. What stands out from the graphs and the tables, is that small differences between in- and outlet in the measured values, result in relatively large errors between the predicted and measured outlet values.

	$T_a(°C)$	$T_s(°C)$	$y_a(kg/kg_{dryair})$	$X(\%)$
Inlet	38.1	31.8	0.0153	24.4
Outlet by experiment	29.5	29.2	0.0191	-
Outlet by model	29.3	29.4	0.0202	24.6
Inlet	36.4	33.3	0.0128	036.2
Outlet by experiment	31.6	32.2	0.0156	-
Outlet by model	31.7	31.6	0.0154	36.5
Inlet	32.7	33.9	0.0121	38.9
Outlet by experiment	31.1	31.3	0.0135	-
Outlet by model	31.9	31.2	0.0134	39.0

Table 4-4: Comparison of the experimental and the modelled outlet values for several regeneration measuring points.

	$T_a(°C)$	$T_s(°C)$	$y_a(kg/kg_{dryair})$	$X(\%)$
Inlet	22.5	29.06	0.0164	32.9
Outlet by experiment	27.1	27.8	0.0156	-
Outlet by model	26.6	27.7	0.0153	32.8
Inlet	24.8	30.6	0.0154	35.6
Outlet by experiment	28.1	29.6	0.0150	-
Outlet by model	28.3	29.1	0.0146	35.5
Inlet	28.2	34.9	0.0197	34.9
Outlet by experiment	32.2	33.2	0.0190	-
Outlet by model	32.1	32.9	0.0189	34.8

Table 4-5: Comparison of the experimental and the modelled outlet values for several dehumidification measuring points.

4-2-3 Error Between Model and Measurements

Figures (4-1), (4-2) and tables (4-5), (4-4), show that there's still a difference between the predicted values by the model and the measured values in the experiments. Table (4-6) shows the absolute maximum difference and the absolute average difference between the measured and modelled outlet values for the regeneration and the dehumidification experiments. The average and maximum errors are permissible small compared to the measured values in the experiments.

In chapter 3, table (3-1) showed that the sensors that are used, have a certain uncertainty. This uncertainty can result in different transfer coefficients that are found with the fitting of the model and thus influence the final performance evaluation of the proposed system. With a simple analysis, it can be shown that the the 1.5% error in the relative humidity has the largest effect on the values of the transfer coefficients. Figure (3-4b) and (3-5b) show the absolute humidity as it is measured in the experiments. If a lower and upper boundary is applied of 1.5% to the measured values of the relative humidity, an interval can be found of the transfer coefficients that covers the error of the measured relative humidity. Table (4-7) shows the interval for the mass transfer coefficient, α. The influence on the heat transfer coefficient, $h_{transfer}$ is negligible small.

	Regeneration		Dehumidification	
	Maximum	Average	Maximum	Average
y_a	0.00160 kg/kg	0.00024 kg/kg	0.00050 kg/kg	0.00023 kg/kg
T_a	1.35 $°C$	$\pm$ 0.63 $°C$	0.54 $°C$	$\pm$ 0.24 $°C$
T_s	0.84 $°C$	$\pm$ 0.17 $°C$	0.75 $°C$	$\pm$ 0.29 $°C$

Table 4-6: Overview of the errors in the match of the prediction by the model and the experiments for the regeneration and dehumidification experiments.

	Regeneration	Dehumidification
-1.5 : %	0.00468	0.00241
α	0.00547	0.00317
+1.5 %	0.00663	0.00396

Table 4-7: Interval of the mass transfer coefficient, α, with a lower and higher error of 1.5% in the relative humidity.

Chapter 5

System Evaluation

This chapter gives an evaluation of the new proposed liquid desiccant dehumidification cooling system with regeneration by hot air. The evaluation can be done with the model that is made and the transfer coefficients found after the experiments. By giving the model different inputs, corresponding with the dehumidification and regeneration process, the working range and limitations of the pads itself and the complete proposed system will be evaluated.

5-1 Dehumidification Process

The countries mentioned in the introduction with subtropical climates, have reasonable steady outside air characteristics throughout the year. The liquid desiccant dehumidification cooling system is shown in figure (5-1) on the top of the next page.

The blue pad on the left corresponds with an evaporative cooling pad and receives the outside hot and humid air from a subtropical climate. The middle orange pad, is the dehumidification pad over which the calcium chloride will flow and this receives the air with almost 100 % RH from the first cooling pad. The most right blue pad is the final evaporative cooling pad, which cools the dried air coming from the dehumidification pad to the greenhouse inlet air temperature. Due to the relative constant temperature and humidity that enters the left pad, the entering air characteristics of the dehumidification pad are also relatively constant. This cooling system can be modelled with the use of a model for an evaporative cooling pad by Van der Hoeven, Appendix (C-2), and the model that is made in this thesis for the dehumidification pad.

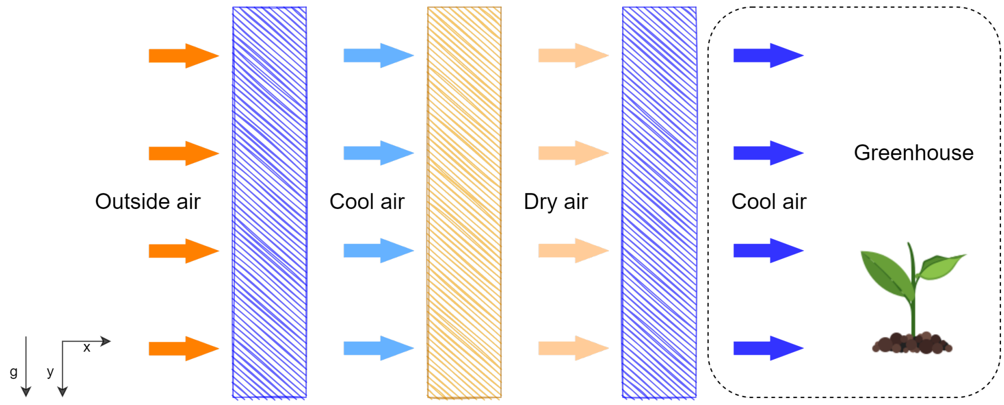


Figure 5-1: Two cooling pads with liquid dehumidification pad in between and the greenhouse entering cool air on the right side.

There's a clear effect on the final temperature and humidity when the dehumidification pad is used with calcium chloride. Table (5-1) shows three cases with different input temperature and humidity for the inlet outside air. The most left column describes the three inlet air characteristics cases. The blue and yellow columns, illustrate the location of the cooling pads and the dehumidification pad respectively, just as in figure (5-1). In all three the cases, the dehumidification pad lowers the ultimate outlet temperature of the final cooling pad. The added effect is the difference between the exit of the first cooling pad and the final cooling pad, which corresponds with comparing the second column with the last column. The size of the dehumidification pad in these cases is equal to the size of the pad used in the experiments and the temperature and concentration of the desiccant at the inlet is set at $T_{s,in} = 20\ °C$ and $X_{s,in} = 35\%$ with a constant mass flow of the desiccant of $0.05\ kg/s$ and air of $0.127\ kg/s$.

Outside air		Cool air		Dry air		Cool air
$T_{a,in} = 25°C$ $y_{a,in} = 0.017\ kg/kg$		$T_a = 23.3°C$ $y_a = 0.0176\ kg/kg$		$T_a = 24.3°C$ $y_a = 0.0141\ kg/kg$		$T_a = 21.3°C$ $y_a = 0.0152\ kg/kg$
$T_{a,in} = 30°C$ $y_{a,in} = 0.020\ kg/kg$		$T_a = 26.7°C$ $y_a = 0.0211\ kg/kg$		$T_a = 26.7°C$ $y_a = 0.0167\ kg/kg$		$T_a = 23.7°C$ $y_a = 0.0177\ kg/kg$
$T_{a,in} = 35°C$ $y_{a,in} = 0.022\ kg/kg$		$T_a = 29.5°C$ $y_a = 0.0237\ kg/kg$		$T_a = 28.6°C$ $y_a = 0.0187\ kg/kg$		$T_a = 25.5°C$ $y_a = 0.0198\ kg/kg$

Table 5-1: Air characteristics between the cooling and dehumidification pads as shown in figure (5-1) for three different cases. The blue columns correspond with the cooling pads and the orange column with the dehumidification pad.

The result of the added dehumidification pad is a further decrease in temperature of the air that enters the greenhouse of up to four degrees Celsius in the case of an entering outside temperature of $35°C$. It also results in a lower absolute humidity, but these values still correspond to around 85% RH. This shows that the added effect of the dehumidification pad is positive and a substantial decrease in temperature is achieved. There is however one factor that influences the performance of the dehumidification significantly. Namely the temperature of the desiccant. In figure (5-2), the effect of the temperature is visualised.

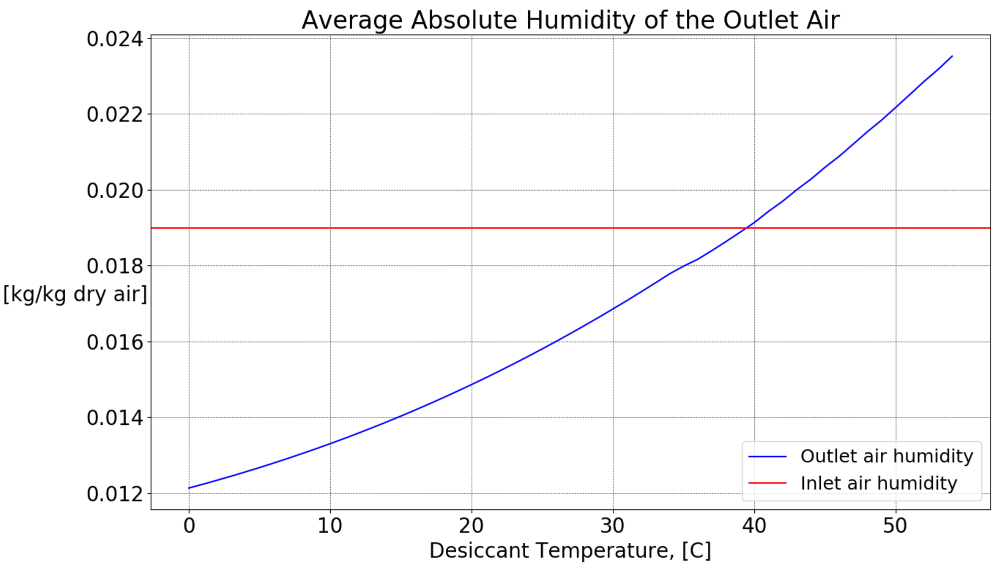


Figure 5-2: Effect of the desiccant temperature on the outlet air humidity for a dehumidification pad. Inlet conditions are: $T_{a,in} = 25°C$, $y_{a.in} = 0.019\,kg/kg$, $X_{s,in} = 0.35$

The graph shows the average absolute humidity of the air at the outlet of a dehumidification pad. The inlet absolute humidity is $y_a = 0.0190\,kg/kg$, indicated by the red line. The inlet air temperature is $T_{a,in} = 25°C$ and the concentration of the desiccant, $X_{s,in} = 0.35$. On the horizontal axis, the entering desiccant temperature is shown. The average outlet humidity of the air for a dehumidification pad should be lower. However, the out coming humidity increases fast with increasing desiccant temperature. At a desiccant temperature, $T_{s,in}$, of over $40\,°C$, the average absolute humidity at the outlet is higher, so on average moisture is added to the air. This shows that for efficient dehumidification, the desiccant temperature should be as low as possible and should never be higher than the temperature at which regeneration starts to occur.
For regeneration, the desiccant must be heated by the hot air to raise the vapor pressure. If the desiccant that comes from the regeneration pad is directly used for dehumidification again, the temperature of the desiccant will probably be too

high to be able to dehumidify. The next section discusses the regeneration process and a more detailed discussion will be presented in chapter 6.

5-2 Regeneration Process

The inlet air for the regeneration process, equals the air characteristics in the top of the greenhouse. Multiple factors influence the humidity and temperature of the greenhouse air. The sun is mostly responsible for heating the greenhouse. Where most greenhouses need to get rid of this heat, this heat can also be used to regenerate the desiccant. Shadowing screens can influence the irradiance on the plants and heat can be collected in the top of the greenhouse. On a sunny day in a subtropical climate, the sun irradiance can be as high as 800 W/m^2. For the inlet air temperature for the regeneration pad it is assumed that the temperature in the top of the greenhouse can increase significantly. Appendix [B-5] shows the calculation of the top of the greenhouse temperature and predicts that temperatures of 50°C or even higher can be achieved.
Humidity of the greenhouse air is influenced by the air that enters the greenhouse and the evaporation by the crop. The absolute humidity for the analysis of the regeneration pad is based on the most extreme environment for the crops. When the temperature around the plant rises, the humidity must increase as well to make sure the vapor pressure difference doesn't become to big between the plant and its surroundings. Around 30°C is the limit for the plant and an 80% RH at this temperature corresponds with approximately an absolute humidity of $y_a = 0.024\,kg/kg$. At these temperatures it's very hard to reach close to 100% RH in a greenhouse. The temperature in the top of the greenhouse can rise higher than 30 °C, but the absolute humidity in the top can not rise with it.
In contrast to the dehumidification pad, the goal of the regeneration pad is not to alter the characteristics of the air that goes through the pad, but to change the characteristics of the desiccant. The performance indicator of the regeneration process is the outlet concentration of the desiccant, X_s. The inlet temperature of the desiccant in the regenerator equals the desiccant outlet dehumidification temperature. With a dehumidification inlet desiccant temperature of 20 °C, desiccant outlet, thus regenerator inlet, will be around 25 °C − 33 °C. Figure (5-3) on the next page shows the desiccant regeneration pad with the hot air from the top of the greenhouse.

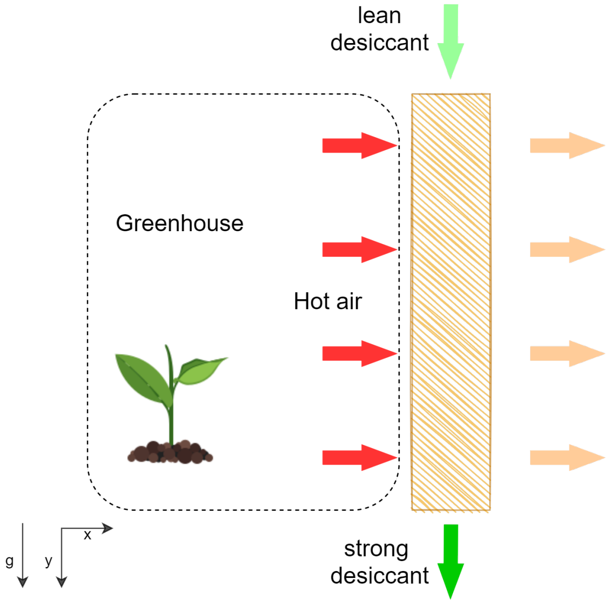


Figure 5-3: Regeneration pad with hot air from the greenhouse.

The hot air from the top of the greenhouse is indicated on the left side by red. The desiccant coming from the dehumidification pad that needs regeneration is indicated on the top of the pad in light green. By using the model to calculate the outlet values for different inlet values of the regeneration process, the working range of the regeneration system can be found. Figure (5-4) shows the influence of the desiccant inlet temperature on the performance of the regeneration pad.

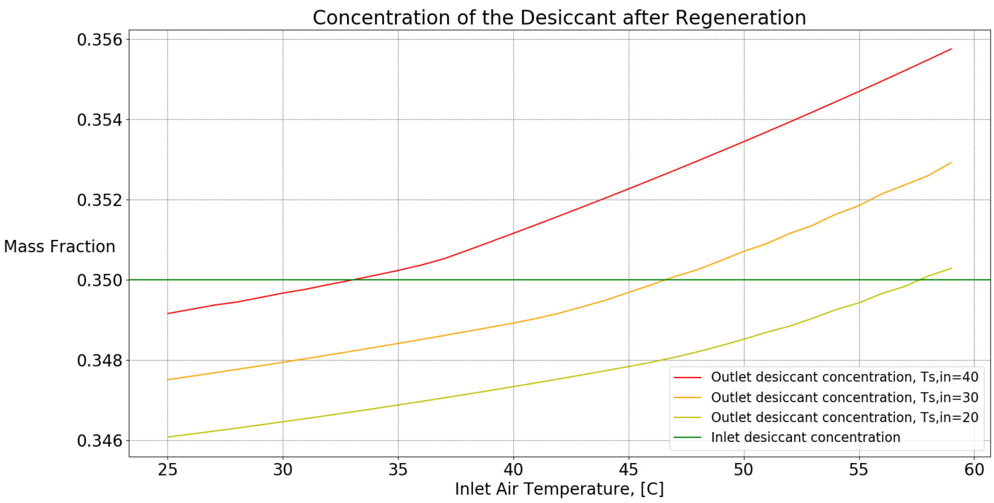


Figure 5-4: The Concentration of the desiccant at the outlet of the regeneration pad for different desiccant and air inlet temperatures. The inlet conditions are : $X_{s,in} = 0.35$, $y_{a,in} = 0.023 kg/kg$.

This figure shows the desiccant concentration at the outlet of the regeneration pad for different air temperature coming from the top of the greenhouse. The inlet concentration of the desiccant is $X_{s,in} = 0.35$ and is indicated by the green horizontal line. The three lines show the desiccant outlet concentrations for different desiccant inlet temperatures of $T_{s,in} = 20$, $T_{s,in} = 30$ and $T_{s,in} = 40$ where only the desiccant with a starting temperature of $T_{s,in} = 40\ °C$ is regenerated over almost the complete air temperature range. The goal of the hot air is to increase the temperature of the desiccant on the pad and therefore increase its vapor pressure. The desiccant is slowly heated from top till bottom by the hot air. The desiccant that leaves the regeneration pad is therefore significantly hotter than the desiccant inlet of the pad.

For desiccant inlet temperatures $T_{s,in} = 20\ °C$ and $T_{s,in} = 30\ °C$, the desiccant outlet concentration stays below the green line for much of the inlet air temperature range, which means that the desiccant concentration has not increased but even lowered. The vapor pressure of the air is still higher than the vapor pressure of the desiccant, thus dehumidification takes place, which means that the vapor pressure of the desiccant needs to go up further. This analysis shows that significant heating of the desiccant is needed to regenerate the desiccant. the desiccant gets heated by the hot air and reaches the highest temperature at the bottom of the pad. Heating of the desiccant prior to the regeneration process, can increase the final concentration of the desiccant significantly. More cases with different air and desiccant temperatures are presented in table (B-2) in Appendix [B-6].

5-3 Modelling of the New Dehumidification and Regeneration System

This section describes the complete liquid desiccant dehumidification system with regeneration with hot air. The complete system that is modelled is shown in figure (5-5).

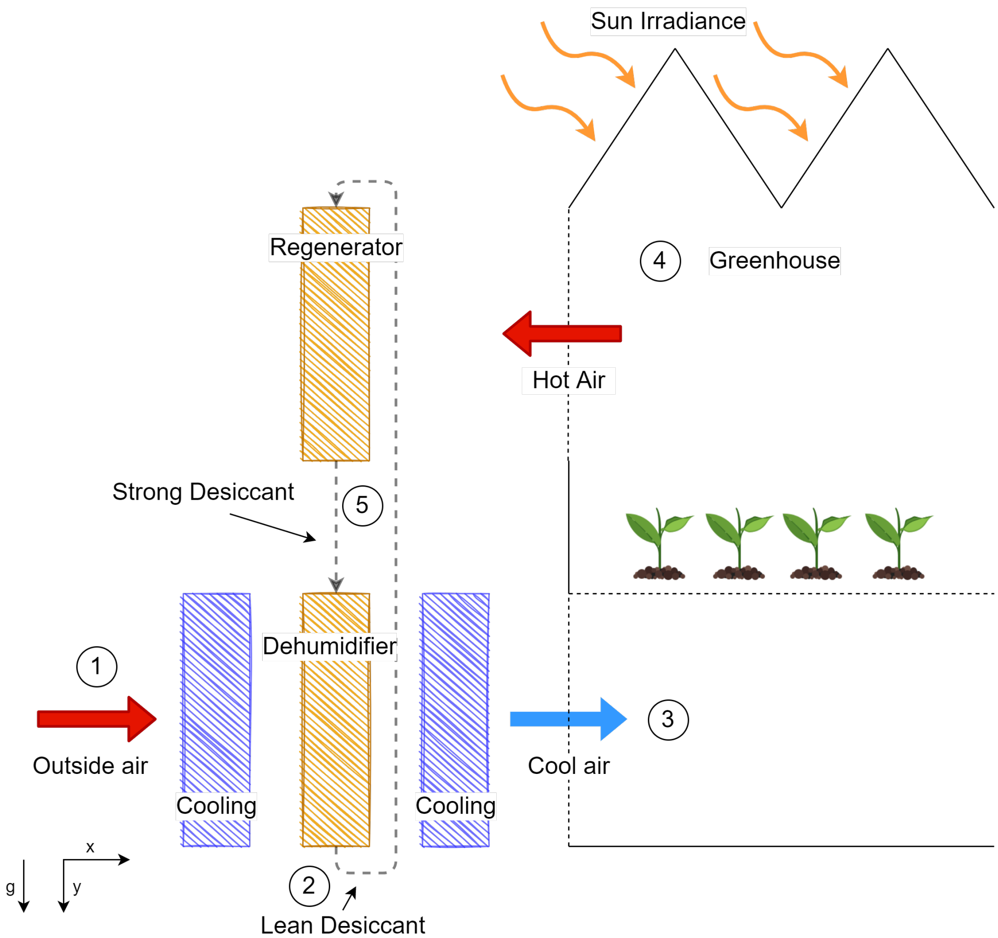


Figure 5-5: Complete desiccant dehumidification system with regeneration with hot air. Timescale of the desiccant loop is around 1-5 minutes. The fans that suck the air in the greenhouse from point 1 to 3 are not visualised.

The desiccant is pumped to the top of the regeneration pad after the dehumidification and back to the dehumidification pad again after regeneration, which creates a closed loop.

This system can be modelled by combining three separate models available for different steps system, namely:

1. Cooling pad model (Appendix C-2)
2. Liquid desiccant pad model (section 2-4-2)
3. Greenhouse climate model (Appendix C-1)

Further elaboration on, especially, the cooling pad model and the greenhouse climate model, can be found in the corresponding Appendices, (C-2), (C-1).

The inputs for the complete system model are: $T_{s,in}$, $X_{s,in}$, $T_{a,in}$, $y_{a,in}$ and I, the sun irradiance in W/m^2. Mass flows of air and desiccant are still assumed constant. Table (5-2), (5-3) and (5-4) below show different values for the outside weather and the corresponding temperatures of the greenhouse inlet air, greenhouse top air and the desiccant temperature and concentration. The positions that are indicated in figure (5-5) with numbers 1 - 5 correspond with the numbers 1 - 5 in the tables.

Outside Air (1)	Outlet Dehumidifier/ Inlet Regenerator (2)	Entering the Greenhouse (3) $I = 800W$
$T_{a,in} = 23°C$ $y_{a,in} = 0.0160\,kg/kg$	$T_s = 26.4°C$ $X = 0.3472$	$T_a = 20.3°C$ $y_a = 0.0143\,kg/kg$
Top of Greenhouse (4)	**Outlet Regenerator (5)**	
$T_{a,in} = 41.9°C$ $y_{a,in} = 0.0163\,kg/kg$	$T_s = 34.2°C$ $X = 0.3478$	

Table 5-2: Complete System characteristics overview with low inlet outside Temperature and 800 Watt sun Irradiance.

Outside Air (1)	Outlet Dehumidifier/ Inlet Regenerator (2)	Entering the Greenhouse(3) $I = 300W$
$T_{a,in} = 30°C$ $y_{a,in} = 0.023\,kg/kg$	$T_s = 32.8°C$ $X = 0.3455$	$T_a = 25.2°C$ $y_a = 0.0194\,kg/kg$
Top of Greenhouse (4)	**Outlet Regenerator (5)**	
$T_{a,in} = 32.9°C$ $y_{a,in} = 0.0203\,kg/kg$	$T_s = 34.2°C$ $X = 0.3448$	

Table 5-3: Complete System characteristics overview with high inlet outside Temperature and 300 Watt sun Irradiance.

Outside Air (1)	Outlet Dehumidifier/ Inlet Regenerator (2)	Entering the Greenhouse(3) $I = 800W$
$T_{a,in} = 30°C$ $y_{a,in} = 0.023\, kg/kg$	$T_s = 32.8°C$ $X = 0.3455$	$T_a = 25.2°C$ $y_a = 0.0194\, kg/kg$
Top of Greenhouse (4)	**Outlet Regenerator (5)**	
$T_{a,in} = 46.7°C$ $y_{a,in} = 0.0214\, kg/kg$	$T_s = 38.4°C$ $X = 0.3470$	

Table 5-4: Complete System characteristics overview with high inlet outside Temperature and 800 Watt sun Irradiance.

The greenhouse top air temperature and humidity is calculated with the greenhouse climate model, which depends on the sun irradiance, the entering greenhouse air temperature and the evaporation of the plants inside the greenhouse. The values in the table are shown with a single loop over the system, which means that the incoming air makes one round from starting outside air till leaving as hot air for the regenerator and the desiccant makes one round starting at the starting conditions for the dehumidifier and ending as regenerated desiccant after regeneration. The start conditions for the desiccant are $T_{s,in} = 20\,°C$ and $X = 0.35$ at point 5 in figure (5-5) for all three cases in the tables.

The difference between point 2 and 5 corresponds with the effect of the regenerator on the desiccant. The difference between point 1 and 3 is the effect of the three pad cooling system on the greenhouse inlet air. The difference between point 3 and 4 corresponds with the heating of the air in the greenhouse and the evaporation of the plants. For all three tables, this system seems to work well, because cooler air than the outside air is entering the greenhouse. However the indicators of this system are not only the inlet air characteristics, but also the ability to regenerate the desiccant for re-use in the dehumidifier.
These three cases show that the concentration of the desiccant at the outlet of the regenerator is not as high as it was at the first entry of the dehumidifier, namely $X = 0.35$ and the temperature is much higher than $T_{s,in} = 20\,°C$. In the two cases with high sun irradiance, table (5-2) and (5-4), the regeneration process does work. However, the regenerator is not able to get the concentration of the desiccant back to where it started at $X = 0.35$. The high temperature of the desiccant upon outlet of the regenerator is not beneficial as said in the previous chapter that the inlet temperature of the desiccant as a big influence on the performance of the dehumidifier and is preferred to be low. The sun irradiance is an important factor in the working of the regenerator because the sun is needed to heat the air in the top of the greenhouse in order for the regenerator to work. It's important to consider that in this case, only one round of the air and desiccant is considered. In the design of the system, the desiccant would enter the dehumidifier straight after regeneration.

However, this analysis shows that the desiccant would enter the dehumidifier at high temperatures and already in the second time on the dehumidifier, would almost no dehumidification take place. So for this particular setup with calcium chloride, the system works, but performance is limited due to high temperatures of the desiccant.

Important points from this analysis:

1. Calcium chloride can dehumidify, so extra cooling is possible, but the desiccant temperature should not rise to much, because this would lower the efficiency of dehumidifying.
2. Regeneration with hot air is possible given that the air temperature in the greenhouse is significantly heated by the sun and heating of the desiccant before regeneration is desired.
3. The desiccant is in this continuous setup not regenerated sufficient to return to the starting desiccant concentration.

5-3-1 Additional Design Steps

From the analysis becomes clear that additional cooling of the desiccant is needed before entering the dehumidifier. The energy needed for cooling of the desiccant prior to dehumidification for an example case, can be calculated with:

$$Q = \Delta T \cdot \dot{m}_s \cdot C_p \qquad [kW] \tag{5-1}$$

The difference in temperature is calculated from the most extreme case in table (5-4) for the complete system, which corresponds to a ΔT of $18.4°C$, the total mass flow for the system is the length of the pad times the mass flow per meter pad. For this example, a pad wall with a length, L, of 100 meters is taken and the desiccant flow is equal to that in the experiments, which corresponds with approximately $0.20\,kg/s$ for the top of a pad with length 1 meter. which is $20\,kg/s$ for the complete pad. The specific heat of a calcium chloride solution is taken constant at $2.6\,kJ/kgK$. This gives the energy needed for cooling of the desiccant:

$$Q = 18.4 \cdot 20 \cdot 2.6 = 957\,[kW] \tag{5-2}$$

To see if the new system is feasible when cooling of the desiccant is applied, the required energy for cooling must be compared with the obtained cooling energy saved by the dehumidifier. Assuming in this calculation that the regeneration pad fully regenerates the desiccant to the starting dehumidifier concentration and the desiccant does not need heating before entering the regeneration pad. The total cooling energy provided by the dehumidification pad can be read from the psychrometric graph by comparing the energy state before and after the dehumidification pad. Appendix (A-2) shows a psychrometric graph where the two evaporative cooling pads and the dehumidification pad are illustrated. The difference in enthalpy values between the starting and the end point of the dehumidifying process is the energy that is removed per kg of air. The difference in this case is:

$$\Delta h = 77 - 90 = -13\,[kJ/kg] \tag{5-3}$$

Average air speed, v, through a pad in a greenhouse is around 0.9 m/s which corresponds with a total air mass flow of:

$$\dot{m} = L \cdot H \cdot v \cdot \rho = 100 \cdot 1 \cdot 0.9 \cdot 1.2 = 108\,[kg/s] \tag{5-4}$$

Which gives a cooling capacity of:

$$Q = \Delta h \cdot \dot{m} = -1404\,[kW] \tag{5-5}$$

This example calculation is still in the benefit of the cooling system. More efficient cooling methods can be used to cool the desiccant prior to dehumidification. The cold desiccant needed for dehumidification and the hot desiccant needed for regeneration can be combined in a heat exchanger, which could make the process of cooling and heating more efficient. The cold air that enters the greenhouse can also act as a cooling medium for the desiccant. Furthermore the current setup as single loop over each pad can be adjusted. This would make the setup somewhat more complex in terms of pumps, piping and control systems, but could increase efficiency.

5-3-2 Summary

In this chapter the proposed system of the dehumidification pad, the regeneration pad and the complete system is analysed with the model. The dehumidification pad works well, provided that the inlet desiccant temperature is low and the concentration of the solution is high, the air enters the greenhouse cooler than without the dehumidification pad. The regeneration pad works as well. This is, provided that the air in the top of the greenhouse is hot enough, and preferably the desiccant is heated prior to regeneration. This means that regeneration is only possible if the sun's irradiance is large enough, because this is the main contributor to the heating of the greenhouse. The proposed system with a closed continuous loop of desiccant flow does not manage to increase the concentration of the desiccant back to the starting concentration and temperature of the desiccant is too high at the regenerator outlet. In future work attention should be paid to efficient cooling and heating of the desiccant to make the pads more efficient, because this is currently limiting the performance of the system. Also some more complex systems with multiple loops over the regeneration pad should be investigated, because this may also increase the total regeneration effect.

Chapter 6

Discussion

In this chapter a critical view is presented on the research that is done in this thesis. First, the experiment setup of the executed experiments will be discussed. Secondly, the model and the validation of the model with the experiments to find the heat and mass transfer coefficients. And finally, the performance of the new proposed system of dehumidification with calcium chloride and regeneration with hot air will be discussed.

6-1 Experiment

In the dehumidification and regeneration experiments, the outlet desiccant temperature is lower than the desiccant temperature at the inlet of the pad. In a closed system as depicted in figure (3-2), the desiccant would then cool down over time, however in these experiments the inlet desiccant temperature is continuously higher than the outlet desiccant temperature. A cause for this, is that heat is added by the pump system. To achieve the desired mass flow, the pump outlet is pinched off by a valve. This adds friction to the flow and together with the pump itself and the friction in the pipes, this can be the reason for the temperature increase. The added heat energy can be calculated using the temperature difference, the mass flow and the specific heat of the solution. The increase in temperature in the experiments differs between one and four degrees Celsius.

$$Q = \Delta T \cdot \dot{m}_s \cdot C_p = 1 \cdot 0.05 \cdot 2.6 = 0.130\ [kW] \tag{6-1}$$

$$Q = \Delta T \cdot \dot{m}_s \cdot C_p = 4 \cdot 0.05 \cdot 2.6 = 0.520\ [kW] \tag{6-2}$$

Energy in the form of heat required for these temperature differences are 130 Watt and 520 Watt respectively. The electrical energy used by the pump was on average 250 watt at the socket. This corresponds with $\Delta T = 1.9°C$ and thus in the same order of magnitude as the added heat energy and therefore assumed to be the cause of the increase in temperature.

In the experimental setup, the air is pushed through the packed pad. The air enters the box from a tube with a diameter of 20 cm and goes through a perforated plastic sheet to distribute the air in the height. In a greenhouse, the air is sucked through the packed pad instead of pushed. This gives a more equal distribution of the air that enters the pad. If this is also done in the experiment setup, this would give a more realistic situation with more equal inlet conditions over the height of the pad. Pushing the air through the pad, as done in the experiments can lead to uneven distributed air mass flows, which can influence and differ the transfer coefficients locally. However, the effect of this is neglected in this thesis.

6-2 Modelling

Some factors in the model can change depending on the method chosen for calculation. For example, the vapor pressure of air and the calcium chloride solution. The vapor pressure of the air is taken from Buck, [28]. There are however more sources that present relations between temperature and vapor pressure. Although these do not differ so much as the different relations for the vapor pressure of the calcium chloride solution. The relation in this thesis is taken from Conde, [18], but relations from other sources are slightly different, which can result in a different vapor pressure difference and thus a different mass transfer coefficient. Conde's relation is assumed as the most average of all the relations. [18].

As explained in chapter 4, the new model outlets with the mass and heat transfer coefficients, α and $h_{transfer}$, do not match the experiment outlet values exactly and there's still a mismatch. This raises the question of what causes these differences. The error between experiment measurements and model predicted values can be a consequence of little differences between the experiments. For example, the mass flow of the desiccant is assumed constant but can differ a bit between the experiments. This is inevitable and more attention should be paid to precision in further work. Looking at the figures of the fitted model, figure (4-1) and (4-1), in some ranges the errors are bigger. This implies that maybe the relation as presented in equation (2-14) is not linear. This equation shows a linear relationship between the driving pressure and the outlet humidity. This relation may be nonlinear and thus not fully describable by a linear relation what may cause the mismatch in the fit and experimental values.

The last thing to be discussed about the model are the heat and mass transfer coefficients, $h_{transfer}$ and α, that are found. The transfer coefficients are shown in section (4-2-1). A way to check if the transfer coefficients are in the right order of magnitude is by comparing them with known transfer coefficients in literature. The mass transfer coefficient is not directly comparable because no coefficient in literature can be found with the same units. For heat transfer there's no direct value known for heat transfer between water and moist air in condensing and evaporating state, however the order of magnitude can be checked with values from Moran & Shapiro [16] and Mills [29] for free convection of gases and gas to water heat exchangers which are around 2 - 30 $W/m2K$, which is the range of the heat transfer coefficients found in this thesis.

6-3 System Performance

One of the intentions for the new regeneration method of the liquid desiccant from the dehumidification system, is that the design would be simple. Consisting of one long packed pad that runs from the top of the greenhouse till the bottom where in the upper part regeneration takes place and in the lower part dehumidification. The system evaluation showed that for efficient regeneration and dehumidification, the system needs additional cooling and heating. If innovative additional desiccant cooling and heating methods are applied, the system can still be beneficial in terms of energy use. If the system remains a simple design with continuous operation, complex control systems can be avoided. As the temperature in the greenhouse increases due to increasing sun irradiance, the air in the top of the greenhouse becomes hotter as well and regeneration is started. The regenerated desiccant is now ready to be used for dehumidification again and additional cooling of the greenhouse is provided, which was necessary due to the raising temperature between the plants. In this way, the new system can be self controlling which is beneficial.
Depending on the exact climate conditions of the area in which the greenhouse is located, this new system may be forced to operate alongside other systems for indoor climate management. This can increase complexity and the use of complex control systems that manage the operation of these different systems alongside each other is inevitable. A challenge on the design of the new system is the use of salts. Salts bring a high corrosion risk and maybe clogging if crystallization occurs. More expensive piping is needed to prevent this. Research showed that not many ions enter the greenhouse air, [24]. However, no investigation of the effect on the plants was performed, which is recommended. Also, the packed pads lifetime may be lowered with the use of salts. Currently pad systems and desiccant need replacement every 10,000h to 100,000h, [15]. With salt solutions as desiccant, this may be more often. Altogether, if no effect on the plants is observed, the use of salt is an easy surmountable challenge.

An important factor in the feasibility of this system, is the ability to reach the high temperatures that are needed in the top of the greenhouse for regeneration. It's necessary to separate the plants from this heat and still enough light must reach the plants. As the air is becoming hotter, more mass flow of cool air is needed. Appendix [B-5] shows that high temperatures can be reached in the top of the greenhouse and enough screens can separate this heat from the plants. Still a test facility must test this setup with subtropical climate sun irradiance.

General findings of the performance of a heat and mass transfer packed pad can be compared with what is found in literature. The desired values of the characteristics of the solution and air upon inlet of the dehumidifier and regenerator are given in chapter 5. These desired values result in a better performance of the dehumidifier and regenerator and can be compared with literature, [27], [17], [23]. The general findings of high concentration of salts, low temperatures of the desiccant and high humidity of inlet air for the dehumidification process are confirmed in literature. Even as high temperature of the desiccant prior to regeneration. Which substantiates the findings in this thesis.

Chapter 7

Conclusion

This chapter provides a conclusion to the research that is done in this thesis. The research question was as follows:

Is the proposed liquid desiccant regeneration system, that works with hot air from the top of the greenhouse, able to regenerate the liquid desiccant sufficient for re-use in dehumidification?

Temperatures in the top of the greenhouse can rise significantly in subtropical climates due high sun irradiance. Locally, the temperature can be further increased by collecting heat in the top of the greenhouse with screens. The new proposed system of regenerating the desiccant of a liquid desiccant dehumidification system, is using this collected hot air from the top of the greenhouse to remove water from the desiccant. This technique was assessed for dehumidification and regeneration to check whether it's feasible. Packed pads, with high contact area between air and desiccant are used. An analysis of the process of heat and mass transfer is done with a mathematical model. Literature was reviewed to find different ways of modelling heat and mass transfer on a packed pad. Iterative differential element methods provide the highest accuracy. Calcium chloride is chosen as desiccant because of the low cost, relatively good performance and high availability.

To verify the assumptions in the model on heat and mass transfer coefficients and validate this model, an experimental study is conducted. Multiple measurements of the solution and the air are taken in dehumidification and regeneration experiments. The transfer coefficients are found by minimizing the error between the experiment outlet values and the model predicted outlet values. A good agreement is shown between the experimental measurements and the modelled results. The model is therefore a good representation of the process of heat and mass transfer between a calcium chloride desiccant solution and air over a packed pad.

The model is used to evaluate the performance of the new proposed system. Results show that dehumidification can significantly lower the entering temperature of the air in the greenhouse. Dehumidification efficiency can be improved by cooling the desiccant upon entry of the dehumidification pad. Results also show that regeneration of the desiccant solution is possible, provided that the air in the top of the greenhouse is significantly heated by the sun. Regeneration efficiency can be improved by pre-heating the desiccant upon entry of the regenerator. However, if these two processes are directly coupled without additional desiccant cooling or heating, the regenerator does not manage to increase the concentration of the desiccant back to the starting concentration and temperature of the desiccant is too high at the regenerator outlet. In future work attention should be paid to efficient cooling and heating of the desiccant to make the pads more efficient, because this is currently limiting the performance of the system. Also, some more complex systems with multiple loops of the desiccant over the regeneration pad should be investigated, because this may also increase the total regeneration effect.

Chapter 8

Recommendations

During the thesis and with the conclusions that are drawn from this thesis, further points of research are created. The most important recommendations for further research are:

(i) In section (2-2), a consideration is made between different salt solutions as desiccant and ultimately chosen for calcium chloride. Calcium chloride is not the strongest desiccant and if other efficiency enhancing solutions fail, for further research, other salts or combinations of salts should be investigated for use. Whilst keeping the availability high, price low and increase performance.

(ii) In chapter 2, a relation is presented between the difference in vapor pressure of air and desiccant and the in- and outlet absolute humidity to find the mass transfer coefficient. This is a linear relationship which may not be able to fully describe this relation. A more complex nonlinear relation can be sought and this may improve the model's accuracy.

(iii) The performance evaluation showed that cooling of the desiccant is needed before dehumidification and heating is desired before regeneration. Efficient cooling and heating techniques for the two flows must be developed. If this is added to the model, a new evaluation can be done on the performance of the total system.

(iv) For the next step in the feasibility study, the complete setup must be designed in detail to decide on the size and location inside the greenhouse. Adding climate data and making the model of the system dynamic to see how it reacts on sudden changes in the ambient can give more information on the performance and feasibility of the system.

Appendix A

A-1 Solubility Diagram Calcium Chloride

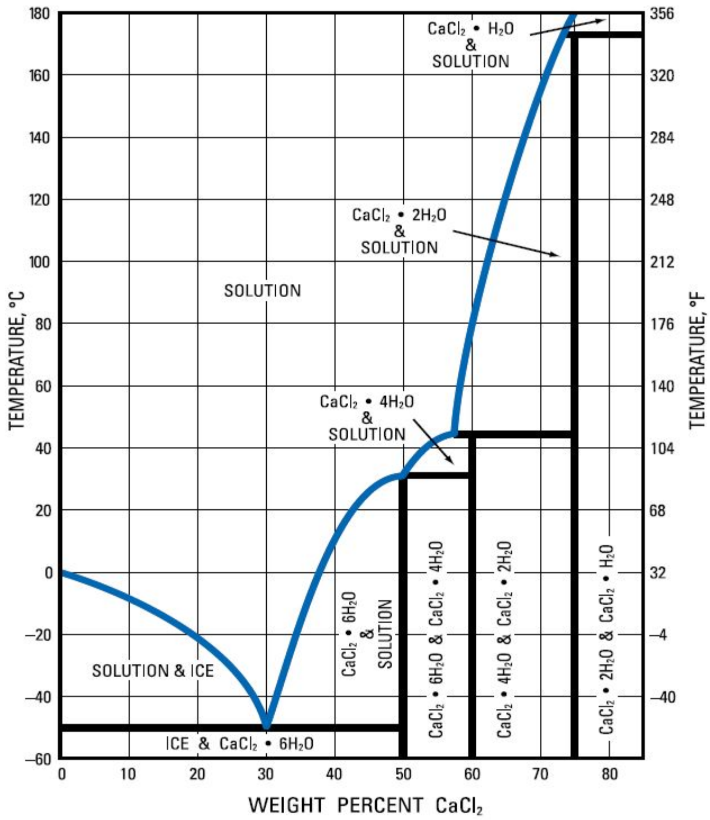


Figure A-1: Solubility diagram of CaCl2 solutions, [9].

A-2 Psychrometric Chart

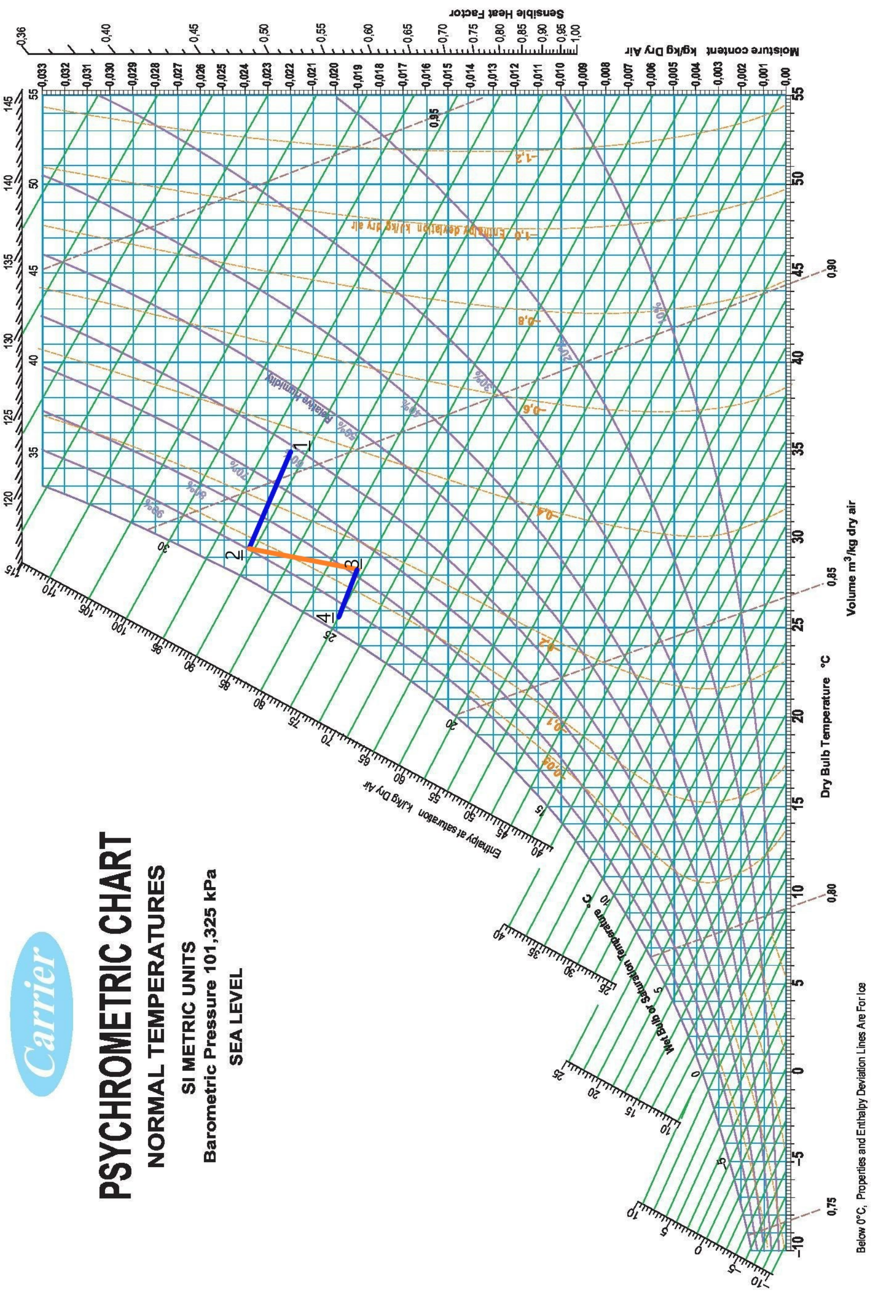


Figure A-2: Psychrometric chart featured with evaporative cooling step 1 to 2 (blue), dehumidification step 2 to 3(orange) and evaporative cooling from step 3 to 4 (blue).

Appendix B

B-1 Differential enthalpy of dilution

The differential enthalpy of dilution as presented by Conde is calculated with equation (B-1), [18].

$$\Delta h_d = \Delta h_{d,0} \left[1 + \left(\frac{\zeta}{H_1} \right)^{H_2} \right]^{H_3} \tag{B-1}$$

Where ζ is defined as the salt mass fraction as

$$\zeta = \frac{\xi}{H_4 - \xi} \tag{B-2}$$

$$\Delta h_{d,0} = H_5 + H_6 \theta \tag{B-3}$$

With θ the reduced temperature with the critical temperature of water.

	$CaCl_2 - H_2O$
H_1	0.855
H_2	-1.965
H_3	-2.265
H_4	0.8
H_5	-955.690
H_6	3011.974

Table B-1: Parameters of the differential enthalpy of dilution equations for solutions of calcium chlorides

B-2 Clausius-Clapeyron Equation

$$\left(\frac{\mathrm{d}\ln p}{\mathrm{d}\,T}\right)_{sat} = \frac{h_{sat,vap} - h_{sat,liquid}}{R\,T^2}$$

With $h_{sat,vap}$ the enthalpy of saturated vapor and $h_{sat,liquid}$ the enthalpy of saturated liquid, both in kJ/kg. R is the gas constant of 8.314 $J/Kmol$, [16].

B-3 Finite Difference Model

This appendix shows the finite difference modelling method as shown by Liu [25], chen [26] and Niu [8].

Governing equations are supported by figure (2-3) and (2-4) and given by equations (A-1)-(A-5):

$$\frac{\dot{m}_\mathrm{a}}{H} \cdot \frac{\partial h_\mathrm{a}}{\partial y} + \frac{1}{L} \cdot \frac{\partial\left(\dot{m}_\mathrm{s} h_\mathrm{s}\right)}{\partial z} = 0 \tag{B-4}$$

$$\frac{\dot{m}_\mathrm{a}}{H} \cdot \frac{\partial \omega_\mathrm{a}}{\partial y} + \frac{1}{L} \cdot \frac{\partial \dot{m}_\mathrm{s}}{\partial z} = 0 \tag{B-5}$$

$$\mathrm{d}\left(\dot{\mathrm{m}}_\mathrm{s} \cdot \xi\right) = 0 \tag{B-6}$$

$$\frac{\partial h_\mathrm{a}}{\partial y} = \frac{NTU}{L} \cdot \left(h_\mathrm{e} - h_\mathrm{a}\right) \tag{B-7}$$

$$\frac{\partial \omega_\mathrm{a}}{\partial y} = \frac{NTU}{L} \cdot \left(y_\mathrm{e} - y_\mathrm{a}\right) \tag{B-8}$$

With the boundary conditions:

$$\begin{aligned} T_\mathrm{s} = T_\mathrm{s,in}, \quad \xi = \xi_\mathrm{in}, \text{ at } z = 0 \\ T_\mathrm{a} = T_\mathrm{a,in}, \quad \omega_\mathrm{a} = \omega_\mathrm{a,in}, \text{ at } y = 0 \end{aligned} \tag{B-9}$$

Overall heat and mass transfer between air and the desiccant given by:

$$\frac{\partial h_\mathrm{a}}{\partial y} = \frac{NTU \cdot Le}{L} \cdot \left[\left(h_\mathrm{e} - h_\mathrm{a}\right) + \lambda_{T_\mathrm{s}}\left(\frac{1}{Le} - 1\right) \cdot \left(y_\mathrm{e} - y_\mathrm{a}\right)\right] \tag{B-10}$$

$$Le = \frac{h}{K c_{p,m}} \tag{B-11}$$

$$NTU = \frac{KAV}{\dot{m}_\mathrm{a}} \tag{B-12}$$

B-4 Effectiveness NTU-model

The main equations and step by step calculation process of ϵ - NTU model as given by Stevens [30] and Luo [12], is summarized as follows:

1. Calculate the Number of Transfer Units (NTU) with equation (B-12).

2. In terms of the similarity with the heat exchanger, the effectiveness could be expressed as

$$\epsilon = \frac{1 - e^{-NTU(1-m^*)}}{1 - m \cdot e^{-NTU(1-m^*)}} \tag{B-13}$$

   Where m^* was a capacitance ratio, defined analogous to the capacitance ratio used in sensible heat exchangers, and it was given in the following equations,

$$m^* = \frac{\dot{m}_a \, C_{sat}}{\dot{m}_{s,in} \, C_{p,s}} \tag{B-14}$$

   where C_{sat} was the saturation specific heat, and $C_{sat} = (dh_e/dT_s)$ in KJ/kgK.

3. With NTU and ϵ, the air outlet enthalpy could be obtained with the following equation,

$$h_{a,out} = h_{a,in} + \epsilon(h_{eq} - h_{a,in}) \tag{B-15}$$

4. Used an energy balance to calculate the solution outlet enthalpy.

5. Then an 'effective' saturation enthalpy was found by

$$h_{eq,eff} = h_{a,in} + \frac{h_{a,out} - h_{a,in}}{1 - e^{-NTU}} \tag{B-16}$$

6. Using the enthalpy and saturated conditions, the effective humidity ratio, $y_{eq,eff}$ could be obtained.

7. Then, by the following equation, the air outlet humidity ratio could be calculated,

$$y_{out} = y_{eq,eff} + (y_i - y_{eq,eff})e^{-NTU} \tag{B-17}$$

8. With the mass balance and known inlet and outlet parameters, all of the outlet parameters were acquired.

B-5 Greenhouse Top Temperature

Calculation for an estimation of the temperature in the top of a greenhouse.

$$T_{top} = T_{in} + \frac{\tau \cdot I - Evaporation}{Cp_a \cdot \dot{m}_a} \tag{B-18}$$

With T_{in} the temperature that is being supplied to the greenhouse from the cooling system. I is the irradiance from the sun in watts and τ is the transmission factor for the glass of the greenhouse and structure and commonly in the range of 0.6 - 0.8. $Evaporation$ is the energy a plant uses for evaporation from the sun irradiance in W/m^2. Cp_a is the specific heat of air in kJ/kgK and $\dot{m}_a$ is the airflow on one square meter of greenhouse surface in m/s. With this formula for irradiance of 800 W/m^2 and a high airflow of 60 $[kg/hr]$, it's still possible to reach top temperatures of 50 $°C$ or more. Script can be found in Appendix [C-1].

B-6 Regeneration Performance

This table shows the characteristics of the desiccant at the outlet of the regenerator with different air and desiccant inlet characteristics.

Inlet Desiccant	$T_{s,in} = 20.0\,°C$, $X = 0.350$		
Inlet Air	$T_{a,in} = 25.0\,°C$ $y_{a,in} = 0.018\ kg/kg$	$T_{a,in} = 35.0\,°C$ $y_{a,in} = 0.023\ kg/kg$	$T_{a,in} = 45.0\,°C$ $y_{a,in} = 0.023\ kg/kg$
Outlet Desiccant	$T_{s,out} = 28.4\,°C$ $X_{s,out} = 0.3470$	$T_{s,out} = 34.2\,°C$ $X_{s,out} = 0.3464$	$T_{s,out} = 37.1\,°C$ $X_{s,out} = 0.3475$
Inlet Desiccant	$T_{s,in} = 35.0\,°C$, $X = 0.350$		
Inlet Air	$T_{a,in} = 25.0\,°C$ $y_{a,in} = 0.018\ kg/kg$	$T_{a,in} = 35.0\,°C$ $y_{a,in} = 0.023\ kg/kg$	$T_{a,in} = 45.0\,°C$ $y_{a,in} = 0.023\ kg/kg$
Outlet Desiccant	$T_{s,out} = 31.0\,°C$ $X_{s,out} = 0.3494$	$T_{s,out} = 36.5\,°C$ $X_{s,out} = 0.3492$	$T_{s,out} = 39.1\,°C$ $X_{s,out} = 0.3510$
Inlet Desiccant	$T_{s,in} = 35.0\,°C$ $X = 0.350$	$T_{s,in} = 40.0\,°C$ $X = 0.350$	$T_{s,in} = 40.0\,°C$ $X = 0.350$
Inlet Air	$T_{a,in} = 35.0\,°C$ $y_{a,in} = 0.018\ kg/kg$	$T_{a,in} = 45.0\,°C$ $y_{a,in} = 0.023\ kg/kg$	$T_{a,in} = 55.0\,°C$ $y_{a,in} = 0.023\ kg/kg$
Outlet Desiccant	$T_{s,out} = 33.9\,°C$ $X_{s,out} = 0.3507$	$T_{s,out} = 39.2\,°C$ $X_{s,out} = 0.3524$	$T_{s,out} = 41.2\,°C$ $X_{s,out} = 0.3555$

Table B-2: Effect of regeneration on the desiccant with different air and desiccant inlet temperatures, humidity's and concentrations.

Appendix C

C-1 Greenhouse Top Temperature Script

```python
import numpy as np
import matplotlib.pyplot as plt
#----- INPUTS ------#
T_in = np.arange(20,30,0.5)   # [Celsius], Temperature of the inlet air
y_in = 0.013    # [kg/kg], Humidity of the inlet air
I = 800    # [W/m2], Irradiance from the sun
hfg = 2450   # [KJ/kg], latent heat of vaporization

CP_air = (1.005 + y_in*4.2)*1000   # [J/KgK], Heat capacity of the incoming air
rho = 1.3-(0.0045*T_in)   # [kg/m3],Density of the incoming air

evap_m2 = (I/800*300*0.8*0.6 + 17)/1000/3600 # [Kg/s], evaporated moisture in one second,transmission of glass is 0.7 and shadowscreens is 0.6

P_evap_m2 = evap_m2*hfg*1000 # [W/m2], energy for evaporation used from sun irradiance
flow_m2 = 40/3600*rho   # [kg/s], air flow per m2 greenhouse per second
y_g = y_in + evap_m2/flow_m2 # [kg/kg], absolute humidity in the greenhouse

T_top = T_in + (I*0.80-P_evap_m2)/CP_air/flow_m2 # [Celsius], Temperature of the air leaving the greenhouse in the top

#----- Plot ------#
plt.plot(T_in, T_top)
plt.xlabel('Temperature of the air [Celsius]')
plt.ylabel('Temperature of the air [Celsius]')
plt.title('Greenhouse top')
plt.grid(linestyle="--", linewidth=0.5, color='.25', zorder=-10)
plt.show()
```

C-2 Cooling Pad Script

```python
# Function of a cooling pad with temperature and absolute humidity as input, formulas copied from HACo sheet
# Provided by Van der Hoeven Horticultural Projects B.V.
import numpy as np
import matplotlib.pyplot as plt

def Cool(T,y):
    #___________________- CONSTANTS -____________________

    Eff = 0.85   # Efficiency of the cooling pad. taken 85% as in the Haco sheet

    Psat = 0.61121*np.exp((18.678 - (T/234.5))*(T/(257.14 + T)))*1000     # Saturated vapor pressure of the incoming air, [Pa]
    yeqs = (0.622*Psat)/(101325-Psat)                                     # Absolute humidity corresponding with Psat, [kg/kg]
    RH = y/yeqs                                                           # Relative humidity of the incoming air
    Pvap = (RH*Psat)                                                      # Partial vapor pressure of the incoming air, [Pa]
    yeqvap = (0.622*Pvap)/(101325-Pvap)

    hain = (1.006*T) + yeqvap*((2500.8-2.36*(T)+0.0016*(T)**(2)-0.00006*(T)**(3)) + T*1.84) # Enthalpy of incoming air, [KJ/kg]

    Twb = T*(np.arctan(0.151977*(RH*100 + 8.313659)**(0.5))) + np.arctan(T + RH*100) - np.arctan(RH*100 - 1.676331) + (0.00391838*(RH*100)**(3/2))*(np.arctan(0.023101*RH*100)) - 4.686035 # Wet bulb Temperature

    moist = (hain - 1.006*(T - Eff*(T - Twb))) / ((2500.8-2.36*(T)+0.0016*(T)**(2)-0.00006*(T)**(3)) + 1.84*(T - Eff*(T - Twb))) - yeqvap # Transferred moisture

    #____________________- OUTPUT -______________________

    Taout = (hain - (2500.8-2.36*(T)+0.0016*(T)**(2)-0.00006*(T)**(3))*(yeqvap + moist)) / (1.84*(yeqvap + moist) + 1.006) # Output air temperature, [Celsius]

    Psatout = 0.61121*np.exp((18.678 - (Taout/234.5))*(Taout/(257.14 + Taout)))*1000 # Saturated pressure of the temperature of the outcoming air, [Pa]
    yeqsout = (0.622*Psatout)/(101325-Psatout) # Absolute humidity corresponding with Psatout, [kg/kg]
    RHout = (yeqvap + moist) / yeqsout # Relative humidity of the outcoming air
    Pvapout = Psatout*RHout # Vapor pressure of the outcoming air, [Pa]
    yout = (0.622*Pvapout)/(101325-Pvapout) # Absolute humidity of the output, [kg/kg]

    return(Taout, RHout, yout)
```

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