Characterization of a Ventilated Latent Heating Unit Using LiCl as Working Fluid for Green House Applications

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by

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Contents

List of Figures

List of Tables

Nomenclature

Abbreviations

Abbreviation	Definition
VLHU	Ventilated Latent Heat unit
VLHC	Ventilated Latent Heat Converter
TESS	Thermal Energy Storage System
COP	Coefficient of Performance
LHS	Latent Heat Storage
STC	Standard Test Conditions
NCV	Net Calorific Value

Symbols

Symbol	Definition	Unit
V	Volume	[l]
m	Mass	[kg]
$\dot{m}$	Mass flow	[kg/s]
Q	Heat	[kW]
$\dot{Q}$	Heat flow	[kW/s]
c	Concentration	[kg/kg]
G_{fuel}	Hourly fuel consumption of the boiler	[m^3/h]
NCV_{fuel}	Net calorific value	[MJ/m^3]
η_{boiler}	Efficiency of the boiler	[%]
η_{distr}	Efficiency of the distribution line	[%]
η_{VLHC}	Efficiency of the VLHC	[%]
ρ	Density	[kg/m^3]

Abstract

Most homes in the Netherlands still heat their homes with traditional systems that use fossil fuels. This vital sector needs to change to reach the country's goals for sustainability. Since most renewable and sustainable sources make electricity directly, switching to renewable heating systems is a big problem. These challenges can be overcome by combining different heating techniques. One way to heat something is to turn the latent heat in the air's water vapor into sensible heat. One of the machines, created by AGAM and Dr. Ten, is located in a greenhouse in Gourdiaan, Almere, Netherlands, and performs the same function. The machine helps with energy savings in the greenhouse. It would be interesting to know if a machine that saves energy in the greenhouse and provides heating could do the same in another environment, especially in a Dutch residential home. The thesis describes and quantifies the machine's behaviour by creating a model to show how the machine works and to help understand how it works in a greenhouse.

The thesis helps to answer three main research questions. First, we need to know how the machine works with heat and how much heat each of its dehumidifiers, regenerator, and boiler produces. A dehumidifier releases heat, that is, the heat of condensation, which is about a tenth of the total heat released, and the rest of the heat is released from the regenerator and boiler, which is the heat released by directly exchanging heat with hot water. Then, the benefits and drawbacks of replacing the gas boiler in the VLHU with an electric boiler can be weighed by comparing the ease of installation, initial and running costs per cycle, and CO2 emissions. It is beneficial to replace gas boilers with electric boilers in new VLHU systems, but this should only be done for systems that still need to be operational. Lastly, a gas boiler and VLHU system a gas boiler are compared for a residential home, indicating that replacing traditional gas boiler heating systems with VLHU and gas boiler heating systems has many physical constraints, such as noise, replacing liquid heating systems with vents and ducts, and is less efficient than traditional gas boilers. It is also hard to give the machine the same working conditions as a greenhouse at a residential home. Furthermore, because future gas prices are unpredictable, comparing the expenses of electric heating systems to those of traditional heating systems is problematic. It also underlines the significance of researching other heating technologies to decarbonize home heating systems and make homes pleasant while keeping living costs low.

Preface

I conducted this research for my master's thesis while a student at TU Delft, specifically for the MSc Sustainable Energy Technology program. I wish to thank a few people in particular for their assistance with my thesis. I want to express my gratitude to Joel, my PhD advisor, for all the help you have given me both within and outside of our weekly sessions. For our project-related brainstorming sessions, our beneficial Matlab sessions, and your supportive chocolates afterward:) I want to thank Laura Ramirez Elizondo for giving me the chance to complete my thesis at DCE&S and for the regular meetings and comments. I would like to thank Diego, Marnix and Gerrit from Dr Ten B.V. for their constant support and extensive knowledge. I also like to thank Pavol Bauer and Arno Smets, who are also on my thesis committee, for their prompt responses to my inquiries. Finally, I want to express my gratitude to my family and friends for always encouraging me and supporting me mentally. I want to thank the "Simons" in especially for all of our fruitful study sessions, coffee walks, and priceless memories that made this journey worthwhile.

Keshav Arora
Delft, November 2022

1 Introduction

Most of the houses in The Netherlands are still using traditional systems which are reliant on the fossil fuels to heat their houses . This is an issue as burning fossil fuels is not an environmental friendly solution and affects each and every living organism. Desiccant is a hygroscopic substance which is used to induce a state of dryness [1], in other words desiccant attracts water and when kept in a room, it absorbs water from the air itself, leaving the air dry. When compared to a traditional system, desiccant systems which uses desiccant liquids as a primary working solution, have the capacity to deliver effective humidity and temperature control while requiring less electrical energy [2]. As concentrated desiccant is brought in contact with air, water vapor in the air is absorbed by the desiccant, i.e., water condenses into the desiccant. Due to the latent heat of the water condensation and the heat of mixing, heat is released throughout this process [2]. Aqueous solutions of lithium bromide, lithium chloride, calcium chloride, salt combinations, and triethylene glycol (TEG) are among the liquid desiccants that are frequently employed.

The Desiccant system that we will study about in this report is the Ventilated Latent heat unit (AGAM 1020 system) produced by Agam, Israel which is a parallel bed desiccant system with dehumidifier and regenerator which uses LiCl as the desiccant solution. This system could be of use in smart grids and smart houses due to the characteristics that the system displays that is naturally producing heat from air, including storage tanks for the desiccant improves the performance of the system [3] and lastly, the storage of desiccant solution is a form of energy storage within the system which reduces the peak load and provides the freedom to operate the system during the off peak hours. However, the behaviour of the VLHU still has to be fully understood and its use as a heating unit in houses, buildings and smart grids networks.

There is a growing need to create more energy-efficient technologies in a world where energy resources are largely responsible for the financial and political problems. The liquid desiccant technology is one of the methods for dehumidifying the air that has a promising performance [3]. This research's main objective is to look at creative ways to address heating problems using liquid desiccant technology.

1.1. Research Objective and Research Question

The main objective of this research is to improve the understanding of a ventilated latent heat unit (VLHU) in a greenhouse in the Netherlands. The thesis aims to achieve the following research objective

”**How to describe the heat supply process of a ventilated latent heat unit in a greenhouse in the Netherlands?**”

Further to fulfill the research objective, the entire thesis can be divided into three research questions as mentioned below

1. How can the heat conversion in the dehumidifier, regenerator, and boiler be described?

2. What are the effects of replacing the gas boiler with an electrical heater of the ventilated latent heat unit (VLHU) in a greenhouse?
3. Is the ventilated latent heat unit (VLHU) suitable for the Green Village test house?

By answering the research questions stated above, we can have a better thermodynamics understanding of the machine and analyse the results to reach the research objective of the thesis. In the following section the state of the art of the VLHU

1.2. State-Of-The-Art

Changing latent heat into sensible heat is not new, but it has become more well-known in the last few decades. The main thing that the research on liquid desiccant systems shows is how limited the vapor compression system is at getting rid of latent loads. So, it focuses on how well it heats and cools and works with traditional air conditioning systems. [4]. The Figure 1.1 shows that the research was conducted on familiar topics related to liquid desiccant systems.

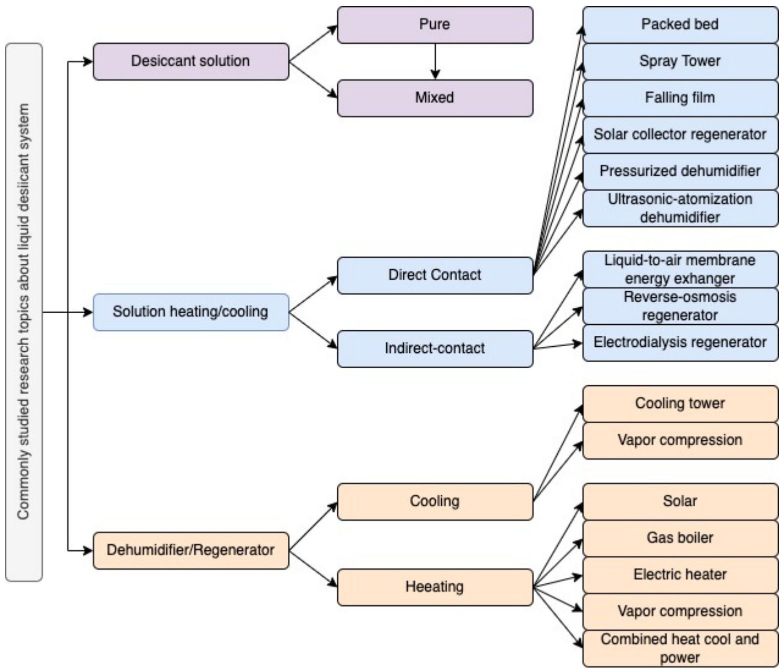


Figure 1.1: Breakdown of commonly studied research topic about liquid desiccant system [4]

This research focuses on the packed bed type direct contact system with a pure solution that uses a gas boiler as the primary heat source.

1.3. Methodology And Report Structure

To answer these research questions for this master's thesis, we must first understand the Agam VLHU system. Then, to clearly understand the heat produced by each subprocess of the system, we recreate the machine in Matlab and experiment with different input values for the machine's parameters to generate different results. The Matlab model will help produce various analyses, such as how the system functions outside of the greenhouse, how we can electrify the system from the conventional gas-based system, and VLHU system analysis in the greenhouse and dutch home

This master's thesis report is structured as follows; Section 2 is a literature review that discusses the machines' history and background and talks about the operating principle and working of the machine, dehumidifier, and regenerator components. The following section is the methodology that describes how the model is created and how it operates to generate outcomes for various machine input values. It is followed by results, analysis, conclusion, and recommendation for future study.

2

Literature Review

2.1. Vapor Heating Technology Background

This section provides the background information required to understand how the system works. The process of vapor condensation naturally warms up the desiccant in this system; the heat is then discharged by the unit into the greenhouse or warehouse as warm, dry air. The VLHU is able to transform the latent heat that is stored in the water vapor into usable heat in an effective and efficient manner. This results in a significant reduction in the amount of energy that is required to maintain the greenhouse environment [5]. This sections begins by explaining the history and background of the VLHU machine, and then explains the principle and the working of the system and also describes the traditional heating technologies currently.

2.1.1. History of Ventilated Latent Heating Unit

Many farmers believe that greenhouse dehumidification is critical. The crop evaporates, and if this moisture is not removed, the greenhouse air reaches an unacceptably high relative humidity, posing a harm to the cultivation [6]. The most typical method of moisture removal is to exchange greenhouse air with outside air. To keep the greenhouse air from chilling too much, this outside air must be heated again.

Traditional humidification and cooling/heating methods are not only inefficient systems in the way that they consume high power but also lead to serious microbial contamination and relative humidity controls that are unsatisfactory, deteriorating indoor air quality and endangering human health.

Liquid desiccant systems using salt solutions are capable of absorbing moisture. As a result, they can be utilized to dehumidify the greenhouse air. Regenerating a saline solution that has absorbed moisture is also necessary. This can be accomplished by heating the saline solution, which causes the moisture in the solution to evaporate. The evaporated moisture can condense again by cooling the wet air via a heat exchanger to, say, greenhouse temperature, allowing the heat of evaporation and the water to be recovered. The VLHU is a device that can dehumidify greenhouse air and recover heat by using a salt solution of Lithium Chloride (LiCl). Dr Ten has commissioned an VLHU machine at Goudriaan - Almere Greenhouse to conduct simulations to see whether such a system will be viable for the greenhouse.

2.1.2. Ventilated Latent Heating Unit Used in a Greenhouse

Greenhouses consume a large amount of heat to reduce the stress induced by low temperatures in cold climates. A large portion of this heat is consumed by evaporation, which is associated with plant and animal activity. The evaporation enhances humidity in a closed building, which induces further stress on plants and animals. To reduce the humidity, one usually ventilates the building and the greenhouses [7].

It is well recognized that evapotranspiration is an essential mechanism which consumes most of the energy input into plants [8]. Greenhouse activity is also associated with intense evaporation. The vapor capacity of air is rather limited, and evaporation in agricultural buildings enhances humidity to high levels. This induces stresses which result in plant diseases. To reduce humidity, the farmers open the windows and ventilate the air. Ventilation consumes heat in cold climates. Conventionally, to remove one kilogram of water vapor one has to replace some 100 to 300 m^3 of inside warm and humid air with cold outside air. The heat which is exhausted and lost amounts to 1.2-1.6 kWh, half of which is latent and half is sensible heat [7].

The air inside the building is continuously circulated across the direct-contact brine-air heat exchanger, which converts latent heat to sensible heat at the same time. The vapour in the air condenses on the hygroscopic brine. The airflow returns to the building area with significantly reduced humidity. Condensation heat raises the brine temperature above the air temperature. As a result, heat is transferred from the brine to the air. A brine evaporator-condenser system is used to keep the brine concentration within an acceptable range. The brine is heated by a hot water coil attached to the water heater system. The heated brine vapour condenses on the inner side of the cylindrical brine-vapour heat exchanger. The same brine that is pumped to the brine-air heat exchanger cools the condensate. The brine absorbs heat, which is recovered as sensible heat and returned to the building via the brine-air heat exchanger. The condensed water inside the condenser is removed as fresh water for irrigation or other uses.

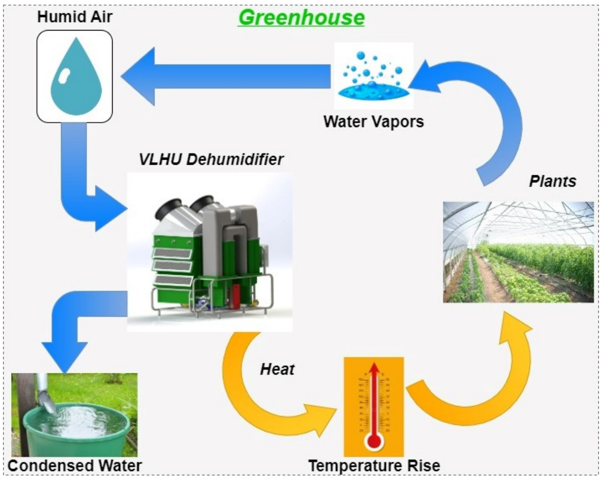


Figure 2.1: Feedback Loop of VLHU in Greenhouse

There are mainly three ways that the heat savings are gained by the VLHU in the greenhouse [5]:

- By converting the vapor into liquid there is a sensible heat gain
- The removal of the water vapor from the greenhouse allows for operation of closed system eliminating the need for opening vents or energy screens.
- The "Feedback Mechanism" theory as shown in Figure 2.1, states that the rate of transpiration of the plants is directly proportional to the rate of heating in the greenhouse. Thus as the dehumidifier heats the greenhouse, plants will transpire more water in the atmosphere which will again go in the dehumidifier to produce heat [5].

2.1.3. LiCl Used as The Desiccant Solution

A desiccant solution is essentially a combination of water and salt (e.g.,$MgCl_2$, $CaCl_2$, LiCl, $LiBr_2$). A desiccant solution's ability to attract water vapor from an air stream is determined by its equilibrium humidity ratio at a given temperature and concentration, as presented in Figure 2.2 for LiCl solution. [9]

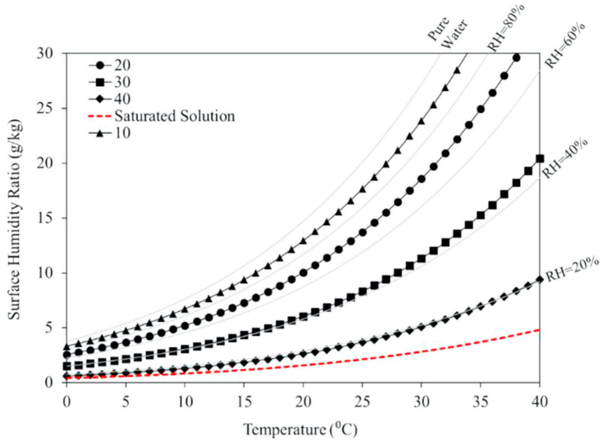


Figure 2.2: Equilibrium humidity ratio of air versus temperature at different concentrations for LiCl [4]

The equilibrium humidity ratio is defined as the equivalent humidity ratio of an air stream in direct contact with the surface of the desiccant solution. If the equilibrium humidity ratio of the desiccant solution is lower than the humidity ratio of the air stream, water vapor will transfer from the air to the solution stream, and vice versa. As can be seen in Figure 2.2,the lower the temperature of a solution at a constant concentration, the lower its equilibrium humidity ratio and thus its ability to dehumidify air. Furthermore, the higher the solution concentration at constant temperature, the lower the equilibrium humidity ratio [4].

The performance of a VLHU system is strongly dependent on the type of desiccant solution used, and thus several studies have been conducted on the thermodynamic properties and economics of different desiccant solutions. In summary, the desired characteristics of a desiccant solution can be summarized as follows: [4]

- Hold large quantity of water vapor;
- Low regeneration temperature;
- Low crystallization point;
- Low vapor pressure;
- Low cost;
- Low viscosity;
- High density and
- High durability

VLHU Use In Different Places

The VLHU is used in places that require dehumidification, such as greenhouses, animal shelters, storage units, etc. After the intense research being done on liquid desiccant systems, researchers have come up with a hybrid system known as the Liquid Desiccant Air Conditioner (LDAC), which is a combination of a liquid desiccant system and a vapor compression system that provides cooling and dehumidification together [10].

2.2. System Description

2.2.1. Principle and Working of the Machine

In the ventilated latent heat converter, dry warm air exits from the dehumidifier at the same enthalpy as the cold humid air introduced therein. This device absorbs and condenses water vapor from the air using brine, a salt-and-water solution. Both saltwater and water are highly hydrophilic, or attracted to one another. This condensation offers free energy [11]. This is achieved because the humidity in the air condenses on the brine. The condensation heats the brine, and the brine heats the air. In other words, the dehumidifier converts the latent heat of the water vapor into the air to sensible heat i.e., air temperature rises [12].

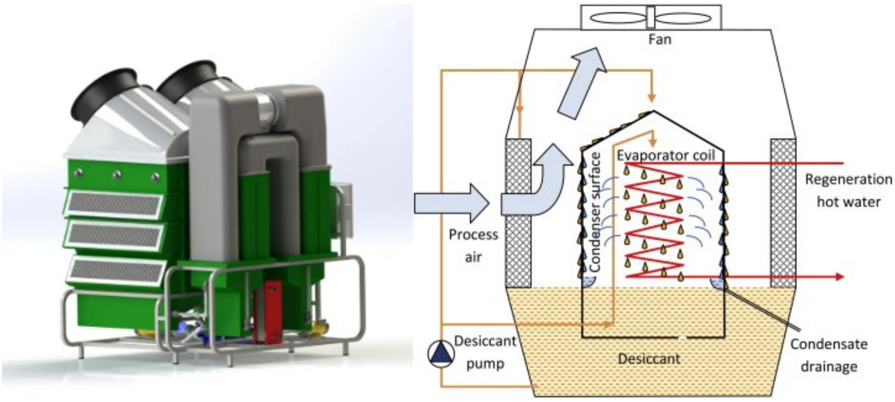


Figure 2.3: Ventilated Latent heat unit (VLHU) System: a) Real View, b) Schematic View [13]

Figure 2.3 shows a real and a schematic view of the VLHU system. The VLHU unit is directly controlled by a hygrometer inside the greenhouse [14]. There is a desiccant reservoir and a desiccant inlet on a desiccant/air heat exchanger. A desiccant heat exchanger warms the diluted desiccant as it flows into the reservoir. The reservoir and the desiccant/air heat exchanger are open to the air. The method lowers humidity by pumping concentrated liquid desiccant from the reservoir to the heater and then back to the desiccant intake at least twice the condensed water mass flow rate [15].

Desiccant is sprayed into the vapor heating unit to soak up water vapor and dry the air. By changing phases, water vapor in the air changes latent heat into sensible heat and warms the desiccant. The desiccant gives heat to the air until it gets hot enough for all its stored energy to come out as heat [16].

This heat can only come from the desiccant, which must be warmer than the air that can be removed. The greater the temperature difference, the more water vapor is condensed from the air. As the desiccant gets hotter, it loses some of its drying power [15]. When a desiccant builds up water vapor, it works less well. A regenerator takes the water vapor from the desiccant and puts it back in the dehumidifier's reservoir. The dehumidifier works better when the desiccant is more concentrated, but the regenerator must work harder to eliminate the water vapor. This heat can only come from the desiccant, which must be warmer than the air that can be removed. This is because the higher the temperature difference between the desiccant and the air, the more water vapor can be removed from the air. However, the hotter the desiccant becomes, the less effective it becomes as a drying agent [15].

Likewise, as the desiccant absorbs water vapor, it becomes more diluted and less effective. In order to address this issue, a regenerator is built into the dehumidifier to remove the water vapor from the desiccant and put the concentrated desiccant back into the dehumidifier's reservoir. There is a practical limit to how concentrated the desiccant can be. On the one hand, the more concentrated the desiccant, the better the dehumidifier works. Nevertheless, on the other hand, the more concentrated the desiccant, the harder it is for the regenerator to get rid of the water vapor that has been absorbed.

The heat flow rate supplied to the VLHU unit is recorded by monitoring the working time ΔT_{boiler} of the dedicated gas oil boiler and multiplying it by the hourly fuel consumption of the boiler G_{boiler}, the Net Calorific Value of the fuel NCV, the efficiency of the boiler η_{boiler} and the efficiency of the distribution line η_{distr} [17]:

$$\Delta E_{\text{t.VLHU}} = \Delta T_{\text{boiler}} \cdot G_{\text{fuel}} \cdot NCV_{\text{fuel}} \cdot \eta_{\text{boiler}} \cdot \eta_{\text{distr}} \tag{2.1}$$

2.2.2. Ventilated Latent Heating Unit Parts and Role of Dehumidifier and Regenerators

The VLHU is consist of the following parts

1. Dehumidifier
2. Regenerator
3. Air-water heat exchanger
4. Solution-solution heat exchanger

5. Condenser
6. Pump
7. Gas heater/boiler
8. Fan blower

The dehumidifier and regenerator are two of the most crucial parts of a VLHU system, and as a result, the research literature has given them the most attention. As shown in [10] dehumidifiers can be generally classified as direct-contact or indirect-contact, and regenerators can be classified as single-stage or multi-stage. In direct-contact dehumidifiers, heat and water vapor transfer take place between air and desiccant solution streams through direct contact. As shown in figure 2.4, the desiccant solution is usually distributed from the top of the packed bed and flows over the packing where it comes into direct contact with the air stream. In the dehumidifier, the temperature of the desiccant solution changes as it flows through the dehumidifier due to the heat transfer with the air stream due to the moisture transfer.

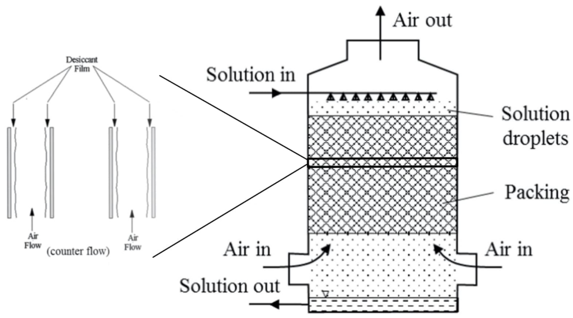


Figure 2.4: Fig. 3.2 Counter flow packed bed dehumidifier [4]

In a packed-bed dehumidifier, the air and the desiccant solution stream may have a cross-flow, counter-flow, or parallel-flow configuration. Liu and Jiang in [18] [19] theoretically studied the influence of the configuration of air and solution streams (i.e., parallel, cross, and counter) on the performance of a structured-packed-bed dehumidifier. When compared to parallel-flow and cross-flow configurations, the counter-flow configuration was found to be the most effective at air dehumidification.The dehumidifier used in the VLHU system is the direct-contact packed bed dehumidifier.

The system also uses a single-stage regenerator system, which includes a gas boiler for providing the external heat to heat the desiccant, which is connected to the regenerator, a solution-solution heat exchanger, and a condenser to remove the water vapors from the desiccant solution [20].

2.3. Traditional Heating systems

2.3.1. Heating system in Greenhouse

In the past, all of the water in the greenhouse was heated by a central gas boiler. This radiant heating method works on the same principle as the average central heating installations in homes [21]. In addition, this radiant heating system works the same way as most central heating systems in homes. The temperature and flow of heated water throughout the greenhouse can be precisely controlled using a mechanical pump and valve system.

Maintaining a greenhouse at an appropriate temperature range is essential to providing optimal conditions for plant growth. As a general guideline, greenhouses are typically kept between 21 to 30 $^{\circ}$C [22].

2.3.1.1 How Does the Boiler System Work

The way the boiler system works is that boilers generally use fuel like oil, gas, coal, or biomass to heat water or turn it into steam. The hot water is then pumped through pipes to areas where heat is needed and distributed. Once complete, the water is returned to be reheated in the boiler. Any water loss is replaced with fresh water [22].

Hot water is the most popular medium for carrying heat from the boiler to the greenhouse for several reasons. First, the temperature of the water in a hot water system can be changed to match how much heat the system needs. Hot water systems often provide better uniformity of heat distribution and can be placed closer to the plants [23].

Once hot water leaves the boiler, it is pumped to the greenhouse using a pipe system, unit heaters, or a combination of both. Pipes are placed overhead, under benches, or on perimeter walls, [24].

2.3.1.2 Advantages and Disadvantages of Central Boiler Heating System There are a number of advantages and disadvantages to the central heating system [23]:

1. A central plant offers greater flexibility to use alternative energy sources.
2. It uses less greenhouse space since the central plant is located in a separate building.
3. Maintenance and control are more accessible and cheaper.
4. Since combustion is done outside the greenhouse; improper combustion does not increase the probability of damaging the crop due to toxic flue gases
5. Produces direct emissions by burning fuel, which is harmful to the environment.

2.3.2. Heating Systems in Residential Homes

2.3.2.1 Gas Boiler

Gas boilers are found in almost every home and workplace, as we rely on boilers to provide reliable heat to the properties. Conventional gas boilers mainly consist of a furnace, heat exchanger, pump, thermostat, and a flue. Each element serves a specific purpose: to keep the home warm and provide the user with a continuous, reliable supply of hot water [25]. Essentially, a boiler is like a giant furnace or fire controlled by a thermostat. The boiler's primary function is to act as a heater and provide buildings with hot water for two primary purposes: providing hot water to the sinks and showers. The other is to provide hot water to the radiators for central heating applications [26].'

The boiler fires up by igniting the natural gas, which is the fuel. The heat exchanger warms up the water. A pump transports the water to the hot water storage tank for daily use. When the user sets the thermostat, the hot water moves through the radiators, emitting its heat energy to warm up the room. When the user turns on a tap, the hot water is also directed to water outlets in the bathroom and kitchen [27].

The Figure 2.5 depicts the general layout of a gas boiler in a typical dutch home. The efficiency of a fossil-fuel boiler is a measure of the amount of useful heat produced per unit of input energy [28]. In general the efficiency of a conventional gas heat can be described in Figure 2.6

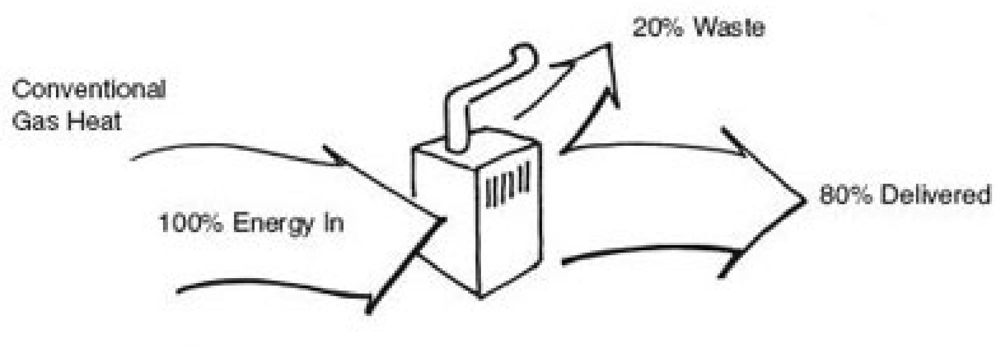


Figure 2.6: The efficiency of a general conventional gas boiler [28]

A natural gas boiler has a specific efficiency η_{Boiler} which is calculated by dividing the delivered heat Q_{output} by consumed chemical energy E_{input} in the natural gas as shown in Equation 3.3 [29]

$$\eta_{\text{boiler}} = \frac{Q_{\text{output}}}{E_{\text{input}}} \tag{2.2}$$

Hot water radiator systems are prevalent in Europe. Expect to replace boilers and radiators about every 10 to 15 years, which typically costs between $3,700 and $8,200 [30]

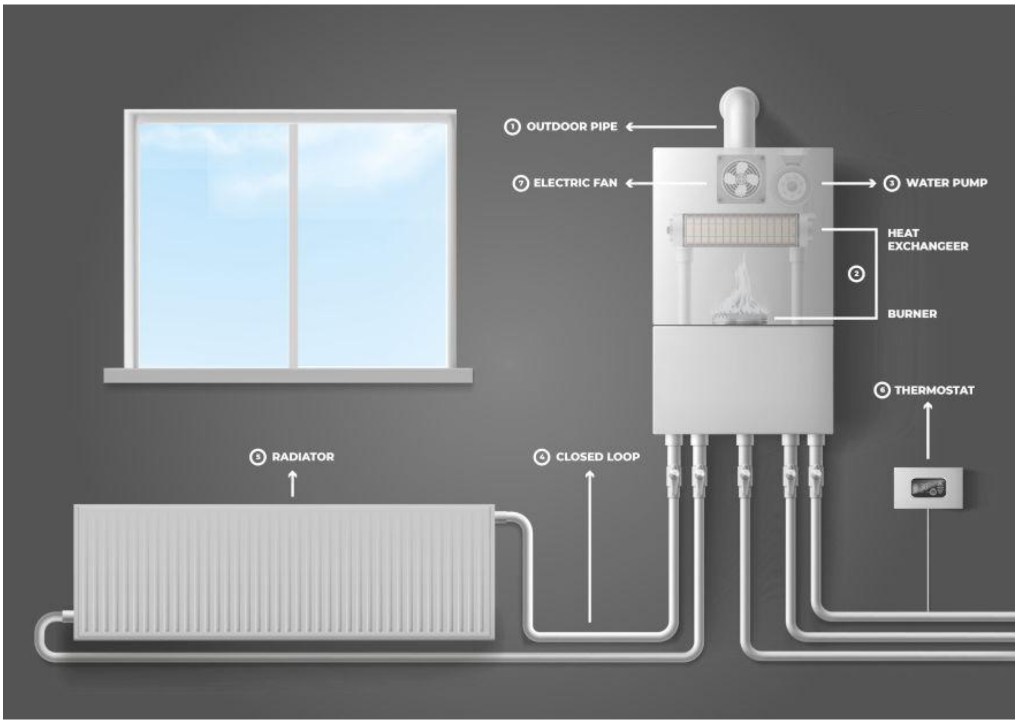


Figure 2.5: The components of a gas boiler [27]

2.3.2.1.1 Advantages and Disadvantages of a Gas Boiler System There are a number of advantages and disadvantages to the gas boiler heating system [31]

Advantages	**Disadvantages**
Less dry than forced air heating systems	Radiators can be unsightly
Radiators can be updated to baseboard or wall panel options	The placement of radiators may limit the placement of furniture or window coverings.
Energy-efficient with new boilers	Air conditioning cannot be combined with boiler-based systems.

Table 2.1: Advantages and disadvantages of gas boiler system

2.3.2.2 Electric Heating

Electric central heating can mean two things: replacing the old gas-powered boiler with an electricity-powered boiler or replacing the old radiators with electric radiators, which are decentralized [32]. Electric heaters have elements that make heat from electricity, which is then spread by convection. Electrical heating can be zoned, with thermostats in each room. The zoning out of heaters can help reduce overall consumption by decreasing temperatures in infrequently used areas. In radiated electrical heaters, heated air rises through metal fins, while cold air is drawn in through the bottom [33]. The best place to put the electrical heater is under windows, where the most heat will be lost. Also, they need to be set up an inch above the floor so that air can get in through the bottom [34].

Figure 2.7: Electrical Heaters [31]

The above Figure 2.7 shows how the electrical radiator looks like. Electric heaters are easy and inexpensive to install, typically costing between $450 and $1,200 [30], and they require no duct work, pumps, air handlers, or other distribution equipment. The units are inexpensive, have no moving parts, and require virtually no maintenance [31].

2.3.2.2.1 Advantages and Disadvantages of an Electrical Heating System There are a number of advantages and disadvantages to the electrical heating system [31]:

Advantages	Disadvantages
Versatile; can be installed anywhere with an electrical circuit.	Expensive to operate.
Silent operation without fans.	Use a lot of electricity; can overload electrical circuit.
No duct work or major installation needed.	Can contribute to air pollution and atmospheric carbon when using electricity powered by coal.

Table 2.2: Pros and cons of electrical heating.

2.3.2.3 Heat Pumps

The heat pump is the newest way to heat and cool a home. It uses a system similar to air conditioners to pull heat from the air and send it into the house through an air handler. Standard home systems are air-source heat pumps that draw heat from the outdoor air [31]. In essence, it accomplishes the following: The same as a gas-powered boiler, but without the use of fossil fuels.

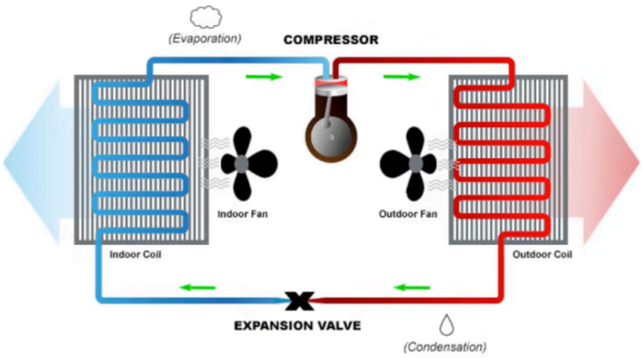


Figure 2.8: A schematic overview of the operation of a heat pump. [35]

The figure Figure 2.8 illustrates the operational principle of the heat pump. Heat pumps move heat by cycling a refrigerant through an evaporation and condensation cycle. The refrigerant is pumped between two heat exchanger coils by the compressor. In one coil, the refrigerant evaporates at low pressure and absorbs heat from the coil's surroundings. The refrigerant is subsequently compressed and delivered to the opposite coil, where it condenses under high pressure. It now releases the heat it collected earlier in the cycle. Because the heat pump cycle is completely reversible, heat pumps can provide year-round climate management for your home. Providing heat in the winter and cooling in the summer [35].

This method has the advantage of dehumidifying in the summer. Because the earth and air outdoors always contain some heat, a heat pump can provide heat to a house even on the coldest winter days. In the winter, an air-source heat pump takes heat from the external air and releases it in the summer. At the moment, the most prevalent form of heat pump found in Dutch homes is an air-source heat pump [29].

Heat pumps can be energy efficient, but they are suitable only for relatively mild climates; they are less effective in very hot and very cold weather. These systems usually last 15 years or more and cost about $4,200 to $7,300 to replace [31] [30].

2.3.2.2.1 Advantages and Disadvantages of a Heat Pump System There are a number of advantages and disadvantages to heating through heat pumps [31]:

Advantages	Disadvantages
Heating and cooling can be combined without needing ductwork	Best suited for relatively mild climates
Energy-efficient	Distribution of hot or cold air is limited
Precise temperature control for each room with quiet fans	Each unit must be controlled individually from separate rooms

Table 2.3: Pros and cons of a heat pump.

3
Methodology

After conducting the literature research, it was clear that most of the work done on the liquid desiccant systems was about the hybrid systems and how the liquid desiccants can be used to increase the efficiency of the existing systems by regenerating the waste heat and providing adequate cooling and dehumidification.

Our goal of this thesis, as shown in Figure 3.1 is to derive the thermodynamic equation of the heat released from the machine and a control scheme for the VLHU by creating a model in MATLAB. The methodology consists of a general model description, a specific model description, and mathematical equations.

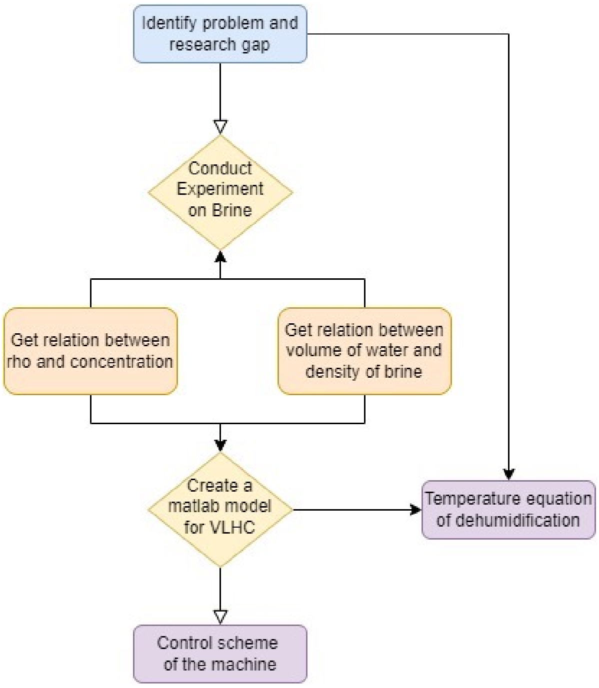


Figure 3.1: Flowchart for creating Matlab model for VLHU

3.1. Assumptions and Estimations

These are the list of the estimations and assumptions made for the VLHU for the ease of calculations and are considered while developing the model of the VLHU Unit.

Assumptions and estimations	
The temperature of the brine is on average 23℃ in the vapour heating unit.	Estimation from Dr Ten
The lower limit of density of brine is 1.12Kg/L.	Estimation from Dr Ten [36]
The upper limit of the density of the brine is 1.19Kg/L.	Estimation from Dr Ten [36]
The temperature of the water flowing from the regeneration unit to the dehumidifier reusing the regeneration is 41.2℃	Estimation from Dr Ten[36]
The temperature of the water flowing back to the regeneration unit is 34.2℃.	Estimation from Dr Ten[36]
Temperature of the water flowing from boiler to the dehumidifier is at 80℃.	Estimation from Dr Ten [36]
Temperature of water flowing from the dehumidifier back to the boiler is 50℃.	Estimation from Dr Ten [36]
A drop of brine takes 5 seconds to drop from top to the bottom of the dehumidifier.	Estimation from Dr Ten [36]
Heat from the boiler used to directly heat the air is 8.6 kW	Estimation from Dr Ten [36]
Gas going into the boiler is 0.955 liter/s	Estimation from Dr Ten [36]
Water flow from the boiler is 0.82Kg/s	Estimation from Dr Ten [36]
All the energy from condensation of water vapor is transferred as heat energy in the air.	Assumption
The temperature of the brine remains constant in the dehumidifier at 23℃.	Assumption
The machine works in steady state	Assumption
Heat exchangers are ideal, no heat loss	Assumption
Brine in the tank and dehumidifier are mixed uniformly	Assumption

Table 3.1: Assumptions and Estimations

3.2. General Model Description

We now know that the VLHU is a liquid desiccant system that turns latent heat into sensible heat to make heat energy. However, the energy output of the VLHU machine is composed of three principal energy flows:

(i) Heat of condensation
(ii) Heat reused from the regeneration
(iii) Heat from the boiler

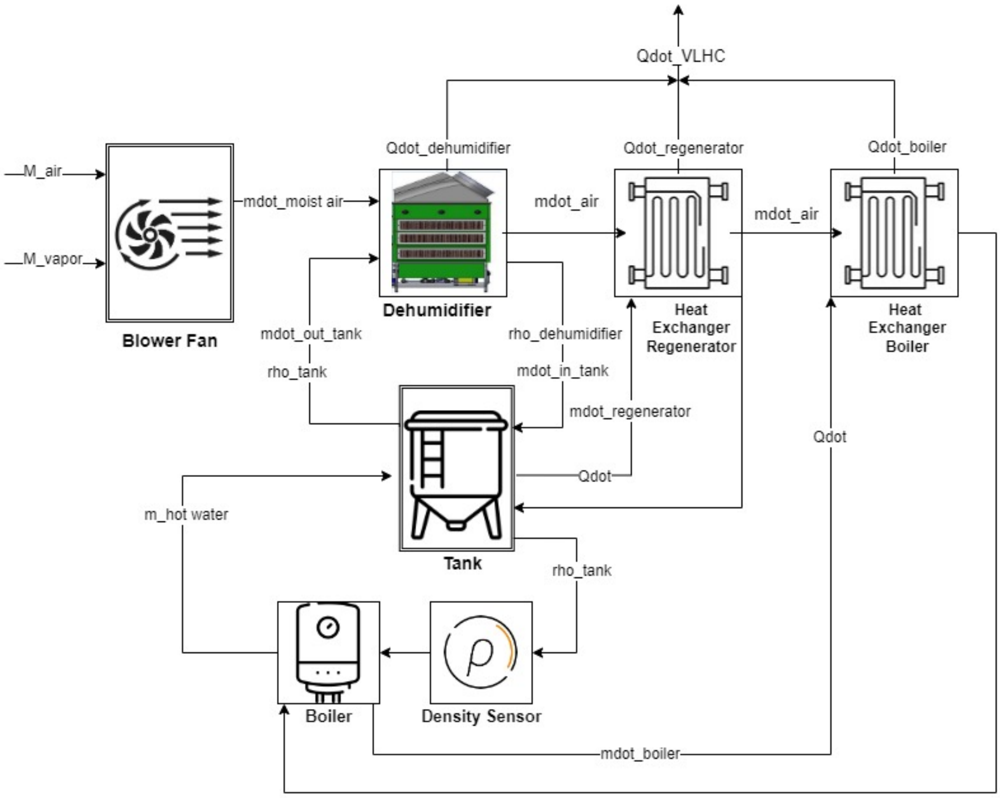


Figure 3.2: General model block diagram

Heat of condensation:

Condensation heat is the heat that is given off when the latent heat of condensation water is turned into sensible heat. It is assumed that all of the energy released when the water vapor in the air condenses in the dehumidifier is put into the air that comes out. It is given to us that the $\dot{m}_{\text{vapor}}$ = 5.5 g/s indicates that the water is entering the dehumidifier at the rate of 5.5 g/s. The heat of condensation of water vapor is 2260 kg/kj.

Heat Reused from Regeneration:

This heat flow is excess heat from the regeneration of the brine. The hot water that enters the regenerator at 80°C leaves the regenerator at 41.2°C with enough heat energy to directly exchange heat with the outgoing air. The water enters the direct water-air heat exchanger at 41.2°C and exits at 34.2°C. Thus, the extra heat is used to heat the air leaving the VLHU.

Heat generated by the boiler:

This heat flow is heat from the boiler that is not being used. Instead, some of the water from the boiler goes straight into the water-air heat exchanger of the VLHU, which heats the air leaving the

VLHU. The water enters the direct water-air heat exchanger at 80°C and exits at 50°C.

The Figure 3.2 explains the flows of the system. First, the blower sucks the mixture of air and water vapor into the dehumidifier. Then, as the name suggests, the dehumidifier absorbs the water vapor into the brine flowing through it and releases the heat of condensation.

Two loops are now formed, one for the air flows and one for the brine flows. The air that comes out of the dehumidifier first touches a water-air heat exchanger. Next, water heated by the reclaimed regeneration heat flows through this heat exchanger and heats the air. Finally, the heated dry air comes into direct contact with a second direct water-air heat exchanger, through which water directly from the boiler flows and transfers heat to the air. Finally, a blower fan distributes the air to the surrounding area.

As a result, the above loop requires specific relationships between the amount of water added and the density to model a VLHU machine control scheme. I conducted experiment on brine at Dr. Ten's lab to determine the relationship. Condensed water, on the other hand, is added to the brine in the tank. The brine begins with a density of 1.20 kg/L. As more water is added, the density of the brine decreases, and the process is repeated until the density reaches 1.12 kg/L. Once the density reaches 1.12 kg/L, the water in the brine must be evaporated in order for the density to return to 1.20 kg/L.

As a result, the brine enters the regenerator, where hot water from the boiler exchanges heats with the brine via a heat exchanger, evaporating the water in the brine. The density of the brine increases as the water evaporates. The boiler is turned off when the brine reaches a density of 1.20 kg/L, and the brine is returned to the dehumidifier. The brine's density should be, at most, the upper limit because it increases the likelihood of crystallization in the brine.

3.3. Specific Model Description

This section defines the mathematical approach towards constructing the model and the important loops running in the model to provide the results.

3.3.1. Density and Concentration

Modeling the control system of the VLHU machine requires knowing how the density of brine changes with its concentration. This is needed to make an algorithm for the workflow. As water is added to the brine solution, the salt mass stays the same, but the concentration of the brine changes, and the solution's mass keeps changing. Furthermore, by adding water to the brine, the brine is diluted, resulting in a change in density. The data from the experiment was noted in Table A.1, the observations were plotted, and an equation was made to show the relationship between density and concentration when brine is diluted.

3.3.2. Density and Heat Released

Also, we need to find a link between the density of the brine and the amount of heat it gives off so that we can use the primary equation as the basis for an algorithm to control the system. The dehumidifier releases the condensation heat as the water vapor condenses and dilutes the brine. Therefore, we plot a relationship between the density of the brine and the rise in temperature using the observation table Table A.1

3.3.3. Algorithm Workflow

Firstly, to understand the workflow of the algorithm, it is important to realise that a dehumidifier and a tank are two different but interconnected entities. The water vapor condenses into the brine in the dehumidifier, and the boiler is turned on and off using the humidity sensor which is housed in the tank.

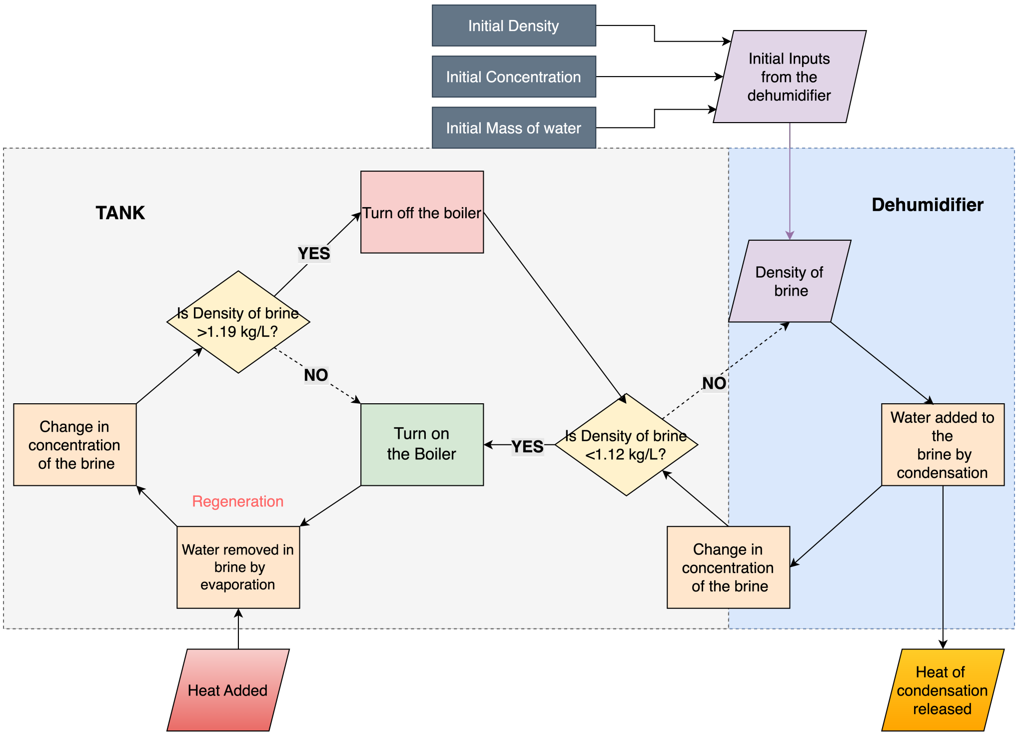


Figure 3.3: Algorithm workflow of the model.

In the Figure 3.3, it is shown that the workflow begins at the dehumidifier. Firstly, initial conditions are defined for the dehumidifier. When the boiler is off, water vapor will be added to the brine in the dehumidifier, condensing into the brine and producing the heat of condensation. This is the only source of heat released which is the heat of condensation when the boiler is off. By adding water vapor to the brine, it will change the concentration of the brine in the dehumidifier. This diluted brine will go into the tank, which will change the density of the brine in the tank. The system will again confirm the density of the brine in the tank using the liquid density sensor in the tank. If the density of the brine is greater than the ρ_{min} = 1.12 kg/L, the loop will continue as it is, and the tank will keep flowing the water through the dehumidifier.

If the value of the brine density in the tank is less than the ρ_{min}, then it sends a signal to turn on the boiler. It is assumed that the boiler has no delay. As the boiler is turned on, a new loop begins with the regeneration process. The regeneration process increases the density of the brine by evaporating water present in the brine.

Furthermore, as the water is evaporated from the brine in the second loop, it changes the brine concentration in the tank. Therefore, as the density of the brine goes up, the system recalculates the density of the brine in the tank. If the brine density reaches its maximum value, defined as ρ_{max} = 1.20 kg/L, the boiler is turned off, or else the boiler remains on.

It is vital to know that the dehumidifier loop is always on, no matter the state of the boiler. The regeneration loop is only activated when the brine density drops below the minimum value defined. When the boiler is on, more water is removed from the brine than is added, and when the boiler is off, only water is added to the brine, gradually diluting the brine.

3.4. Mathematical Definition of the Proposed model

This section explains the mass and volume balance of the system and the mathematical equations used to produce the mathematical model.

Firstly, we figure out how much liquid is in the machine and how much liquid is in the dehumidifier. The total mass of the liquid in the system is $m_{\text{total}} =$ 110 kg, and the initial density of the brine is $\rho =$ 1.12 kg/m^3 [36]. The mass flow of the brine in the dehumidifier is $\dot{m}_{\text{pump}} =$ 1.21 kg/s and the time taken by the brine to pass through the dehumidifier is $t_{\text{brine}} =$ 5 s [36]. We use the following equation to find the brine volume in the dehumidifier at a particular moment. [37]

$$v_{\text{dehumidifier,initial}} = t_{\text{brine}} \cdot \frac{\dot{m}_{\text{pump}}}{\rho} \tag{3.1}$$

It is critical to know the volume of brine in the dehumidifier, the amount of water vapor entering and leaving the dehumidifier because the heat emitted by condensation of water will be calculated based on the brine volume in the dehumidifier in contact with the water vapor in the air. We use the equation:

$$\dot{q}_{\text{boiler}} = \dot{m}_{\text{out}} \cdot cp \cdot \Delta T + \dot{m}_{\text{out}} \cdot cl \tag{3.2}$$

where Cp is the specific heat of water and Cl is the latent heat of evaporization water. [38]

3.4.1. Volume and Mass Balance

The further calculation is based on the system's mass and volume balance. The mass balance is done by assuming that the system's mass does not change when matter enters and leaves the system.

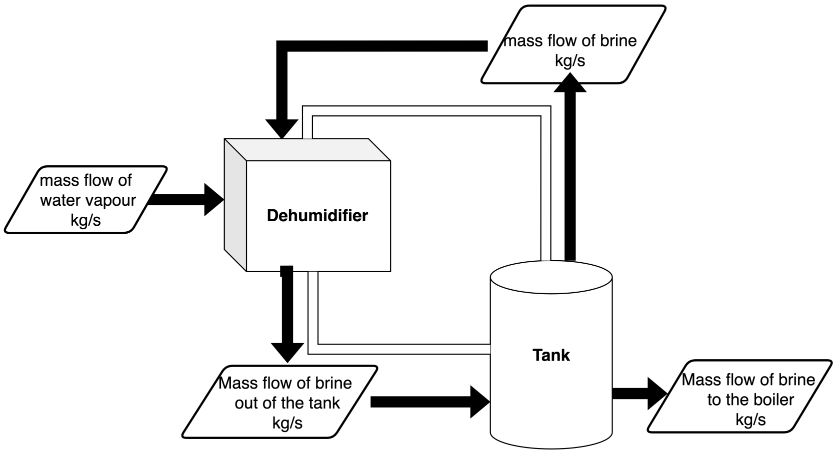


Figure 3.4: Inputs and outputs in the machine

In the Figure 3.4 it is visible that there is a constant loop between the tank and the dehumidifier. Assuming the total mass of the brine remains the same at the start and end of the cycle, the volume balance of the brine is applied to the loop. According to the Figure 3.4 by adding the water in the dehumidifier denoted by $m_{\dot{\text{vapor}}}$, it changes the volume of the brine in the dehumidifier, that changes the concentration and density of the brine in dehumidifier and tank separately.

Volume balance in the dehumidifier is given by the equation 3.3

$$V_{\text{Dehumidifier}}(t+1) = V_{\text{Dehumidifier}}(t) + \sum_{i=1}^{n} V_i^{\text{Dehumidifier}} \Delta t \tag{3.3}$$

where,

$$\sum_{i=1}^{n} V_i^{\text{Dehumidifier}} = V_{\text{Vapour}} + V_{\text{out\_tank}} - V_{\text{in\_tank}} \tag{3.4}$$

which can also be written as

$$\sum_{i=1}^{n} V_i^{\text{Dehumidifier}} \Delta t = \frac{\dot{m}_{\text{vapour}} \cdot \Delta t}{\rho_{\text{Water}}} + \frac{\dot{m}_{\text{out\_tank}} \cdot \Delta t}{\rho_{\text{tank}}(t)} - \frac{\dot{m}_{\text{in\_tank}} \cdot \Delta t}{\rho_{\text{Dehumidifies}}(t)} \tag{3.5}$$

so, from Equation 3.3 , Equation 3.4 and Equation 3.5, we get

$$V_{\text{dehumidifier}}(t+1) = V_{\text{dehumidifier}}(t) + \left(\frac{\dot{m}_{\text{vapor}}}{\rho_{\text{water}}} + \frac{\dot{m}_{\text{out\_tank}}}{\rho_{\text{tank}}(t)} - \frac{\dot{m}_{\text{in\_tank}}}{\rho_{\text{dehumidifier}}(t)} \right) \cdot \Delta t \tag{3.6}$$

Now similarly for the mass balance of the system,

$$m_{\text{dehumidifier}}(t+1) = \rho_{\text{dehumidifier}}(t) \cdot V_{\text{dehumidifier}}(t+1) \tag{3.7}$$

and for concentration balance of the brine in the dehumidifier,

$$C_{\text{dehumidifier}}\,(t+1) = \frac{m_{\text{salt\_dehumidifier}}}{m_{\text{dehumidifier}}} \tag{3.8}$$

All of the above equations are used to change the brine density used to control the machine by using the empirical equation Equation 4.1 analysed in chapter 4.

$$\rho_{\text{dehumidifier}}(t) = 0.6927 \cdot C_{\text{dehumidifier}}\,(t) + 0.9352 \tag{3.9}$$

Similarly equations are used for the volumetric and mass balance in the tank

$$V_{\text{tank}}\,(t+1) = V_{\text{tank}}\,(t) + \left(\frac{-m_{\text{boiler}}}{\rho_{\text{tank}}}(t) - \frac{\dot{m}_{\text{out\_tank}}}{\rho_{\text{tank}}\,(t)} + \frac{\dot{m}_{\text{in\_tank}}}{\rho_{\text{dehumidifier}}\,(t)} \right) \cdot \Delta t \tag{3.10}$$

and mass balance is

$$m_{\text{tank}}(t+1) = \rho_{\text{tank}}(t) \cdot V_{\text{tank}}(t+1) \tag{3.11}$$

and for concentration balance of the brine in the dehumidifier,

$$C_{\text{tank}}(t+1) = \frac{m_{\text{salt\_tank}}}{m_{\text{tank}}}(t+1) \tag{3.12}$$

To define the relationship between temperature and change in density, empirical equation Equation 4.2 is used which is analysed in chapter 4.

$$T(\rho) = -2609.1\rho^2 + 5872.6\rho - 3270.7 \tag{3.13}$$

Furthermore, for the machine's control scheme, we define the maximum and minimum value of the ρ. The boiler is turned on if the density is below the minimum value until the density reaches the maximum value. Then the boiler is turned off until the density reaches its minimum point. Hence the machine is controlled by the density of the brine, which depends on the volume and the mass balance of the machine defined above.

Furthermore, to calculate the heat release, we use the empirical equations Equation 3.9 and Equation 3.13 for the relationship between the brine's temperature and the brine's density. As we can define the temperature in terms of density, we use the following equation to calculate the amount of heat released from the dehumidifier.

$$\dot{Q} = \dot{m} \cdot c_p \cdot \Delta T(\rho) \tag{3.14}$$

To calculate the heat released from the heat exchanger by the reuse of the regenerator water, the following equation Equation 3.15 is used where the T_{out} and T_{in} are the temperature of the water going out from the regenerator and coming in to the regenerator respectively.

$$\dot{Q}_{\text{regenerator}} = \dot{m}_{\text{regenerator}} \cdot c_p \cdot (T_{\text{out}} - T_{\text{in}}) \tag{3.15}$$

Similarly, to calculate the heat released from the heat exchanger by the boiler water, the following equation Equation 3.16 is used where the $T_{\text{out boiler}}$ and $T_{\text{in boiler}}$ are the temperature of the water going out from the boiler directly to the heat exchanger and coming back to the boiler respectively.

$$\dot{Q}_{\text{boiler reuse}} = \dot{m}_{\text{boiler reuse}} \cdot c_p \cdot (T_{\text{out boiler}} - T_{\text{in boiler}}) \tag{3.16}$$

4

Results and Analysis

In this chapter the results obtained from the performed study are presented and discussed. This section discusses the empirical equations derived which are used in the mathematical model on Matlab, various results derived from the model, the advantages and challenges of replacing the gas boiler with an electrical boiler and whether the machine is suitable for heating the residential houses of The Netherlands.

4.1. Heat Conversion

This section discusses the results obtained from the Matlab model for the heat conversion that takes place in each component of the VLHU machine that is the boiler, dehumidifier and the regenerator. To understand the results obtained, it is important to know how the derived empirical equations is useful simplify a complicated model. Furthermore the results obtained from the model is analysed

4.1.1. Empirical Equations

Empirical equations are based on observations and experience rather than theories [39]. As explained in subsection 3.3.1 and subsection 3.3.2 to produce an equation between density, concentration and heat, the experiment was performed on the LiCl brine explained in Appendix A. The data collected from the experiment for density, concentration and heat released of the LiCl brine as put together in the observation table Table A.1 and plotted together to derive a relationship between two quantities.

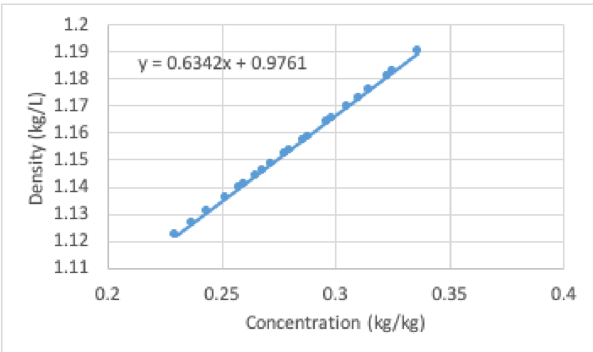


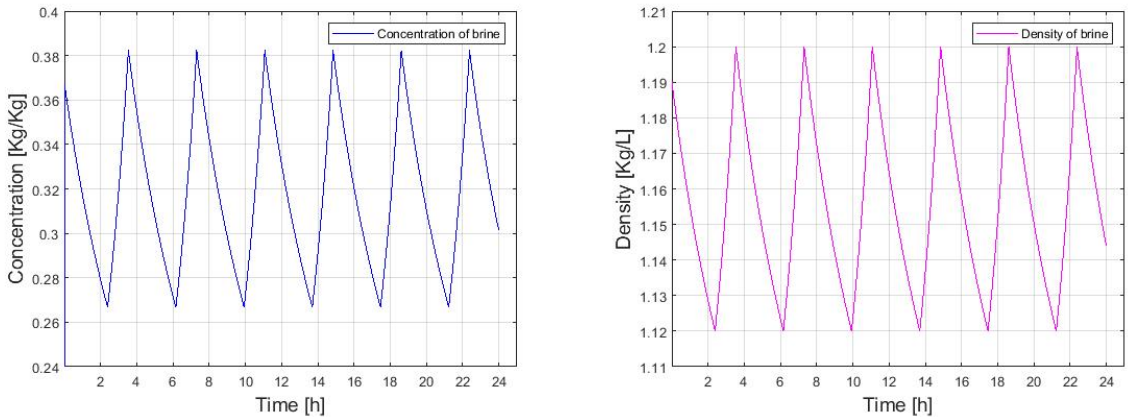
Figure 4.1: Density vs concentration

The plot in Figure 4.1 shows a linear relationship between the density and concentration. Thus by plotting the graph in the curve fitter [40] the following equation is derived.

$$c(\rho) = (\rho - 0.9352)/0.6927 \tag{4.1}$$

This equation is required to provide a relation between ρ that is the function of the concentration. As the water $\dot{m}_{\text{vapor}}$ is added to the concentrated brine, the concentration of the brine decreases, which changes the density of the brine.

As change in density is the primary driver of the machine, the control scheme is modeled based on the empirical equation equation Equation 4.1. The graphs Figure 4.2b , Figure 4.2a depicts the change in concentration and change in density with respect to time respectively. The density is always between the minimum and maximum value defined for the model which in this case is 1.12 kg/L and 1.20and how the concentration changes along with it.



(a) Change in concentration of the brine

(b) Control scheme of the model based on density

To produce the equation between density and temperature, the experiment Appendix A is performed on the brine where the affect on temperature of the brine is recorded along side with the change in density of the brine. The data of density and temperature is then plotted Figure 4.3

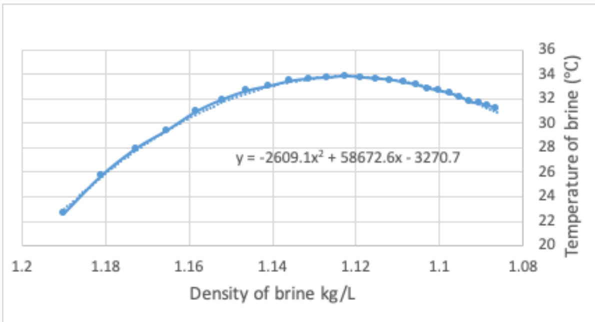


Figure 4.3: Temperature vs Density

As seen in Figure 4.3, we can see that the relation is parabolic in nature. Thus by plotting the graph in the curve fitter [40] we derive the following equation

$$T(\rho) = -2609.1\rho^2 + 5872.6\rho - 3270.7 \quad (4.2)$$

So now as we can clearly see that the increase in temperature is not linear to the decrease in density. Thus the heat released by the condensation of the water is directly proportional to the change in temperature ΔT. This equation is important for the model as it helps derive the amount of heat released with respect to the decrease in density.

4.1.2. Model Results

Before, discussing the model results, it is crucial to know the initial conditions that were considered for the calculations done below.

In the model, we first define the initial conditions as defined in Table 4.1 which are provided by Dr. Ten and specification sheet of VLHU machine and other initial conditions considered.

Initial Conditions		Units
$\dot{Q}_{boiler}$	50000	W
Cp	4200	J/kg
Cl	2260000	J/kg
T_{tank}	23	$^{\circ}C$
$\dot{m}_{vapor}$	0.005	kg/s
ρ_{water}	1	kg/L
$\dot{m}_{out,Tank}$	1.21	kg/s
m_{total}	110	kg
m_{salt}	40	kg
$\dot{m}_{boiler}$	0.019	kg/s
ρ_{min}	1.12	kg/L
ρ_{max}	1.20	kg/L
c_0	0.3678	kg/kg
G_{fuel}	3.94	m^3
NCV_{fuel}	31.65 [41]	MJ/m^3
η_{boiler}	0.85	%
η_{boiler}	0.95	%

Table 4.1: Initial Conditions

As discussed in chapter 3 the final output of the heat from the VLHU machine is from three different sources. As mentioned in section 3.2 the total heat produced from the VLHU is the sum of heat of condensation, heat reused from regenerator and heat from the boiler as shown in Figure 4.4. The tower in the graph corresponds to the total heat emitted by the VLHU per cycle.

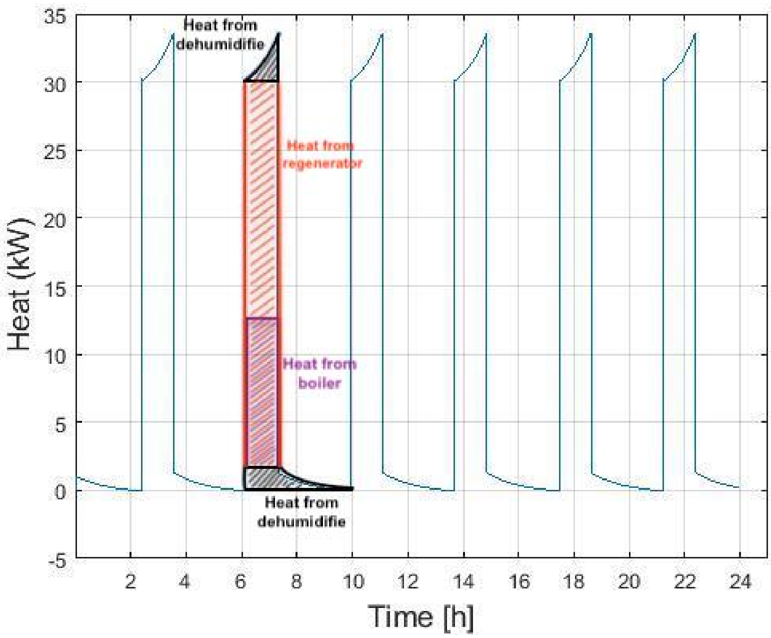


Figure 4.4: Total Combined heat released from the machine

The area marked with red in Figure 4.4 is the heat energy produced by the reused heat from the regenerator as once the brine is regenerated in the regenerator, the hot water used for regeneration still has enough energy left to directly generate heat with the heat exchanger. Similarly the area marked with violet in Figure 4.4 is the heat energy produced by the extra energy released by the boiler, as the extra hot water from the boiler directly goes to the heat exchanger to release the heat from the boiler.

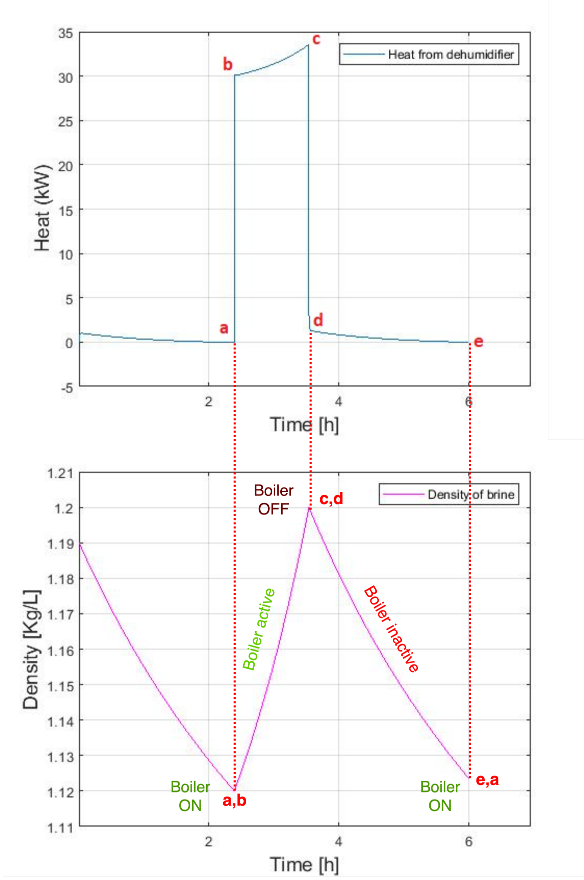


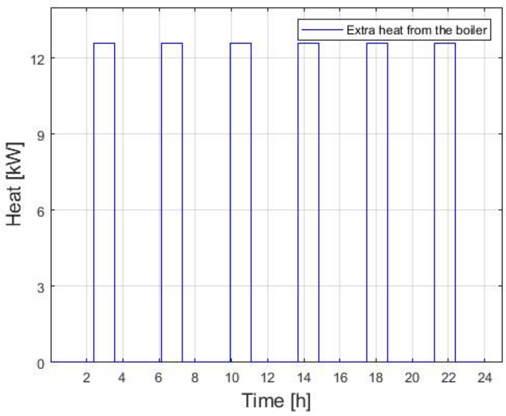
Figure 4.5: Total Heat released by the machine in a single cycle with respect to density change

Finally, the area marked with black is the heat produced by the condensation of the water vapors in the dehumidifier. This is the additional heat produced by the VLHU compared to the traditional gas boiler systems. The heat produced by dehumidifier is directly exchanged with the air blowing through the dehumidifier and into the surroundings. Thus by adding all the three release of heat energy, we get a total energy released when the boiler is turned on with the peak of energy released due to the heat of vaporization captured in the machine.

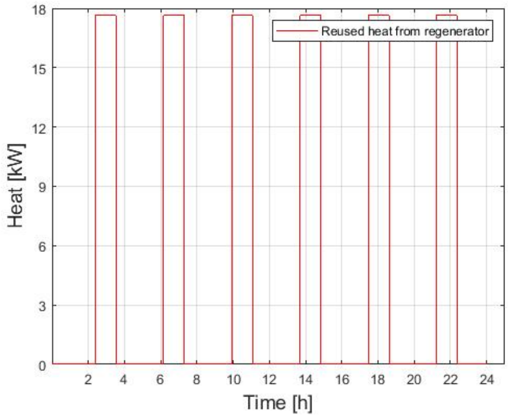
To better explain how the total energy flows, Figure 4.5 shows a single cycle of the total energy flow concerning the change in density.

1. From a-b, the boiler is active. As the boiler is active, as explained in subsection 3.3.3 the regeneration process begins. The heat from the regenerator and boiler is released as the boiler is switched on.
2. From steps b-c, the boiler remains active as the regeneration process begins, and the density increases. As the density increases, additional heat is released from the dehumidifier. The relationship between the heat released and the density is $\Delta\rho \propto \dot{Q}$. Therefore, heat is released proportionally as the density change rate increases.
3. The boiler then becomes inactive from steps c-d as the brine density reaches its maximum value. As the boiler is switched off, the heat extra heat from the regenerator and the boiler stops. Thus, the heat released drops and the only source of the heat released is the heat of condensation.
4. In the next step from steps d–e, the boiler is inactive until the density reaches its minimum value. The heat is then released proportionally to the density change as the density in the dehumidifier is reduced. This is the heat of condensation being released from the dehumidifier of the VLHU. And then, the cycle repeats as the density reaches its lowest point.

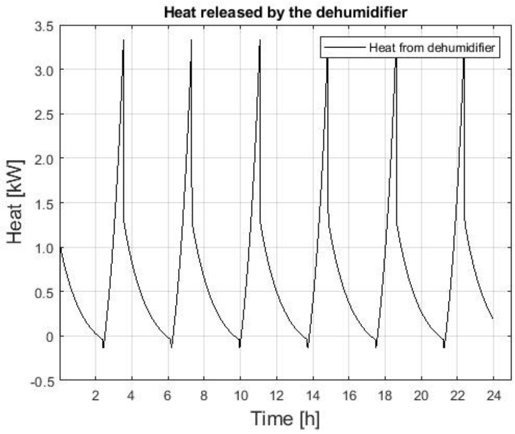
Furthermore, to have a better understanding of the heat released, we have a look at the individual



(a) Extra heat released from the boiler



(b) Reused heat from the regenerator



(c) Heat released by the dehumidifier

heat released. First one is the heat released from the use of extra boiler water that goes directly to the dehumidifier to exchange the heat with the air being released. The amount of heat produced just by the boiler alone is shown in the Figure 4.6a.

As seen in the Figure 4.6a we can see that whenever the boiler is turned on for the regeneration purpose, it also send excess hot water directly to the heat exchanger in the dehumidifier and releases heat to the air. Now the second source of heat is the heat that is reused from the heat of regeneration as after regenerating the brine. As the hot water from boiler, heats the brine, the boiler water is still hot and is sent to the second heat exchanger in the dehumidifier and thus it releases the unused heat directly to the air in the dehumidifier itself. Figure 4.6b shows the amount of heat released by the heat exchanger by reusing the regenerator waste heat. And finally, the third source of the heat from the machine is the heat released by the dehumidifier. The Figure 4.6c shows the heat released from the dehumidifier by converting the latent heat of the water absorbed to the sensible heat.

4.1.3. Validation of Model Results

As we have discussed the results produced from the model above, it is crucial to validate the results.

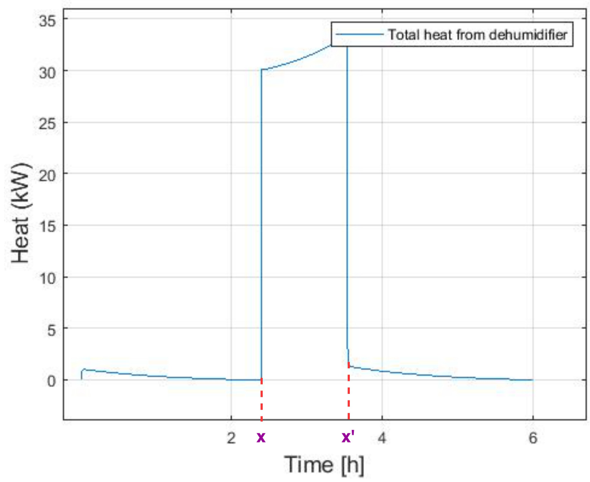


Figure 4.7: Total time taken by once cycle of the VLHU

The Figure 4.7 shows the amount of time taken to complete one cycle. Firstly, we have to compare the theoretical and calculated values of the VLHU machine's efficiency to validate the model's results. From Equation 2.1 we know the efficiency of the boiler is

$$\eta_{\text{boiler}} = \frac{Q_{\text{output}}}{Q_{\text{input}}} \tag{4.3}$$

For one cycle of the dehumidifier, as shown in Figure 4.7 the gas boiler switched on at point **x** and is active till point **x'**. The time between x and x' is calculated, and it comes out that the boiler remains switched on for 4125 seconds, or ΔT = 1.145 h. We know from the initial data mentioned in Table 4.1 that the gas flow to the boiler is 0.955 liters per second. Thus we know that for each cycle, the gas used by the boiler is $G_{\text{fuel}} = 3.93m^3$ and from Table 4.1 we know $Q_{\text{input}} = 50kW$.

Thus, for the theoretical value, we use the Equation 3.3 to calculate the energy output, which is $Q_{\text{output, theory}}$ = 119.36 MJ, which, when converted to kW, gives us $Q_{\text{output,thoery}}$ = 33.15 kW [42]. So, the efficiency of the theoretical VLHU is

$$\eta_{\text{VLHU,theory}} = \frac{33.15kW}{50kW} \tag{4.4}$$

that is equal to $\eta_{\text{VLHU,theory}}$ = 66.3%

Furthermore, for calculated value of the efficiency of VLHU, from the graph Figure 4.4, we get $Q_{\text{output,calc}}$ = 33.56 kW. Thus the efficiency of the calculated value of VLHU is given by

$$\eta_{\text{VLHU,calc}} = \frac{33.56kW}{50kW} \tag{4.5}$$

that is equal to $\eta_{\text{VLHU,calc}}$ = 67.12%

The efficiency of the VLHU systems calculated are peak efficiencies as the efficiency depends on the current concentration of the brine. As the percentage error between the theoretical value and the calculated efficiency value of the VLHU is less than 2%, it is safe to say that the model created has a valid result.

4.2. Effects of Replacing Gas Boiler With Electrical Boiler in VLHU

This section explains the effects on the system by replacing the gas boiler in VHLU with an all-electric boiler to reduce the direct emission release and see weather this can be achieved.

4.2.1. Efficiency

It is assumed that that the heat output of the boiler in the VLHU unit remains the same, to replace the gas boiler with electrical boiler, first we have to look at the efficiency of each boiler. The gas boiler is

88% efficient [43] and the efficiency of the electric boiler is 99.5% [32]. It is considered to use a 50 kW heat output electrical boiler.

4.2.2. Installation

Since there are no waste gases produced by an electric heating boiler, there is no need for a chimney or flue system, making the installation of the boiler quicker and less expensive than that of a gas or oil boiler (no oil tank is needed, for example). Electric boilers can be installed by any qualified heating expert, and their installation costs are less than those for gas boilers.[32].

Even though the electrical boilers are easier to install, they have specific electrical requirement analysed below

1. The nominal electric supply voltage required for the electric boiler is 230 / 400V ± 10%, 50 HZ,3-phase, 4-wire with separate neutral and protective conductor [44].
2. Cable reuired for the connection of 50 kW electric boiler is 3x25 mm^2 copper wires [45].
3. Heater fuses required are 5 x 3P C25A [46]
4. Main circuit breaker should be 80 A [45].

As the electrical boilers do not produce waste gases, they do not require a flue or chimney, the unit is significantly more compact and lighter, giving more option in where you install it. This increases their versatility in terms of where they can be positioned on the land. The majority of electric boilers are compact in size.[32]

4.2.3. Cost Analysis

This section compares the initial and running cost on the system of replacing the gas boiler in VHLU with an electric boiler. As explained in chapter 2 the initial cost of an electric boiler is lower than the initial cost of the gas boiler because they do not have gas valves, fans, burner or additional gas tanks; electric boilers are cheaper to buy than gas boilers [32]. Electric boilers are easier to keep up with because they have fewer moving parts and need less service than gas boilers. However, it is costlier to run an electric boiler directly from the grid than a gas boiler, as seen in the table Table 4.2

Greenhouse Usage (Calculated)	Per Cycle	Costs (€/Unit)	Cost (€/Cycle)
Electricity	30.56 kWh	0.2203 [47]	6.73
Gas	3.93 m^3	0.7868 [47]	3.09

Table 4.2: Comparison of the running cost of gas and electrical boiler per cycle

The comparison of the running cost and environmental impact of the gas boiler and electric boiler is done per cycle of VLHU. In the current scenario, the VLHU consumes 0.955 L/s of gas per and each cycle is 4125 s or 1.145 h. Thus volume of gas consumed by VLHC per cycle is (1.145 h)x(0.955 L/s)/1000 = 3.93 m^3. It is known that 1 m^3 of gas yields 31.65 MJ [41]. This means that 3.93 m^3 of gas produces 124.4 MJ or 34.45 kWh of heat is released. For a boiler with an efficiency of 88%, that is (34.45 kWh)x(0.88) = 30.4 kWh of proper heat. If an electric boiler is used to supply that amount of energy, you will have that the input energy of the electrical boiler is (30.4 kWh)/(0.995) = 30.56 kWh per cycle.

Comparing the running costs for both boilers, we can observe that an electrical boiler costs more than double the cost of running a gas boiler.

4.2.4. CO_2 Emissions

It important to analyse the emissions released from a gas boiler and an electric boiler per cycle and compare it to each other for a better overview of both the products. As discussed in chapter 2, as gas boiler burns natural gas, there are direct emissions involved. For the electric boiler, even though direct emissions are not involved, but upstream emissions for producing the electricity is involved. As per [48] 0.325 kg of CO_2 is released per kWh of electricity used and as per [49] 2.56 kg of CO_2 is released upon burning of 1 m^3 of natural gas. Both of the emissions include direct emissions factor and upstream emission factor which includes drilling, transportation, distribution etc. The Table 4.3 provides the overview of how much emission is produced by gas and electric boiler per cycle of VLHU.

Greenhouse Usage (Calculated)	Per Cycle	Total Emission (CO_2/ m^3 or kWh)	Total Emission (kg CO_2/Cycle)
Electricity	30.56 kWh	0.325 kg/kWh [48]	9.932
Gas	3.93 m^3	2.56 kg/m^3 [49]	10.1

Table 4.3: Comparison of emissions from gas and electrical boiler

According to the Table 4.3 above, it can be observed that an electrical boiler produces more CO_2 emissions than a gas boiler because the electrical energy being produced at the grid is not entirely sustainable and still uses fossil fuels. Thus, when electricity is produced via burning fossil fuels and that electricity is again converted to heat, it loses efficiency; thus, more CO_2 is produced compared to a direct gas boiler. However, electric boilers do not have direct emissions because the emissions happen where the electricity comes from, not in the boiler. On the other hand, the emissions produced by gas boilers are direct, as they are produced where the boiler is installed. Thus it is more harmful to the environment to switch to electric boilers

4.2.5. Comparison of gas boiler and electrical boiler

From the discussions above, the results can be tabulated to have a precise look at the comparison between gas boiler and electrical boiler which could provide a basis to make the decision of replacing gas boiler with an electric boiler

	Gas Boiler	**Electrical Boiler**
Efficiency	88%	99.5%
Installation	More complicated to install as more parts are involved	Much simpler to install
Location	Require more area to install chimney system for flue gas	Can be installed anywhere as it is safe when operational.
Costs	Even though initial costs are higher but running cost is significantly lower	Though, initial costs are low, the running cost of the electrical boiler is high.
Emissions	10.1 kg of CO_2 released per cycle	9.932 kg of CO_2 released per cycle
Additional equipment	Gas Piping Flue gas Chimney system Gas tank Natural gas connection	400V/80A Electrical connection Fuse box Wiring

Table 4.4: Comparison table for gas and electrical boiler

According to the Table 4.4, it can be determined that it is preferable to replace the gas boiler with an electric boiler, but only in new systems that will be implemented, rather than replacing the gas boilers that are currently in place. It is because, from the Table 4.4, we can see that the electric boilers are more efficient than the gas boilers, can be installed quickly, have comparatively less CO_2 emissions, and reduces the initial cost of the VLHU system as electrical boilers cost less than gas boilers. The only drawback would be that operating costs would increase with integration of the electrical boiler and initial investment to upgrade the electrical fuse box to accommodate the boiler.

4.3. VLHU in a Residential Environment

This section analysis the pros and cons of putting the VLHU machine in a green village home. This section will look into the physical barriers that is faced to install the VLHU system in a residential home. Firstly , let us analyse the possible hindrance and limitations that can occur by installing the VLHU machine in a residential environment :

1. **Brine:** It is essential to identify the health hazards of the brine liquid used in the VLHU. In this case, LiCl, some droplets of the brine can be blown out of the VLHU and directly inhaled by the inhabitant.

2. **Pipe & electrical connections:** A new set of connections for gas pipes will be required to connect the gas boiler to the VLHU system. Also, an additional electrical connection must be given to work the VLHU machine's electrical components, such as pumps and blowers.
3. **Ventilation:** As this is a warm air system, the heating is done through ducts and vents instead of traditional radiator heating, which happens due to convection. It is feasible If a warm air system is installed as part of the initial design of the building, but trying to retrofit ducts into the property is going to be complicated and a costly process, and the house will probably end up with visible ducts all over the house [50]. Moving air also aggravates allergies because the heating system constantly circulates air throughout the room [35].
4. **Engineering:** One of the most significant barriers for the VLHU system to be implemented in a residential setting would be maintaining constant/high humidity levels in the house for the machine to work efficiently. As the machine dehumidifies the air, the air becomes drier because, unlike plants, humans do not perform evaporization. It is also essential to add an extra connection from the boiler to the hot water system to use the hot water directly. Lastly, there are only a few companies that install an air-based heating system, thus finding the installer can be hard

The size of the boiler required for VLHU unit in the residential home would depend on the heat consumption of The average heat consumption of a Dutch household is known to be 9444 kWh [29]. Therefore, if we consider the efficiency of the VLHU system to be 67.12% as calculated above, we would require a gas boiler of the size of approximately 15 kW for the VLHU system. Furthermore, if we only require a boiler for the same average heat consumption, a boiler of size 10-11kW would be required to satisfy the heat demand [43].

Furthermore, comparison between gas boiler and gas boiler heating system with VLHU, is plotted in Table 4.5 to provide an overview of the analysis above.

	Gas Boiler	**Gas Boiler with VLHU**
Efficiency	88%	67.12%
Size of the Boiler	11 kW	15 kW
Ventilation	No ducts required	Ducts are required
Extra connections	No additional connections required	Additional gas pipes and electrical connection is required
Space	Requires small space inside the house	Requires large space, probably outside the housing as gas boiler and VLHU are 2 different units.
Noise	Noise level <48 db	Noise level >80 db as VLHU consist of a additional blower to move the air
Health Hazards	Hazardous pollutants from the boiler can leak into the air. High levels of CO can be harmful	Additional to the threats from the boiler, VLHU also possess a threat of the brine entering directly in the air which can be inhaled. Harmful effects of the brine should be known.
Health Benefits		VLHU helps in maintaining the humidity level of the house between 40-60% which is the ideal room humidity. Higher level of humidity could cause asthma, moulds ,etc and lower humidity causes dryness and sore throat.

Table 4.5: Comparison between traditional and VLHU gas boiler system

According to the table Table 4.5 comparison above, a VLHU system is a large and complex system requiring more space to install and heat. Furthermore, since it makes much noise, it should be set up a little farther away, which is impossible in a residential house. Therefore, installing a VLHU system in a residential house is possible. However, it costs more than just a gas boiler, and it would be an engineering challenge to maintain a constant relative humidity in the house.

5

Conclusion

This chapter, which concludes this thesis report, will react to the research questions by summarizing earlier content in the report. Furthermore, recommendations for further research will be presented.

Research Questions

- How can the heat conversion in the dehumidifier, regenerator and boiler be described?

The heat conversion of the VLHU is that with the input of 50kW, the efficiency of the VLHU is calculated to be 67.12%. Therefore, the total heat released per cycle is 33.56 kW, where the heat produced by the regenerator is 53%, the heat produced by the boiler is 35%, and the remaining heat is produced by the dehumidifier which contributes to 12% of the total heat released.

- What are the effects of replacing the gas boiler with an electrical heater of the ventilated latent heat unit (VLHU) in a greenhouse?.

Initially, it is easier to replace gas boilers with electrical boilers in new installations as the it has lower initial cost of and installation of the electric boiler is simpler. Electric boiler produces 9.932 kg of CO_2 per cycle compared to 10.1 kg of CO_2 per cycle, thus it does not make sense to replace the existing gas systems as it would costly to replace the boiler and it does not provide a significant reduction in the emission of CO_2 because electricity is still produced in the Netherlands by burning fossil fuels.. However, the running cost of the electrical heat is more than double that of the gas boiler.

- s the ventilated latent heat unit (VLHU) suitable for the Green Village test house?

After the comparison of the traditional heating system and gas boiler system with VLHU, it is concluded that VLHU may not be as effective in a residential home as in a greenhouse. Firstly, the VLHU saves much energy in the greenhouse as it decreases the loss of energy by keeping the windows shut, and plants provide a stable environment for the VLHU to function. However, no such thing is happening in a residential house to avoid that loss. Also, ensuring enough humidity in the house for the machine to work well is hard. Also, because the machine is big and noisy, it is more suitable for larger heating spaces, such as hospitals and shopping malls, than residential homes. Moreover, reducing the size of the VLHU could make the machine less effective.

6 Recommendations

Given the mentioned results and their conclusion, several recommendations can be made which would be interesting starting points for the future thesis:

1. The VLHC machine is recommended to be used in at places such as shopping malls, hospitals, offices as the system require a ventilation system and large areas to cover. One could study the feasibility of the system in providing constant heating and additional dehumidification which is important to maintain at such places.
2. It is recommended to develop more precise empirical equations with help of more data on the relationship between the temperature and density of the brine used in the VLHC.
3. As currently we are focusing on natural condensation process by absorbing the water directly from the air. A study could also be focused on whether the efficiency of the machine increases and whether it is easier to control by artificially spraying minute water droplets into the dehumidifier to control the operations in dehumidifier.
4. Lastly, a future study to be conducted could be to look into the feasibility of the machine to be used as a thermal energy storage system because of the following characteristics of the machine:
    - By increasing the volume of the brine 10x, we can observe that the machine could be used as a heat storage device, as the cycle is shown in Figure 6.1

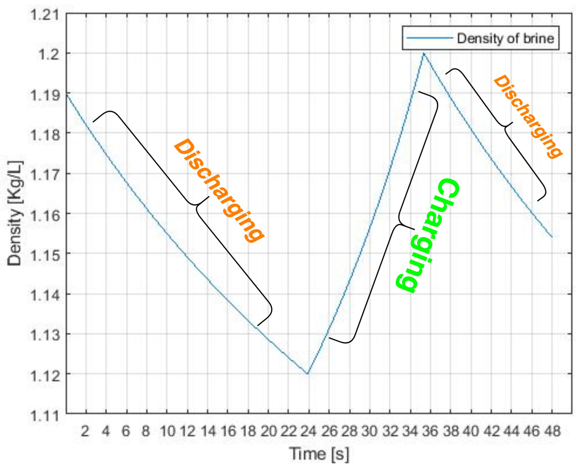


Figure 6.1: VLHC as a battery

    - No need for thermal insulation as the heat is stored in the form of latent heat and not in form of hot water. This is major cost contributing factor of TESS

- The storage system can be sustainable because it can be charged during the day with the use of solar energy and can discharge in the form of heat during the night making the system emissions free.
- Provide heating at peak hours can help reduce reliability on the grid and help in demand response.

Bibliography

[1] Wikipedia contributors. *Desiccant — {Wikipedia}{,} The Free Encyclopedia*. 2022. URL: `https://en.wikipedia.org/w/index.php?title=Desiccant&oldid=1095008877`.

[2] V. Oberg and D. Y. Goswami. "Experimental Study of the Heat and Mass Transfer in a Packed Bed Liquid Desiccant Air Dehumidifier". In: *Journal of Solar Energy Engineering* 120.4 (Nov. 1998), pp. 289–297. ISSN: 0199-6231. DOI: `10.1115/1.2888133`. URL: `https://asmedigitalcollection.asme.org/solarenergyengineering/article/120/4/289/436305/Experimental-Study-of-the-Heat-and-Mass-Transfer`.

[3] Saskatoon By, Ahmed Hamdi, and Abdel - Salam. "A NOVEL LIQUID DESICCANT AIR CONDITIONING SYSTEM WITH MEMBRANE EXCHANGERS AND VARIOUS HEAT SOURCES". In: ().

[4] Ahmed H. Abdel-Salam and Carey J. Simonson. "State-of-the-art in liquid desiccant air conditioning equipment and systems". In: *Renewable and Sustainable Energy Reviews* 58 (May 2016), pp. 1152–1183. ISSN: 1364-0321. DOI: `10.1016/J.RSER.2015.12.042`.

[5] xprt agriculture xprt. *Agam - VLHC - Technology - Greenhouse Dehumidification Systems by Agam Greenhouse Energy Systems Ltd.* https://www.agriculture-xprt.com/products/agam-model-vlhc-greenhouse-dehumidification-systems-412064. 2019.

[6] Jos Balendonck and Frank Helsloot. "Innovatienetwerk Nieuwe Energiesystemen-Gelderland INES-Gelderland". In: (2013).

[7] Gad Assaf. "LHC-The latent heat converter". In: *Journal of Heat Recovery Systems* 6.5 (1986), pp. 369–379. ISSN: 01987593. DOI: `10.1016/0198-7593(86)90224-9`.

[8] T. Takakura et al. "Measurement of evapotranspiration rate in a single-span greenhouse using the energy-balance equation". In: *Biosystems Engineering* 102.3 (Mar. 2009), pp. 298–304. ISSN: 1537-5110. DOI: `10.1016/J.BIOSYSTEMSENG.2008.12.004`.

[9] Jos Balendonck and Frank Helsloot. "Innovatienetwerk Nieuwe Energiesystemen-Gelderland INES-Gelderland". In: (2013).

[10] Alaa H. Salah et al. "Analytical investigation of different operational scenarios of a novel greenhouse combined with solar stills". In: *Applied Thermal Engineering* 122 (July 2017), pp. 297–310. ISSN: 1359-4311. DOI: `10.1016/J.APPLTHERMALENG.2017.05.022`.

[11] B. C. Zhao et al. "Latent heat thermal storage using salt hydrates for distributed building heating: A multi-level scale-up research". In: *Renewable and Sustainable Energy Reviews* 121 (Apr. 2020), p. 109712. ISSN: 18790690. DOI: `10.1016/j.rser.2020.109712`.

[12] "Systems and methods for dehumidification". In: (July 2005).

[13] Giovanni A. Longo and Andrea Gasparella. "Three years experimental comparative analysis of a desiccant based air conditioning system for a flower greenhouse: Assessment of different desiccants". In: *Applied Thermal Engineering* 78 (Mar. 2015), pp. 584–590. ISSN: 13594311. DOI: `10.1016/J.APPLTHERMALENG.2014.12.005`.

[14] Giovanni A. Longo and Andrea Gasparella. "Comparative experimental analysis and modelling of a flower greenhouse equipped with a desiccant system". In: *Applied Thermal Engineering* 47 (Dec. 2012), pp. 54–62. ISSN: 1359-4311. DOI: `10.1016/J.APPLTHERMALENG.2012.03.008`.

[15] Primary Examiner and William C Doerrler. "(12) United States Patent". In: 2.12 (2002).

[16] G. Assaf and N. Zieslin. "Novel means of humidity control and greenhouse heating". In: *Acta Horticulturae* 614 (2003), pp. 433–437. ISSN: 05677572. DOI: `10.17660/ActaHortic.2003.614.65`.

[17] Giovanni A. Longo and Andrea Gasparella. “Three years experimental comparative analysis of a desiccant based air conditioning system for a flower greenhouse: Assessment of different desiccants”. In: *Applied Thermal Engineering* 78 (Mar. 2015), pp. 584–590. ISSN: 1359-4311. DOI: 10.1016/J.APPLTHERMALENG.2014.12.005.

[18] X. H. Liu et al. “Experimental study on mass transfer performances of cross flow dehumidifier using liquid desiccant”. In: *Energy Conversion and Management* 47.15-16 (Sept. 2006), pp. 2682–2692. ISSN: 0196-8904. DOI: 10.1016/J.ENCONMAN.2005.10.035.

[19] X. H. Liu et al. “Experimental investigation of the heat and mass transfer between air and liquid desiccant in a cross-flow regenerator”. In: *Renewable Energy* 32.10 (Aug. 2007), pp. 1623–1636. ISSN: 0960-1481. DOI: 10.1016/J.RENENE.2006.07.002.

[20] X. H. Liu and Y. Jiang. “Handling zone dividing method in packed bed liquid desiccant dehumidification/regeneration process”. In: *Energy Conversion and Management* 50.12 (Dec. 2009), pp. 3024–3034. ISSN: 0196-8904. DOI: 10.1016/J.ENCONMAN.2009.07.022.

[21] *Greenhouse Heating System | DutchGreenhouses*. URL: https://www.dutchgreenhouses.com/en/technology/heating/.

[22] *Greenhouse Boiler Systems: How They Work & Why You Need One*. URL: https://www.wattco.com/2022/07/greenhouse-boiler-systems-how-they-work-why-you-need-one/.

[23] *Greenhouse Central Heating Systems*. URL: https://www.greenhouse-management.com/greenhouse_management/greenhouse_heating/greenhouse_central_heating_systems.htm.

[24] *Condensing boilers and heaters - Greenhouse Management*. URL: https://www.greenhousemag.com/article/tech-solutions-condensing-boilers-and-heaters/.

[25] *How a Boiler System Heats Your Home | Heatwave Heating & Cooling*. URL: https://heatwaveheatingandcooling.com/how-a-boiler-system-heats-your-home/.

[26] *7 Home Heating System Types | Service Champions Northern California*. URL: https://www.servicechampions.net/blog/7-home-heating-system-types.

[27] *Gas Boilers Guide | All You Need to Know | Ideal Heating*. URL: https://idealheating.com/gas-boilers#how-does-a-gas-boiler-work?.

[28] *Types of Heating Systems | Smarter House*. URL: https://smarterhouse.org/heating-systems/types-heating-systems.

[29] Celine van der Veen. “Analysing Thermal Energy Storage in Residential Buildings: Towards Decarbonization of the Heating Sector”. In: C (2022), p. 63955654. URL: http://resolver.tudelft.nl/uuid:c1fca7b7-a7cb-4ddc-936e-239a8f0a6cb7%0A%0A.

[30] *2022 HVAC System Replacement & New Unit Installation Cost - HomeAdvisor*. URL: https://www.homeadvisor.com/cost/heating-and-cooling/.

[31] *7 Types of Home Heating Systems and How to Choose One*. URL: https://www.thespruce.com/types-of-home-heating-systems-1824772#citation-1.

[32] *Electric Central Heating Boilers -0.5 to 45kW Electric Heating Boiler*. URL: https://www.flexiheatuk.com/product/electric-central-heating-boilers/.

[33] *Electric heating - Energy Saving Trust*. URL: https://energysavingtrust.org.uk/advice/electric-heating/.

[34] *Heating with Electricity, Advantages & Disadvantages of Electric Heat - Ecohome*. URL: https://www.ecohome.net/guides/2318/heating-with-electricity/.

[35] *Warm Air Ducted Heating vs. Wet Central Heating*. URL: https://www.thegreenage.co.uk/warm-air-ducted-heating-vs-wet-central-heating/.

[36] Christiaan Bronsveld. “Research for creating an electric VLHC”. In: (2022).

[37] *Total Volume & Total Time to Flow Rate Calculator*. URL: https://www.sensorsone.com/volume-and-time-to-flow-rate-calculator/#volflow.

[38] *Cooling and Heating Equations*. URL: https://www.engineeringtoolbox.com/cooling-heating-equations-d_747.html.

[39] *Empirical Equations*. URL: https://www.engineeringtoolbox.com/empirical-equations-d_1400.html.

[40] *Curve Fitting - MATLAB & Simulink - MathWorks Benelux*. URL: https://nl.mathworks.com/help/curvefit/curve-fitting.html.

[41] Emma Koster et al. “The natural gas phase-out in the Netherlands”. In: ().

[42] *Convert Megajoule to Kilowatt-hour*. URL: https://www.unitconverters.net/energy/megajoule-to-kilowatt-hour.htm.

[43] quinta-pro-installation-and-service-manual and optimised. “quinta-pro-installation-and-service-manual_optimised”. In: ().

[44] *(14) REGULATIONS FOR ELECTRICAL INSTALLATIONS | aneesh yehakoob - Academia.edu*. URL: https://www.academia.edu/41853530/REGULATIONS_FOR_ELECTRICAL_INSTALLATIONS.

[45] “Operation and Maintenance Manual for Electric Boilers (user manual) THERM EL 5 THERM EL 9 THERM EL 14 THERM EL 8 THERM EL 15 THERM EL 23 THERM EL 30 THERM EL 38 THERM EL 45 2 1. CONTENTS”. In: (2010).

[46] *Commercial Electric Boilers -50kW to 5 Megawatt - Industrial - UK*. URL: https://www.flexiheatuk.com/product/commercial-electric-boilers/.

[47] *Crownstone | Sustainable Households*. URL: https://crownstone.rocks/2021/02/24/sustainable-households.

[48] *Netherlands: power sector carbon intensity 2000-2021 | Statista*. URL: https://www.statista.com/statistics/1290441/carbon-intensity-power-sector-netherlands/.

[49] *What is an emission factor? | Clim’Foot*. URL: https://climfoot-project.eu/en/what-emission-factor.

[50] *Forced air vent vs radiator*. URL: https://www.eastgateradiators.com/forced-air-vent-vs-radiator-heating.html.

A

Experiment Conducted on LiCl Brine

Testing LiCl brine for model correlation Experiment conducted on the density of LiCl Brine.

Aim: Aim of the experiment is to determine the relationship between density and concentration and temperature of the brine.

Material used:

1. LiCl Solution (40% mass concentration)
2. Distilled water
3. Measuring scale
4. Dropper (10ml)
5. Measuring cylinder
6. Beaker for the brine
7. Gloves and protective glasses
8. Electronic thermometer

Set up: The figure below depicts the experimental setup. The LiCl solution is stored in the bottle.
Method:

1. Take two 100 ml of 40% concentration LiCl brine in the beaker.
2. Measure the mass of the liquid.
3. Dip the electric thermometer in the brine.
4. In the first beaker, add 5g of water at each step.
5. In the second beaker, add 4g of water at each step.
6. Record the temperature of the brine at peak.

Observations
After conducting the experiment, we recorded the following observation table.

Figure A.1: Overview of experimental set up

S.No.	Total Volume (ml)	Volume of water added (ml)	Mass of Salt (g)	Total mass (g)	Density (g/ml)	Temperature (°C)	Concentration (w/w)
1	100	0	40	119	1.19	22.6	0.336134
2	104	4	40	123	1.182692308	25.6	0.325203
3	105	1	40	124	1.180952381	25.7	0.322581
4	108	3	40	127	1.175925926	27.4	0.314961
5	110	2	40	129	1.172727273	27.9	0.310078
6	112	2	40	131	1.169642857	28.3	0.305344
7	115	3	40	134	1.165217391	29.4	0.298507
8	116	1	40	135	1.163793103	29.8	0.296296
9	120	4	40	139	1.158333333	30.9	0.28777
10	121	1	40	140	1.157024793	31.1	0.285714
11	124	3	40	143	1.153225806	31.9	0.27972
12	125	1	40	144	1.152	32	0.277778
13	128	3	40	147	1.1484375	32.4	0.272109
14	130	2	40	149	1.146153846	32.6	0.268456
15	132	2	40	151	1.143939394	33	0.264901
16	135	3	40	154	1.140740741	33.1	0.25974
17	136	1	40	155	1.139705882	33.3	0.258065
18	140	4	40	159	1.135714286	33.4	0.251572
19	145	5	40	164	1.131034483	33.6	0.243902
20	150	5	40	169	1.126666667	33.7	0.236686
21	155	5	40	174	1.122580645	33.8	0.229885

Table A.1: Observation Table - LiCl Brine

B Datasheet

Data sheet for the boiler used in the VLHC machine

remeha

3.2 Technical data

Boiler type		**Quinta 45**	**Quinta 65**
General			
Casing Colour	BS RAL	9016	
Boiler control options (External input) (Two wire control)		On/off, High/low, Analog 0 -10V Communicating Modulation	
Nominal output (80/60ºC)	kW	8.0 - 40.0	12.0 - 61.0
Nominal output (50/30ºC)	kW	8.9 - 43.0	13.3 - 65.0
Nominal input (GCV / Hs)	kW	9.1 - 45.7	13.6 - 68.8
Nominal input (NCV / Hi)	kW	8.2 - 41.2	12.2 - 62.0
Weight dry	kg	57	64
Noise level at 1 m from boiler	dB(A)	<48	
Gas- and flue details			
Min/Max Inlet pressure natural gas	mbar	17 - 30	17 - 30
Min/Max Inlet pressure propane	mbar	37 - 50	37 - 50
Gas consumption (natural gas)	m^3/h	1.0 - 5.0	1.5 - 7.5
Gas consumption (propane)	m^3/h	0.3 - 1.7	0.5 - 2.5
NO_x-emission *)	mg/kWh	< 37	
NO_x -emission (O_2 = 0%, dry) *)	ppm	< 21	
Residual fan duty	Pa	150	100
Mass flue rate	kg/h	14 - 69	21 - 104
Classification due to discharging flue gases		B23, C13, C33, C43, C53, C63, C83	
Water side			
Maximum flow temperature	ºC	100 (110)	
Operating flow temperature	ºC	20 - 90	
Operating pressure min. (open vented)	bar	0.3	
Operating pressure min. (pressurised)	bar	0.8	
Operating pressure max.	bar	4.0	
Water contents	ltr	5.5	6.5
Water resistance at 11 °C Δt	mbar	300	430
Water resistance at 20 °C Δt	mbar	90	130
Electrical			
Main supply	V/Hz	230 / 1 / 50	
Electric rating	W	30 - 85	30 - 90
Insulation class	IP	20	

Table 01 Technical data remeha Quinta 45 and Quinta 65

*) DIN 4702, part 8

Figure B.1: Datasheet for the gas boiler used at Gourdiaan -Almere Greenhouse [27]

Data sheet used as reference for the electric boiler

Technical data	Unit	FHEL8	FHEL15	FHEL23	FHEL30	FHEL38	FHEL45
Nominal heat output	kW	7.5	15.0	22.5	30.0	37.5	45.0
Minimum regulation level of the output	W	2500	2500	2500	2500/5000	2500/5000	2500/5000
Rated current (single-phase connection)	A	11 (33)	22 (66)	33	44	55	66
Level of electric coverage	IP	40	40	40	40	40	40
Supply voltage / frequency	V/Hz	3 x 400/230 + N + PE/50 ~		3 x 400 + N + PE/50 ~			
Maximum rated current	A	3 x 12 (1 x 36)	3 x 24 (1 x 72)	3 x 36	3 x 48	3 x 60	3 x 72
Main circuit breaker for electric installation	A	16 (40)	25 (80)	40	50	63	80
Rated current of the control circuit breaker	A	1.25	1.25	1.25	1.25	1.25	1.25
Electric service life of relay	-	1.10^5 cycles (16 A, 250 V/50 Hz)					
Mechanical service life of relay	-	10.10^6 cycles					
Input - output for heating water	-	3/4" male			1" male		
Min. - maximum working overpressure of heating system	bar	0.5 – 3.0	0.5 – 3.0	0.5 – 3.0	0.5 – 3.0	0.5 – 3.0	0.5 – 3.0
Maximum temperature of heating water	°C	80	80	80	80	80	80
Water volume of the boiler	l	14.5	14.5	14.5	28.0	28.0	28.0
Efficiency at the rated power	%	99.5	99.5	99.5	99.5	99.5	99.5
Volume of expansion tank	l	7	7	7	site based (location outside the boiler)		
Dimensions: height/width/depth	mm	820/475/238			805/475/238		
Weight of the boiler without watter	kg	37	38	39	43	44	45
Class of seasonal energy efficiency of heating	-	D	D	D	D	D	D

Figure B.2: Datasheet for a 45 kW electric boiler [32]