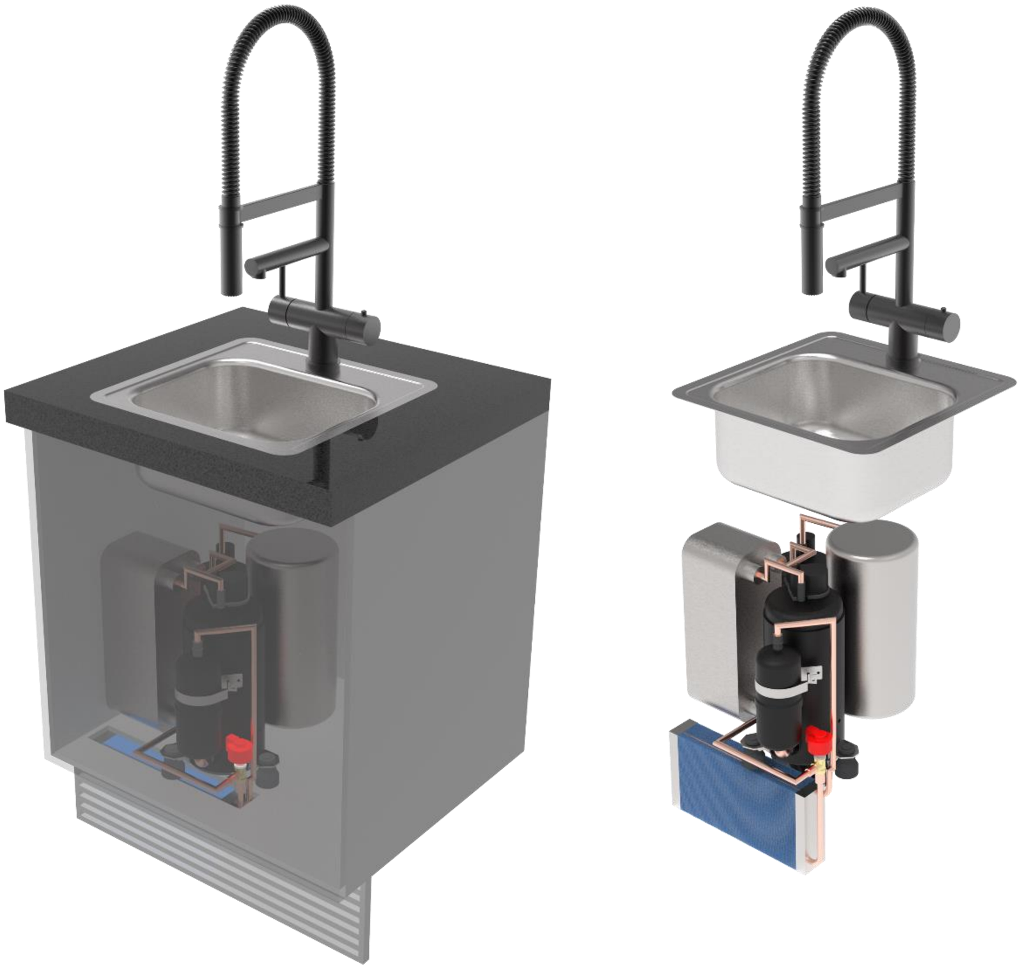
Development of an Air-Source, Cascade Heat Pump, Water Boiler

Master Thesis, Industrial Design Engineering



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Preface

Dear reader,

Over a year ago, I had my first appointment at Vadac. During this initial interview, I met with the managing director of the company, Marco van Rooijen. First, he started by telling me about who he was and introduced me to the company and the markets they develop products for. During this explanation I quickly found out that the company portfolio contained many impressive products, which immediately got me interested. After this, I started by also introducing myself. I showed my own portfolio and discussed the motivation for starting the Master assignment. And finally, we discussed the assignment the company was offering.

After this first introduction, I got really excited and left with a very satisfied feeling. And not much later this feeling had proven to be correct, because I got a message from Marco, saying that I was welcome to execute my graduation assignment there. So, together with this approval and the approval from the IDE Master coordinator Eric Lutters, I could officially start with the Master assignment. So not much later, about a year ago, that is exactly what I did.

At the start of the assignment it was hard to find a suitable UT supervisor. But luckily this did not prevent me from continuing with my research. At first, the assignment was to research the possibility of implementing heat pump technology in a camper cooktop, but I quickly found out that this was not possible. For this reason I had to rethink the assignment and come up with an alternative. Just in time I got in contact with a potential UT supervisor, Davoud Jafari, and he was willing to help me further investigate the possibilities.

All things considered, I found a nice solution for the previously mentioned drawback. By changing the type of heat pump application from a cooktop, to a kitchen boiler, I was able to continue with the project. Although this meant that I had to design a product for a different market than the markets the company is normally working in, they still provided me with the necessary knowledge and financial support to generate a working proof-of-concept.

During the time I was working at the company, I learned a lot. I think the main reason for this is because my colleagues were very helpful and, because the design team was small, I had much more responsibilities. For example, within the assignment I had to contact many of the stakeholders, like suppliers, manufacturers, development partners and customers, myself and that helped me to also develop skills outside the scope of my study. Also, I am glad that I gained more knowledge about the design of refrigeration/heat pump systems, learned to work with MATLAB and got more experience with thermodynamics and electrical engineering.

In the end, I would like to give a special thanks to Marco van Rooijen and Brian Markerink from Vadac, for giving me the opportunity to work with them and for spending time and effort in supporting me during this learning experience. Also, I would like to thank my UT supervisor Davoud Jafari for his helpful feedback and honest opinions. Harry Kruiper, for helping me to assemble and charge the system. And Henk-jan Moed for providing me the necessary lab space for testing the prototype.

Yours sincerely,

Joost Bessembinder

April 2023, Deventer

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Glossary

Accumulator: a suction accumulator is used to prevent a damaging overflow of liquid refrigerant and oil from entering the compression chamber of a compressor.

ASHRAE: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Bivalent: working principle in which two system types are used to obtain a mutual goal.

Buoyancy: the ability or tendency of something to float in water or other fluid.

Cascaded: a process whereby something, in this case thermal energy, is successively passed on between stages.

CE-marking: "Conformite Europeenne" marking, certifies that a product has met EU health, safety, and environmental requirements, which ensure consumer safety.

Cocurrent: involving flow of materials in the same direction.

Compressor: an instrument or device for compressing something, in this case compression of refrigerant in gaseous state.

Condenser: an apparatus or container for condensing a vapor.

Conduction: the process by which heat is directly transmitted through the material of a substance when there is a difference of temperature between adjoining regions, without movement of the material.

Convection: the movement caused within a fluid by the tendency of hotter and therefore less dense material to rise, and colder, denser material to sink under the influence of gravity, which consequently results in transfer of heat.

COP: the ratio between the heating (or cooling) capacity of the overall system and the supplied required compressor power.

Countercurrent: involving flow of materials in the opposite direction of one another.

Critical temperature: the temperature of a gas in its critical state, above which it cannot be liquefied by pressure alone.

Crosscurrent: involving flow of materials perpendicular to one another.

Diffuser: an attachment or duct for broadening a gas flow and reducing its speed.

Enthalpy: a thermodynamic quantity equivalent to the total heat content of a system. It is equal to the internal energy of the system plus the product of pressure and volume.

Evaporator: an apparatus or container for evaporating a liquid.

Expansion valve: a valve through which liquid or gas under pressure is allowed to expand to a lower pressure and greater volume.

GWP: Global Warming Potential, a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (CO_2).

HC: Hydrocarbons, compounds consisting of hydrogen and carbon atoms, such as any of those which are the chief components of petroleum and natural gas.

HCFC: Hydrochlorofluorocarbons, artificial compounds consisting of hydrogen, chlorine, fluorine and carbon atoms.

Heat exchanger: a device for transferring heat from one medium to another.

Heat pump: a device that transfers heat from a colder area to a hotter area by using mechanical energy.

Hermetic: complete and airtight seal.

HFC: Hydrofluorocarbons, artificial compounds consisting of hydrogen, fluorine and carbon atoms.

HRAI: Heating, Refrigeration and Air-Conditioning Institute of Canada.

Hydrophobic: tending to repel or fail to mix with water.

Impeller: component of a machine designed to move a fluid by rotation.

Isentropic efficiency: the ratio of real work to work in an ideal (isentropic) thermodynamic process.

Mass flow rate: the mass of a substance which passes per unit of time.

Monovalent: working principle in which a single system type is used to obtain something.

NIST: National Institute of Standards and Technology.

ODP: Ozone Depletion Potential, a measure of how much damage a chemical can cause to the ozone layer compared with a similar mass of trichlorofluoromethane (CFC-11).

PID controller: Proportional-Integral-Derivative controller, is a control loop mechanism employing feedback to a system.

Reciprocating: moving backwards and forwards in a straight line.

Refrigerant: a working fluid used in the refrigeration cycle of air conditioning systems and heat pumps.

Reversing valve: a component that is able to change the direction of fluid flow.

Subcritical: below a critical threshold, in this case below the critical temperature.

Superheat: the excess of temperature of a vapor above its saturation temperature.

TRL: Technology Readiness Level, an indication of the maturity of a particular technology.

Volumetric efficiency: the ratio of the volume of fluid actually displaced to its swept volume.

Volumetric heating capacity: the amount of energy that must be added, in the form of heat, to one unit of volume of a material in order to cause an increase of one unit in its temperature.

Summary

This report outlines the design and development of a cascade heat pump system for a water boiler. This system is designed to operate at high temperatures and draws heat from the surrounding air, making it an ecofriendly and energy-efficient option for a water boiler. The findings of this study have important implications for the field of renewable energy and could pave the way for the widespread adoption of cascade heat pump systems in various applications.

In particular, the designed system is related to one of the recently designed products from Vadac B.V., the Coolmach, an energy-efficient climate control system for caravans and campers. The system is based on the heat pump principle and it was introduced to replace the current gas heating systems. During the R&D phase, the company became familiar with the technology behind this system and that was the main motivation for researching possible other applications. For the sake of this research, the focus was mainly on energy consuming household appliances.

The definition of a heat pump states: “a device that uses a compressible refrigerant to transfer heat from one body, as the ground, air, or water, to another body, as a building, with the process being reversible”. This definition shows that a heat pump can be ground, air or water source. The most suitable heat pump type for household appliances is the air-source heat pump, because it is the least expensive and most versatile. The system consists of the following components: evaporator, condenser, compressor, expansion valve and refrigerant.

The application, proven to be most suitable for optimization by means of a heat pump, is the kitchen boiler. This device has the highest energy consumption and a suitable temperature range. Currently heat pumps are already used for heating water, but most of them can only reach a temperature of around 55 ^{o}C and they are much more efficient at temperatures in between 35-45 ^{o}C. The goal of this research was to reach a much higher temperature, namely a minimum temperature of 100 ^{o}C (a so called: ‘High Temperature Heat Pump’).

Focusing on the high-temperature heat pump water boiler system, the theoretical models and physical prototype are employed to address the following challenges:

1. What is the most effective method for bridging a significant temperature difference of 90 ^{o}C in boiling water systems?

To be able to bridge the big temperature difference of 90 ^{o}C (from 10 ^{o}C tap water to 100 ^{o}C boiling water), a cascade heat pump system is the best option. In this system the temperature range can be divided over two or more refrigerants, in two or more separate heat pump cycles, which decreases the required mass flowrate and maximum required pressure, and subsequently the required amount of total compressor power (thus saving energy).

2. What are the ideal refrigerants based on European regulations for high-temperature heat pump systems?

For the refrigerants, there are currently a total of 27 substances suitable for the required temperature range, while also in accordance with the European rules and regulations regarding ozone depletion potential (ODP) and global warming potential (GWP). The most promising refrigerant pair, for the cascade heat pump system (looking at the coefficient of performance (COP), required maximum pressure and volumetric flowrate), consists of the combination with R1234ze(e) in the lower temperature cycle and R600 in the higher temperature cycle.

3. How can the coefficient of performance (COP) of a heat pump system be calculated, taking into consideration various factors, such as heat source and sink temperatures, refrigerant properties, and system components, in order to optimize the energy efficiency of the system?

By using ‘MATLAB R2022a’ a first theoretical COP value of 2.55 could be calculated (without taking into account superheat, subcooling, volumetric- and isentropic efficiency). After having selected the right components and sizing them according to the requirements and specifications, more parameters could be used as input for calculating the COP value. By using a software called ‘Genetron Properties 1.4.2’ a more realistic COP value of 2.22 was calculated (compressor and heat exchanger efficiencies taken into account). And finally, to check if the calculated theoretical values were the same as in the real life situation, a test setup was constructed.

The main goal of the physical test was to check if the cascaded heat pumps system was able to get water to its boiling point at standard atmospheric pressure, while simultaneously being more efficient than traditional electric water boilers. The test setup consisted of a prototype test rig with a control system (superheat and fan speed controllers) and onto this system, pressure and temperature sensors where installed, to be able to retrieve data (with a datalogger) and analyze the performance during each test.

Several key performance parameters were able to affect the efficiency of the system during testing. These influencing factors are the air flowrate of the fan, the heat transfer area of the heat exchangers, the superheat values, the compressor pressure ratios, the refrigerant mass flowrates and the intermediate heat exchanger temperature difference. Each time one of the variable parameters of the aforementioned performance parameters was changed to finetune the system and find the most optimal system settings.

Finally, the physical test resulted in a COP value of 1.26. And, even though this is lower than the expected theoretical value, it does not mean that the results are not promising. First of all, the system is actually able to bridge the temperature difference of 90 ^{o}C and is thus able to boil water. And secondly, the main reason for the lower COP value can be traced back to two components, namely the lower temperature cycle evaporator and electronic expansion valve. Because these components are not sized correctly, the system is currently only able to extract 331 Watts of thermal energy from the air, instead of the preferred 1500 Watts. And that limits the overall system capacity already at the start of the system.

So, to conclude, the first proof-of-concept succeeded, but the next step is to increase the size of the LT cycle evaporator and to select an expansion valve with a bigger tube diameter and valve opening, to be able to increase the heat exchanger capacity, increase the overall heating capacity and with this improve the currently calculated COP value.

1. Introduction

1.1 Vadac B.V.

First a small introduction of the company. Vadac is a company located in Deventer and started in 1997. The first line of products they designed and produced were insurance certified mechanical locks for trucks, trailers, caravans and outboard motors, which are called PowerLock. Now, many years later, the team at Vadac has already designed a widening range of products with an increasing level of complexity for the caravanning and marine industry (Vadac, n.d.). Some examples of products and brands are the Coolmach caravan air-conditioning, Satenne satellite antenna, Heatek infrared caravan heating, Odesea boat and motor covers and the P1 Mover caravan mover.

A couple of years ago, in 2018, Vadac faced a new challenge. Namely rethinking all components in caravans, campers and boats to make camping more sustainable. This was a logical step for them, because it removed the risks and inconveniences of outdated equipment, like for example gas heaters and it takes the vehicles fast forward to the pinnacle of climate control. During the more than two decades of designing these technical accessories for the caravanning and marine industry, the company has accumulated a profound knowledge and understanding of their current market and products. And with this expertise they are now also willing to expand to other markets.

During the research and development phase of the air-conditioning system, Vadac became familiar with the principle of using compressors and heat exchangers for increasing temperature. This then sparked the idea of implementing the same type of technology in other applications as well. Compared to the residential sector, in industry there are already many more processes in which this principle is being applied. This is why there is still an opportunity for researching possible applications for this type of technology in energy consuming household devices. Also, because of the increasing energy prices, homes are nowadays increasingly facing the need to reduce their electricity consumption. And because homes will be disconnected to gas networks in the future, a power friendly alternative, as proposed by Vadac, can also be very promising.

1.2 Problem Statement

Because of the ever increasing concern of climate change and the decreasing reserve of fossil fuel, together with increasing energy demand around the world, a high pressure is put on the energy sectors to provide sustainable and green energy solutions. One of the systems Vadac has been developing, to help tackle this problem, is a compact camper air-conditioner/heat pump. These type of devices are now mainly being used for heating and cooling of buildings and in the industrial sector they are also used to collect the thermal energy from waste heat so it can be put back into production processes like paper production, chemical treatment and drying (Arpagaus, Bless, Uhlmann, Schiffmann, & Bertsch, 2018; IEA, 2022; Wu et al., 2021).

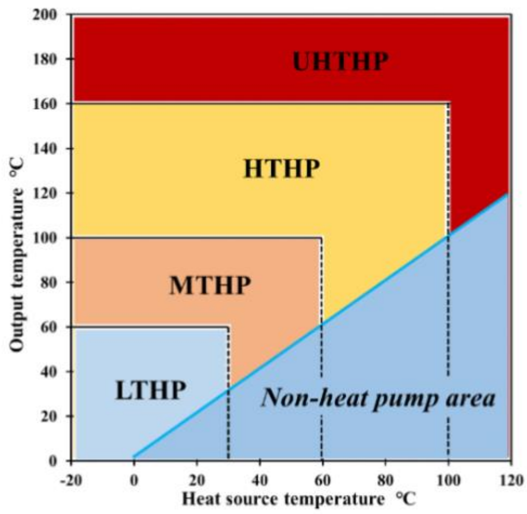

Figure 1 classification scheme of vapor compression heat pumps (Wu, Hu, & Wang, 2021)

The types of heat pumps that will be examined in this research are closed system, subcritical, vapor compression, heat pumps. Closed system meaning that the refrigerant will stay in the same cycle and does not leave the system during the whole process and subcritical meaning that the heat sink temperature will stay below the critical temperature of the refrigerant type. "Vapor compression heat pumps can be classified as low temperature heat pumps (LTHPs), medium temperature heat pumps (MTHPs), high temperature heat pumps (HTHPs), and ultra-high temperature heat pumps (UHTHPs)" (Wu et al., 2021). The focus of this research will mainly be on the HTHPs with a heat sink temperature of above 100 ^{o}C (see Figure 1).

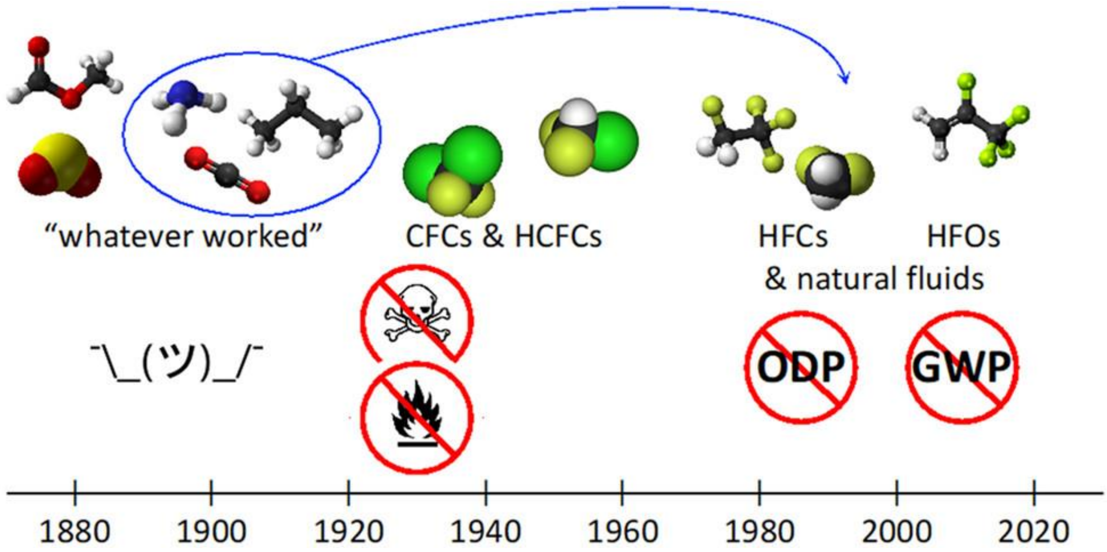

Figure 2 Refrigerant evolution over the years, because of changing regulations (McLinden & Huber, 2020)

Regarding the rules and regulations, heat pump systems have faced a lot of challenges over the years (Figure 2). For the first generation there where basically no laws that prohibited the use of some type of fluids. But, as the technology began to gain more popularity, the second generation of refrigerants introduced regulations regarding safety and durability. Meaning that highly flammable and toxic substances could not be used, or the allowed charge amount was being limited drastically. Then, after the discovery was made that some types of refrigerants could also be harmful for the ozone layer, these fluids slowly needed to be phased out as well. This meant that for the third generation, refrigerants with an ozone depletion potential above zero, could not be used anymore. And finally, for the fourth and current generation, the global warming potential of refrigerants is also being taken into account, which shortens the list of substances that can be used even more (McLinden & Huber, 2020). Because of this drastically shortened list, together with the urgent need for sustainable refrigerants, manufacturers are developing new types of substances and researchers are re-examining the possibility of using some of the flammable/toxic substances (that were phased out in the second generation), by improving system safety and reliability (Wu et al., 2021).

To sum up, the previously mentioned problem description comes with the challenge to research the question if it is possible to use compressor and heat exchanger technology to improve an existing household device. When this is possible, the current refrigerant safety and sustainability regulations should be taken into account and an extensive research in the current system types and innovations needs to be executed. To already give an idea of the state-of-the-art, research status and application potentials, the next section will show a market overview of currently existing heat pump systems and projects.

1.3 State-of-the-Art

High temperature heat pumps are currently only being used in industrial applications for waste heat recovery purposes. The majority of these applications require supply temperatures of 100 °C and above (Elmegaard et al., 2021). But most of the systems that are able to reach these temperatures are still under development and at lower technology readiness levels (TRL). Looking at the nine-level NASA TRL scale (Héder, 2017), level 8 (actual system completed, demonstrated and tested) heat pump technologies currently only exist with heat source temperatures in the range of 30 to 70 °C and heat sink temperatures in the range of 70 to 100 °C (Schlemminger et al., 2019). Heat pump systems with heat sink temperatures above 100 °C (HTHPs) are currently in between level 3 (analytical proof-of-concept) and level 7 (system prototype demonstration) (Arpagaus et al., 2018). Table 1 gives an overview of the high temperature heat pumps that are now being developed, with most of them expected to be available by 2025 (Elmegaard et al., 2021).

Table 1 Industrial HTHPs with sink temperatures above 100 °C (Arpagaus et al., 2018; Elmegaard et al., 2021; IEA, 2022)

Manufacturer	System name	Refrigerant	Max heat sink temperature	Max heating capacity
Olvondo	HighLift	R704 (He)	180 °C	1.5 MW
Hybrid Energy	Hybrid Heat Pump	R717 (NH_3) & R718 (H_2O)	120 °C	0.5-5 MW
Weel & Sandvig	WS-TURBO	R718 (H_2O)	160 °C	1-5 MW
ToCircle	Free2Heat	-R717 (NH_3) -R718 (H_2O)	180 °C	1-5 MW
MAN Energy Solutions	MAN ETES	R744 (CO_2)	150 °C	10-50 MW
Mayekawa	Eco Sirocco	R744 (CO_2)	120 °C	100 kW
Dürr Thermea	ThermeCO2	R744 (CO_2)	110 °C	2.2 MW
GEA Process Engineering	-	R744 (CO_2)	130 °C	0.1-1.2 MW
SINTEF	HeatUp/SkaleUP	R290 (C_3H_8) & R600 (C_4H_{10})	115 °C	300 kW
EUDP	SuPrHeat	-R718 (H_2O)/ R744 (CO_2) -R600 (C_4H_{10}) -R601 (C_5H_{12})	200 °C 120 °C 150 °C	500 kW
Kobe Steel/ Kobelco	-SGH 120 -SGH 165 -MSRC160L	-R245fa -R134a/R245fa -R718 (H_2O)	120 °C 175 °C 160 °C	1.9 MW 400 kW 700 kW
Ochsner Energie Technik GmbH	-IWWDS R2R3b -IWWDS ER3b	-R134a/R245fa -R245fa	130 °C	750 kW
Viking Heat Engines	HeatBooster S4	R245fa/ R1336mzz(z)	150 °C	188 kW
Heaten	HeatBooster	HFOs	165 °C	1-6 MW
Combitherm	HWW 245fa	R245fa	120 °C	252 kW

Concluding from Table 1, the maximum temperature out of the currently developed and tested technologies is 200 °C, but R718 (H_2O) is currently the only refrigerant type that can reach this temperature. R134a and R245fa are the next refrigerant types that show high maximum temperatures, but since R134a (NCBI, 2022a) and R245fa have a high global warming potential (NCBI, 2022b), these substances are harmful for the environment and not up to the climate standards. The heat pumps using hydrocarbons (R290, R600, R601) also show relatively high heat sink temperatures, but these substances come with high flammability safety issues. Regarding the presented technologies it is thus important to more closely research the possibilities for using certain substances and to investigate their market potential. And finally, since the heat capacity of the presented systems is high (because they are developed for industry scale), this needs to be scaled down as well, to be suitable for residential use.

1.4 Research Questions and Objective

The main objective of this research is to find out if it is possible to use heat pump technology for improving an existing household application and make it more sustainable and energy efficient. To be able to answer this, there are three central research questions that need to be answered:

1. How does a heat pump system work?

To be able to answer the first question, a better understanding of what a heat pump is, what the main components and their functions are, and how these components work together, need to be acquired. Also, to get a better insight in the system requirements, the European regulations, the users, the stakeholders and the current market need to be analysed.

2. How can compressor and heat exchanger technology be used to improve one of the existing household devices?

To answer the second question, it is important to analyse current high temperature household appliances and their energy consumption to find out which device is most suitable for optimization by means of heat pump technology. And, to also get a better overview of the market potential, the current heat pump applications and the competitors also need to be investigated.

3. How feasible is the implementation of heat pump technology in the new type of application?

With the second question answered, the list of requirements can be completed and used to generate ideas and concepts for the chosen application. And, by creating a prototype of the final concept, the real-life performance of the system can be analysed and used to answer the third question.

For a complete overview of the research plan, the main research question, the central questions and the sub-questions, see **Appendix A**.

1.5 Report Structure

The report begins with a chapter in which the first research questions are being analysed and answered as complete as possible. **Chapter 2** contains the outcome of this preliminary research and shows how a heat pump system works (by analysing its working principles, core components and the rules and regulations that apply to these type of devices), what the use cases are (by analysing current heat pump applications and appliances suitable for optimizations), who the current competitors are (by looking at the existing devices that are already available on the market) and by analysing the currently existing heat pump system configurations and deployment methods.

Next, to get even more information about the types of heat pump systems and to be able to completely answer the remaining sub-questions, the first part of **Chapter 3** goes deeper into the machine itself and the corresponding workflow. This is done by going into more detail about some of the most important system components (working fluids, compressors and heat exchangers) and by analysing different combinations of the configuration and deployment methods.

Then, the second part of **Chapter 3** uses the previously established research results, to form a list of the system requirements (that are needed to meet the project goals). This list was used to be able to start with the ideation and concept generation phase. The resulting outcome of this chapter is the final selection of the heat pump system components and the required sizing of these components. And, to give a clear overview of the final concept, a 3D CAD model of the configuration is also displayed.

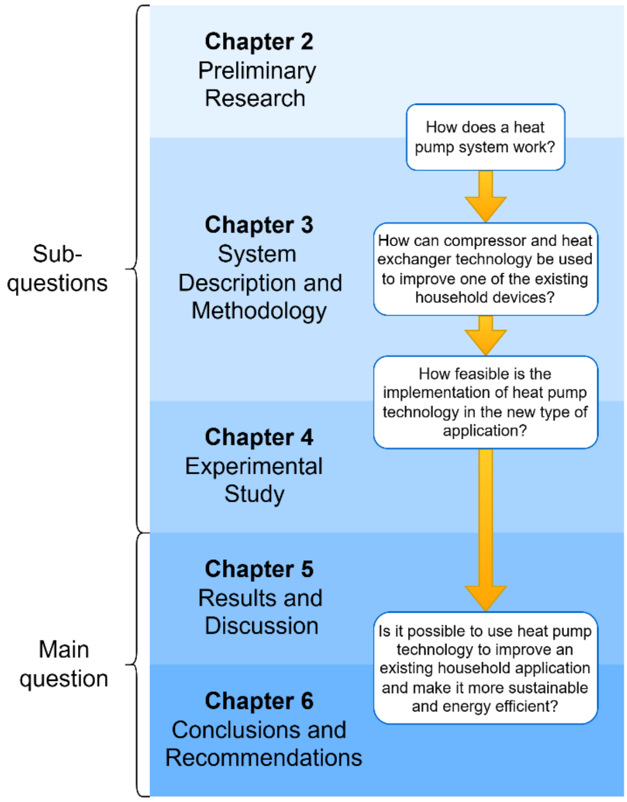

Figure 3 Report structure and research question overview

Finally, in **Chapter 4**, a simulation of the final system and an overview of the prototype is shown. Together with this prototype, physical tests were executed to test if the system was actually working according to the predicted values. And **Chapter 5** and **Chapter 6** showcase the resulting test data (including the overall system performance and coefficient of performance (COP)) and evaluates the potential improvements.

2. Preliminary Research

This chapter explains what a heat pump is, how it works, the functions of each component, the rules and regulations that apply to these type of devices and which heat pump types are already available on the market. This information will provide a sufficient basis for getting familiar with the subject and the background, helps with understanding the information in part 3.1 (Heat Pump Components) and it already highlights many of the requirements the final system should meet.

2.1 Heat Pump Analysis

In the first analysis, the types of heat pumps and their working principles are explained, for this the questions: what? and why? are more or less discussed. The second part goes more into detail about the individual components and their functions within a heat pump and answers the question: how?. And in the last part the rules and regulations which apply to these type of devices are also discussed.

2.1.1 Heat Pump Principles

The definition of a heat pump states: "a device that uses a compressible refrigerant to transfer heat from one body, as the ground, air, or water, to another body, as a building, with the process being reversible" (William Collins, 2022). From this definition one can see that there are a variety of heat pump principles to choose from. And to find out which principle is most suitable for the final application, this part will take a look at the most used ones and explains how they work and what their pros and cons are.

Air source

The first type of system is the air source heat pump, this is a type of heat pump that uses two heat exchangers to transfer heat from outside a building to the inside. The way this principle works is by using a fan to force air through the fins on the outside of the heat exchanger and in in this way extract the thermal energy directly from the air so it can be transferred to the inside of the building. This type of heat pump is also able to reverse the process and instead of heating the building, cooling it down. Another big advantage of air source heat pumps is that they are easy to install and inexpensive. And the average COP (Coefficient of Performance) value over a season is generally around 2.5 – 2.8 (Warmtepomp-Info, 2022), meaning that the device provides 2.5 – 2.8 units of thermal energy for each unit of electrical energy used (Yuan & Lee, 2014).

Geothermal (ground source)

This type of heat pump extracts heat from the soil or groundwater. The process is roughly the same as the air source heat pump and is also reversible. But the main advantage in this case is that the heat is drawn from a depth of approximately 9.1 metres, which allows for extracting thermal energy at a relatively constant temperature all year around. The big disadvantage on the other hand, is that geothermal heat pumps are expensive to install because you have to drill boreholes for vertical placement or dig trenches for horizontal placement (for the pipes that carry the refrigerant fluid). An average geothermal heat pump will generally have a seasonal COP of around 3.0 (Warmtepomp-Info, 2022).

Exhaust air source

An exhaust air source heat pump works the same as the air source heat pump, but instead of using only the outside air, it extracts the heat from the air that is leaving a building (waist or exhaust air) as well. Since the air inside a building is on average 20 – 22 ^{o}C all year round, the amount of thermal energy that can be extracted will not vary much according to the seasons (MCS, 2019). Some important factors, like building quality, night time temperature and quality of maintenance have a big impact on the COP value. But on average a standard exhaust air source heat pump has a COP in between 2.9 – 3.4 all year round (Mikola & Kõiv, 2014).

Solar-assisted

The solar-assisted heat pump makes use of thermal solar panels that are integrated into the system and together with a heat pump is used to transfer heat from outside to the inside of a building. Compared to the previous mentioned heat pump types, the solar-assisted heat pump extracts the heat by directly using the thermal energy of the sun. In this system the low temperature heat exchanger is the thermal solar panel and the high temperature heat exchanger one that transfers the heat directly to the air, or one that is used to heat up water (Warmtepomp-Info, 2022). The goal is the same as the other heat pumps, namely to get a high COP and increase the temperature in a more efficient way. The average annual COP value depends on the type of solar-assisted heat pump system. The COP of a serial system is around 3.3 and the parallel system is around 4.3. But by combining these two types and switching from one type to another depending on the season, the average annual COP value can increase to 5.7 (taking into account different types of climates, this number can still vary a lot from one place to another) (Huan et al., 2019).

Water source

A water source heat pump can be compared to a geothermal (ground source) heat pump, but instead of extracting heat from the ground it takes heat from a body of water (Warmtepomp-Info, 2022). In this case the low temperature heat exchanger is located in the water, the high temperature heat exchanger is located inside the building and the system is reversible. A big disadvantage on the other hand is that, for this system to work properly, a big body of water (e.g. a lake, river or stream with a constant temperature level of 7 – 12 ^{o}C) is needed to be able to withstand the freezing effect of the refrigerant and to reduce the effects on wildlife. Taking this into account, the average yearly seasonal COP value for this type of system can be around 5.0 (GreenMatch, 2021).

Hybrid

The word hybrid already reveals a bit about this type of heat pump principle. Hybrid means that something is composed by using different elements. In this case it means that thermal energy is extracted by using more than one type of heat exchanger unit. For example when the outside temperature is above 4 to 8 ^{o}C the air source heat exchanger can be used and when the temperature reaches below these temperatures a geothermal or ground source heat exchanger can be used. This type of system is more expensive, but it has more potential (depending on the location) to be efficient and thus costs can be saved later on (Warmtepomp-Info, 2022). Because there are an unlimited amount of combinations and variations for this type of system, there is not one general average seasonal COP value.

Comparison and remarks

For the device that will be designed, it does not matter if the system is reversible or not, because it only needs to work in one direction. Namely, increasing the temperature at the output. Then, taking into account the other characteristics and the pros and cons of each system, the most suitable heat pump principle is the air source heat pump. The reason for not using the geothermal (ground source) or water source heat pump is simple, they either require a big body of water or drilling deep into the soil, which makes it more expensive and impossible to easily move and position the system. Secondly, although the solar-assisted heat pump seems promising, this system is also not suitable because it strongly depends on the amount of thermal energy that can be retrieved from the sun and that is not convenient when the device should be available at any moment. Finally, looking at the hybrid heat pump principle, this will not work together with the geothermal (ground source), water source or solar-assisted heat pump types. But, because the exhaust air source principle is roughly the same as the air source principle and because in some cases the exhaust system type is more efficient, there maybe is an opportunity for having a hybrid solution in the form of switching between the use of outside or exhaust air.

2.1.2 Components and Functions

Looking at the previous chapter (2.1.1 Heat Pump Principles), the components of each type of heat pump are roughly the same, but the lower temperature heat exchanger differs most of the time. And because the air source heat pump (Figure 4) has proven to be the best option, this part will only discuss this type of heat pump. The components that will be discussed are the heat exchangers (evaporator and condenser), compressor, expansion valve and refrigerant. The reason for also leaving out the reversing valve is because the final system only needs to work in one direction, namely heating up. Next up, each component is briefly explained together with their function.

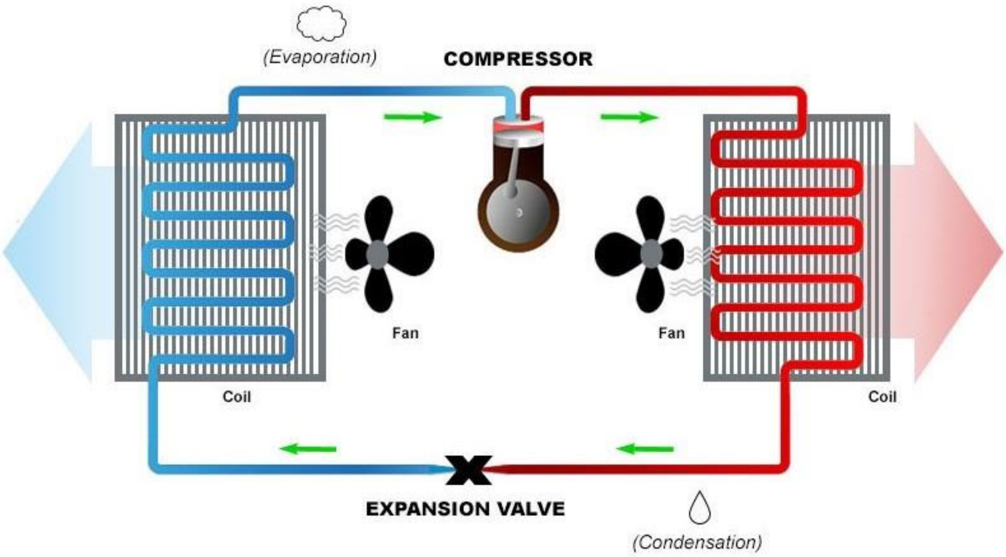

Figure 4 Basic schematic diagram of an air-source heat pump (Carrier, 2022)

Refrigerant

In short, refrigerants are chemical substances which have certain thermodynamic properties that can be used to absorb and reject heat as it runs through the heat pump system (Carrier, 2022). Based on the properties and performance, refrigerants can be classified into three main groups (Leckner, 2008):

- *Working principle:* a distinction can be made between primary and secondary refrigerants, where the primary refrigerant can be used directly as the working fluid (undergo phase change) and the secondary refrigerant is only used for transporting heat.
- *Safety:* a distinction can be made about how safe a refrigerant is by looking at how toxic and/or flammable it is.
- *Chemical composition:* each refrigerant has a certain type of composition type, such as halocarbon compounds, cyclic organic compounds, azeotropes, miscellaneous, oxygen and nitrogen compounds, inorganic compounds and unsaturated compounds.

Evaporator (lower temperature input)

The heat exchanger that is located at the lower temperature input is called the evaporator. This component consists of a coil through which the refrigerant fluid flows and a fan to draw air through the heat exchanger. In this way the thermal energy can be transferred from the air onto the liquid refrigerant fluid and turn it into a gas by evaporating it. After this, the heated vapor is ready to be transferred through tubes, from the output of the heat exchanger to the input of the compressor (Carrier, 2022).

Compressor

The compressor enables the flow and compression of the refrigerant vapor, the most common types used for heat pumps are reciprocating, rotary and centrifugal compressors. After the thermal energy from the air has been transferred to the refrigerant vapor, the compressor (together with the expansion valve) is used to increase the pressure and subsequently the temperature of the refrigerant (Bob, 2019). The formula that shows this relationship between pressure and temperature is called the Ideal Gas Law: $PV = nRT$ with R being the ideal gas constant and the rest of the equation is constructed by using the following laws (ChemFSU, n.d.):

- *Charles' Law* $\frac{V_1}{T_1} = \frac{V_2}{T_2}$*:* when pressure and mass are held constant, the volume is directly proportional to the temperature of the gas.
- *Boyle's Law* $P_1V_1 = P_2V_2$ *:* when temperature and mass are held constant, the volume varies inversely with the pressure of the gas.
- *Avogadro's Law* $\frac{V_1}{n_1} = \frac{V_2}{n_2}$ *:* when pressure and temperature are held constant, the volume is directly proportional to the mass of the gas.
- *Gay Lussac's Law* $\frac{P_1}{T_1} = \frac{P_2}{T_2}$*:* when volume and mass are held constant, the temperature is directly proportional to the pressure of the gas.

Condenser (higher temperature output)

After the refrigerant vapor has passed through the compressor it enters the second heat exchanger. This heat exchanger is located at the higher temperature output and is called the condenser. Similarly to the evaporator this component also consists of a coil through which the refrigerant flows and a fan to draw air through the heat exchanger, but this time it is used to transfer the thermal energy from the refrigerant vapor onto the air again by condensing the gas into a liquid (Carrier, 2022).

Expansion valve

The expansion valve is used for regulating the flow of the refrigerant through the system. And, as mentioned before, together with the compressor the expansion valve can act as a thermostatic metering device to control the pressure and temperature of the refrigerant vapor. Several types of expansion valves exist, but the most used ones are the thermal (for manual regulation) and electronic (for automatic regulation) expansion valves. (Bob, 2019; Carrier, 2022).

2.1.3 Rules and Regulations

The type of components and refrigerant substances used in heat pumps can have a big impact on the environment and the health of people. So, to be able to manufacture, sell and use these type of devices, strict rules and regulations must be followed. The rules and regulations, regarding refrigeration technology and climate control in Europe, are used to show which of rules and regulations apply to heat pump systems. The main topics that are discussed in this part are about the legislation that apply to dangerous substances, energy labelling, mechanical guidelines, safety and environmental impact.

F-gas Regulation (EU) nr. 517/2014

F-gas refrigerants or HFC's are fluorinated greenhouse gases which have a big effect on global warming, they have an even higher global warming potential than the well-known greenhouse gas carbon dioxide. The purpose of the F-gas regulation is therefore to reduce the emission of fluorinated gases and thus better protect the environment (EuropeanUnion, 2022; NVKL, 2022).

Ozone Regulation (EU) nr. 1005/2009

Chlorine containing refrigerants or HCFC's contain ozone depleting substances. Ozone depletion is the process which causes the ozone layer in the upper atmosphere of the earth to gradually become thinner. Since January the first of 2015 the ozone regulation made sure that it was completely forbidden to refill refrigeration and climate control devices with HCFC refrigerants and with that reduce the emission of chlorine containing gases and thus better protect the environment (EuropeanUnion, 2022; NVKL, 2022).

General Product Safety Directive (EU) 2001/95/EG

To protect the consumer health and safety, and to ensure the internal European market from working properly, the general product safety directive was introduced. This directive shows the product safety requirements and how, by means of market surveillance and other enforcement activities, these requirements are met (EuropeanUnion, 2022; NVKL, 2022; ProductIP, 2021).

Pressure Equipment Directive (PED) (EU) 2014/68/EU

The pressure equipment directive shows the responsibilities and requirements of the manufacturer, user, inspection body and authorized supervisor. The main reason for this regulation is to ensure safety for people that come in contact with such devices and also to protect the environment (EuropeanUnion, 2022; NVKL, 2022).

Eco-Design and Energy Labelling (EU) 2009/125/EC

The first part "eco-design" is a guideline that consists of specific minimum requirements in the field of energy achievements for products inside that category. And "energy labelling" is a framework that sets requirements regarding the mentioning of the energy use on the labels of energy-related products (EuropeanUnion, 2022; NVKL, 2022).

Restriction of Hazardous Substances Directive (RoHS) (EU) 2011/65/EU

To ensure that electrical and electronic devices are safer to handle and to limit the amount of hazardous substances in the environment, the restriction of hazardous substances directive was put together. This directive shows which substances can and cannot be used and in which quantities (EuropeanUnion, 2022; NVKL, 2022).

Machinery Directive (EU) 2006/42/EC

The machinery directive exist to ensure that manufacturers oblige to specific requirements with regard to machine safety and reliability. Buyers have the right to have access to a user manual, declaration of conformity and a CE-marking on the device. With the use of the CE-marking a manufacturer declares that their device meets the requirements of the directive and that they are completely responsible for potential defects (EuropeanUnion, 2022; NVKL, 2022).

Registration, Evaluation, Authorization and Restriction of Chemicals Directive (REACH) (EU) EC 1907/2006

The registration, evaluation, authorization and restriction of chemicals directive protects the health of people and the environment against the risks that chemical substances can carry. The directive states that all of the used or traded chemicals need to be registered and the corresponding risks need to be identified and mitigated where needed (EuropeanUnion, 2022; NVKL, 2022).

Summary

Basically, a heat pump system must comply to the following regulations. Firstly, the system itself must meet all of the product safety requirements (to ensure reliability when using the system) and all of the relevant product information should be included or indicated on the outside of the device (to provide the user with enough insight in what they are using). And secondly, the substances used within the system must be in line with the allowable global warming potential and ozone depletion potential values and should be documented according to the “REACH” directive (to make sure it is in line with the current environmental standards).

2.2 Use Case Analysis

To get more insight into the topic and to find out for what the most suitable heat pump application is, information needs to be gathered about the current use cases and the functions of these devices. The outcome of this analysis is then used to further develop one of these devices and to find out what the required temperature range should be. The first part discusses current processes for which heat pumps have already been used. The second part looks at high temperature household appliances and compares their usage and annual costs. And the last part discusses the most suitable application and the corresponding temperature range.

2.2.1 Current Heat Pump Applications

As mentioned before, heat pumps are mechanical devices that use refrigerants to extract thermal energy from a low temperature heat source and increase it to a higher temperature through vapor compression. These devices are now mainly used for heating and cooling of buildings and in the industrial sector they are also used to collect the thermal energy from waste heat so it can be put back into processes to increase the temperature in a more energy-efficient way. Compared to the residential sector, in industry there are already many more processes in which the heat pump principle is applied (Arpagaus et al., 2019). Examples of these are:

- *Drying:* for example used in the food and pharmaceutical industry to remove moisture from products so that they have a longer shelf life or to remain their shape.
- *Space heating:* if products have been painted or have to harden, they must be heated in a small room by a continuous supply of dry air.
- *Baking*: in the food industry this is used for baking bread on a large scale and in another industry it is also being use for brick curing processes.
- *Water heating:* industrial processes that require heated water are for example the preparation of cement and plaster, but it can also be used for washing cars and cleaning deposit bottles.
- *Steaming:* processes in which steam is used include for example the large-scale washing of clothes or the sterilization of tools used in hospitals.
- *Chemical processes:* most chemical processes need a certain temperature at which substances react optimally with each other, or in which they separate from each other, but it can also be used for example for the galvanization of steel.

These are just a few examples of the large number of industrial processes in which the heat pump principle is already being applied. But inside residential buildings or houses it is currently only used for heating and cooling of rooms. This is why research is necessary to find out more possible applications for heat pump technology in household devices.

2.2.2 High Temperature Appliances and Energy Consumption

Most of the high temperature devices inside a house can be found in the kitchen. The appliances that could become more energy-efficient here are the cooktop, oven, kettle and the warm/hot water tap. For each of these household appliances the energy consumption can be reduced. This section therefore compares these processes and based on how much more efficient each process can become and thus how much money can be saved annually, a decision can be made about the ones that are worth optimizing.

The data below was obtained from millieucentraal.nl and energids.be. The energy consumption in kWh is based on an average Dutch and Belgian household and the conversion to euros is based on the current energy price (18-3-2022) of €0.625 per kWh.

Table 2 Average energy consumption of high temperature household appliances

Type	Energy consumption (kWh)	Price (€)
Cooktop:		
Cast iron	260	162,50
Ceramic	225	140,63
Induction	175	109,38
Oven:		
Convection	150	93,75
Kettle:		
Electric	80	50,-
Kitchen boiler:		
Electric (65 ^{o}C)	200	125,-
Electric (100 ^{o}C)	560	350,-

Looking at the energy consumption and the corresponding total price per year, it can be seen that the kitchen boiler costs the most, followed by the three types of cooktops and then the oven, the kettle is negligible due to the low consumption per year.

2.2.3 Appliances Suitable for Optimization

According to the previous part, the three appliances that could be more energy efficient are the cooktop, the oven and the kitchen boiler. This chapter takes a more detailed look at their functions and the required temperature ranges in which they operate. And, because there are three types of cooktops, the one that is currently the most efficient (induction) will only be taken into account.

Induction cooktop

A cooktop needs a certain temperature range to be able to cook food properly. The minimum required temperature to be able to cook all types of food (eggs, vegetables, meat, fish, etc.) is 73.9 ^{o}C (FSIS, 2020). But this does not mean that you can prepare all types of dishes. For example, for slow simmering and smoking food, a temperature range of 93.3 to 148.9 ^{o}C is required and for baking meat, vegetables, eggs, pancakes, etc. and deep-frying, a minimum temperature range of 148.9 up to 204.4 ^{o}C is required (Panna, 2020). Some cooktops also have a temperature range higher than 204.4 ^{o}C, but this is mainly used for searing meat, which is not a big necessity.

Figure 5 Example of an induction cooktop (www.Pinterest.com)

Looking at the previously mentioned data, the new system must have a minimum temperature range of 73.9 to 204.4 ^{o}C to maintain the same function as the current type of cooktops. To get the core temperature of food to this temperature, the temperature range will have to be even slightly higher because during the transfer of heat from the cooktop to the pan and from the pan to the meat, some of the thermal energy is lost. Taking this into account, it will bring the temperature range to a temperature of 73.9 to 214.4 ^{o}C. If you look at the types of induction cooktops currently on the market, they have an average temperature range of 60 to 260 ^{o}C.

A requirement for the new type of cooktop (that will use the heat pump principle) would therefore be that the new system should reach a temperature of at least 214.4 ^{o}C and a wish would be that the cooktop can reach 260 ^{o}C.

Convection oven

Just like the cooktop, an oven also needs a certain temperature range to prepare food correctly. As with the cooktop, the minimum temperature to safely prepare food is 73.9 ^{o}C and the same temperature range of 93.3 to 148.9 is required for slow cooking. But for the other types of preparations, the oven uses a different temperature range. For example, for roasting meat, vegetables and fish a temperature range of 148.9 to 176.7 ^{o}C is required, for baking cookies and cakes a temperature range of 176.7 to 204.4 ^{o}C is required and for baking pizzas and quickly roasting meat and fish a temperature range of 204.4 to 248.9

Figure 6 Example of a convection oven (www.Indesit.ae)

°C is required. If you look at the types of convection ovens currently on the market, they have an average temperature range of 90 to 260 °C.

A requirement for the new type of oven (that will use the heat pump principle) would therefore be that the new system should reach a temperature of at least 248.9 °C and a wish would be that the oven can reach 260 °C.

Kitchen boiler

Compared to the cooktop and oven, a boiler requires a lower temperature range. For example, to provide the user with hot water, the boiler only needs a temperature of 60 °C. The reason for this is that at temperatures lower than 60 °C there is a risk of bacterial growth and at temperatures higher than 60 °C the user can burn his hands. But, if the user also wants to have access to instant boiling water, the boiler must reach a temperature of at least 100 °C.

A requirement for the new type of kitchen boiler (that will use the heat pump principle) would therefore be that the new system should reach a temperature of at least 100 °C.

Figure 7 Example of a boiling water kitchen boiler (www.Vaillant.co.uk)

2.2.4 Chosen Heat Pump Application

The cooktop requires a minimum temperature of 214.4 °C and the convection oven a temperature of 248.9 °C. Taking into account that these appliances will need to heat up from a temperature of about 16 °C (room temperature), this means that the temperature difference is above 200 °C. In literature there is no example of a standalone heat pump system that has achieved this and, if this was possible, it would not have been efficient enough to be worth investing time and effort in. A hybrid system on the other hand can maybe be efficient, but this would not make a big difference compared to the current cooktops and ovens. Also, looking at the energy consumption and the corresponding prices in Table 2, on a yearly basis it would not safe a lot of money and this also makes it less attractive to optimize these types of appliances.

Because of the previously mentioned arguments, the kitchen boiler is the next option to take into consideration. With a required minimum temperature of around 100 °C, this device has a much lower temperature range than the cooktop and oven. Also, compared to all the other appliances, the kitchen boiler has the highest energy consumption (see Table 2). So, taking these two factors into consideration, the kitchen boiler would be the most suitable application.

2.3 Competitor Analysis

Looking at the previous chapter (2.2 Use Case Analysis), the most suitable device for optimization is the kitchen boiler. Because there are currently already some brands on the market, that manufacture and sell kitchen boilers, it is useful to conduct a competitor analysis. For this competitor analysis a total of fifteen devices (from four well-known brands) were analysed. By using the technical data of the devices, a frame of reference can be set for the newly developed boiler. Secondly, the outcome of each analysis are compared to each other, so the outstanding features can be filtered out. The brands used for the analysis are Quooker (Quooker, 2022), Selsiuz (Selsiuz, 2022), Franke (Franke, 2022) and Grohe (Grohe, 2022). And the name of their devices are:

- *Quooker:* PRO3, COMBI, COMBI+ and CUBE
- *Selsiuz:* Single, Combi Extra, Titanium and Cooler
- *Franke:* SOLO S, COMBI S, COMBI XL and COMBI Xcellent
- *Grohe:* Red L, Red Compact and Blue Home

This chapter will only show the comparison and the outstanding features, a complete overview of the devices and their technical data can be found in **Appendix B**.

Comparison

The similarities that were found across the fifteen devices are:

Function	- Most devices can provide instant boiling water (100ºC). - Many devices can also provide instant warm water (ranging from 40 to 60ºC) by using a mixing tap. - Some devices can also provide cooled and/or sparkling water.
Dimensions	- Most devices have a height of roughly 500 millimetres and their width and depth are around 200 millimetres. - Most devices are round, to better withstand the pressure on the inside.
Volume	- The volume of the devices are within a range of 3 to 10 litres. - Most devices can contain 5 litres of water.
Reheating time	- The reheating time ranges from 10 to 35 minutes, but this is strongly dependent on the volume and the performance of the container.
Material	- The devices all use some kind of metal material (stainless steel, copper or titanium) for the construction of the container, because of the rigidity. - Either some kind of insulation material or vacuum seal is used to reduce the amount of heat loss.
Performance	- The heating performance of the devices ranges from 1500 to 2200 Watts. - The stand-by performance of the boilers ranges from 10 to 25 Watts and is strongly dependent on the type of insulation used.

Outstanding features

- *Several colours available*: e.g. chrome, inox, copper, gold, gun metal, Gessi, stainless steel, black and messing.
- *Several designs available*: e.g. twin tap and retractable hose.
- *Safety and feedback*: e.g. two step safety handles, safe touch and feedback light.
- *Optional devices*: for dispensing cooled, sparkling and/or filtered water.
- The use of titanium to make the device more resistant to big temperature differences and corrosion.
- An app to control the device, the settings and to automatically order new CO2 cartridges and filters.
- Vacuum insulation, for reduced heat loss and increased system efficiency.

2.4 System Configurations

There are currently several types of cycle configuration that have proven to work and are used within heat pump systems. Depending on the type of application for which a system is needed, and the external factors, certain types are better than others. This chapter will cover the three main configuration types, which are the single-stage, multi-stage and cascaded systems (Moisi & Rieberer, 2017).

2.4.1 Single-stage

The heat pump used for the explanation in chapter 2.1.2 (Components and Functions) is a so called single-stage system. This is the most basic and simple type of system. It uses a single compressor and one type of refrigerant to increase the temperature, but it is only useful for certain type of applications and small temperature ranges. Single-stage systems come with low equipment costs, low repair costs and are less likely to break, but most of the time also have a low to average efficiency (Langer, 2022).

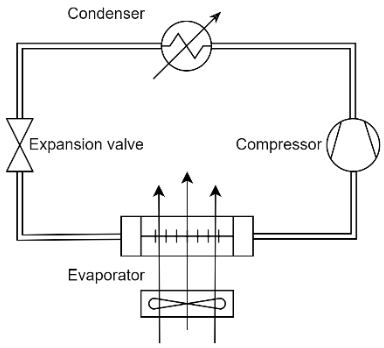

Figure 8 Single-stage heat pump configuration

2.4.2 Multi-stage

A multi-stage heat pump uses multiple compression cycles to increase the temperature. The way this is being achieved is by using two or more compressors to compress one type of refrigerant multiple times. By compressing the refrigerant in steps, the individual compressor power can be reduced and the efficiency can be increased. A disadvantage is that, because this system uses more components, this system is more expensive. The maintenance costs on the other hand do not increase much compared to a single-stage system (Moisi & Rieberer, 2017).

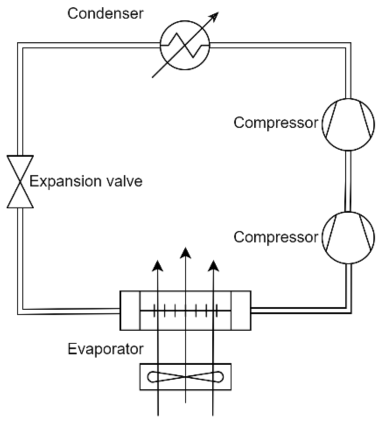

Figure 9 Multi-compression heat pump configuration

2.4.3 Cascaded

The cascaded heat pump system also uses multiple compression cycles to increase the temperature, but the cycles are separated from each other by means of an intermediate heat exchanger. This type of system consists of two or more compressors and one or more refrigerant types to reduce the required individual compressor power and increase the condenser mass flow and thus the system efficiency. Compared to the previous configuration types, this type is more expensive, but the likeliness to break or the repair costs do not increase much compared to a multi-stage system (Langer, 2022).

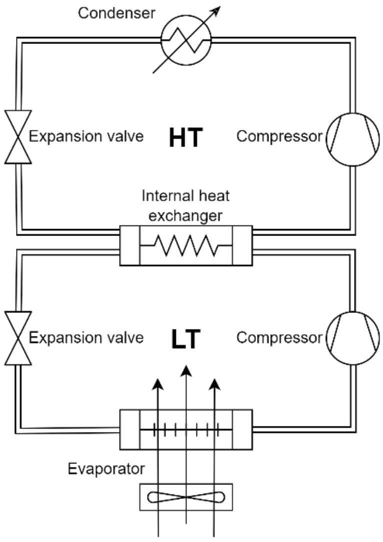

Figure 10 Cascade heat pump configuration

2.5 Deployment Methods

In total there are three main kinds of heat pump deployment methods, these are the monovalent, bivalent-parallel (also called mono-energetic) and bivalent-alternative working principles. Each of these have their own advantages and reasons for why they are being used, this is explained in the next section (hotline_tm, 2015; Jiang et al., 2022).

2.5.1 Monovalent

The most basic heat pump deployment method is the monovalent working principle. This is a type of system that covers the complete heating by only using the heat pump as a heating source (without the need of any additional support). Unfortunately in some situations the heat pump does not have the right specifications, or the external factors are not optimal to be able to heat up the air to the desired temperature. In this case, there are a couple of ways in which the system can be supported. These are the bivalent-parallel (or mono-energetic) and the bivalent-alternative systems, which are explained in the following two sections.

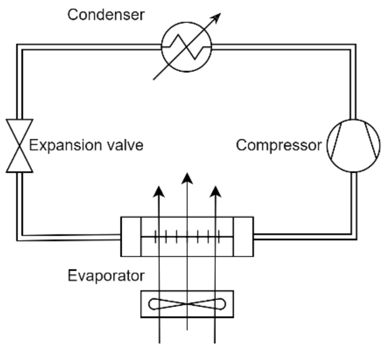

Figure 11 Monovalent heat pump deployment method

2.5.2 Bivalent-parallel

The first type of system support is the bivalent-parallel working principle. This is a type of system in which the heat pump covers the biggest part of the heating, but when necessary, an additional device can be switched on to provide the remaining amount of thermal energy at the output. The integration of the heat pump and the additional heat generator can be used to increase the performance and capacity during moments when the external factors are not optimal. The way this can be achieved is by for example supplying the additional required thermal energy by using an electric heating element, a thermal solar panel or a gas-fired central heating.

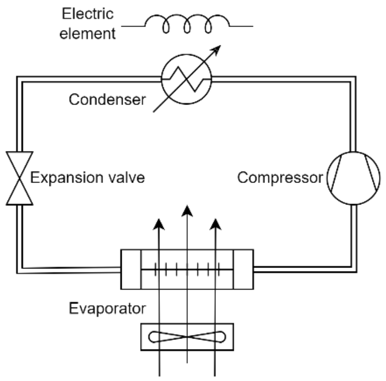

Figure 12 Bivalent-parallel (or bivalent-alternative) heat pump deployment method

2.5.3 Bivalent-alternative

The bivalent-alternative working principle resembles the previous type of system support, but instead of simultaneously providing the thermal energy, this system switches between the different heat generators. For example if the outside temperature is below a certain temperature threshold it switches to the gas-fired central heating or a solid fuel alternative, because in this case it is more energy efficient.

2.6 Summary

A heat pump system can be ground, air, or water source (or hybrid) and each of these types have their own pros and cons. According to chapter 2.1.1 (Heat Pump Principles) the most suitable heat pump type for the newly designed system is the air source heat pump, because it is the least expensive and most versatile one. The same as all the other systems, this type of system consists of the following components: evaporator, condenser, compressor, expansion valve and refrigerant, but the main differences is the type of heat exchanger used as the evaporator and the size of the overall system. The air source heat pump uses a combination of a coil (through which the refrigerant flows) and a fan (to draw in air over the outside of the coil), to transfer the thermal energy from the air to the refrigerant. The condenser on the other hand can be specified later on according to the application for which it will be implemented and since the system will only be used for heating, there is no need for a reversing valve.

The domestic appliance with the most potential for being optimized, is the kitchen boiler. Chapter 2.2.2 (High Temperature Appliances and Energy Consumption), together with chapter 2.2.3 (Appliances Suitable for Optimization), show that out of all the appliances this device has the highest energy consumption and the most suitable temperature range for being optimized. Currently heat pumps are already being used for heating water, but most of them can only reach a temperature of around 55 ^{o}C and they are much more efficient at temperatures of around 35 to 45 ^{o}C. So this means that, with a heat pump, a temperature of 100 ^{o}C (in the residential sector) has not yet been achieved. Which makes it, compared to the state-of-the-art, a novel concept.

To be able to reach this temperature, a variety of system configurations and deployment methods can be used (see chapter 2.4 and 2.5). In the next chapter, these will be combined and investigated in more detail to find the best option for the heat pump kitchen boiler. While also keeping in mind the product safety requirements, relevant documentation and refrigerant environmental impact regulations from chapter 2.1.3 (Rules and Regulations).

3. System Description and Methodology

In this chapter, a more in depth research is conducted to see what the possibilities are when using compressor and heat exchanger technology. First, each of the heat pump components will be analysed in more detail, to complete the list of requirements and to be able to use the information when selecting components in chapter 3.5.1 (System Component Selection). Then, to find out what the possibilities are with regard to optimizing the performance and efficiency, different types of heat pump system configurations and deployment methods are combined to find the most suitable one. And finally, in the last analysis, the previously gained information is used to select the right type of refrigerants and to retrieve a first estimation of the overall system performance.

3.1 System Components

For the component selection in chapter 3.5.1 (System Component Selection), a more in depth analysis needed to be executed into the main components of an air source heat pump. The first goal here was to find out if there are refrigerant types available that can heat up to the required boiler temperatures (100 °C). Then, depending on the outcome, the second task was to find the proper type of compressor for delivering the necessary amount of pressure. And finally, to optimize the heat transfer efficiency, existing heat exchanger types were also investigated.

3.1.1 Refrigerants

The first requirements (that were found during the preliminary research phase) are used to find out which refrigerants can be used in the new heat pump system. But, because in industry there are currently an unnumerable amount of refrigerants and refrigerant blends available, it is impossible to compare every one of them. For this reason, the decision was made to use the ASHRAE list of approved refrigerants (ASHRAE, 2019). This list contains the most used and widely available refrigerants that are currently on the market and limits the total amount of suitable refrigerant types to a total of 260. Together with the chemical property tables from the 'ASHRAE Handbook – Fundamentals 2021' (ASHRAE, 2021), the refrigerant datasheets from Bitzer (Bitzer, 2017) and the refrigerant datasheets from HRAI (HRAI, 2019), the corresponding refrigerants and their properties could be listed.

The next step in this search was to find refrigerants that are according to the European rules and regulation regarding ozone depletion and global warming. This was done by filtering out the substances with an ODP value of 0 and a GWP value of less than 150 from the list. This limits the amount of suitable refrigerant types to a total of 48 substances.

Then, because the refrigerant should be chemically stable at the required pressure and temperatures, the refrigerants with a boiling temperature higher or equal to 16 °C were also filtered out. This limits the list even more and brings the amount to a total of 19 substances.

On the other hand (as explained in chapter 2.4) it is not necessary for all refrigerants to have a boiling temperature lower or equal to 16 °C, because it is also possible to use a cascaded system in which one refrigerant is used for the lower temperature range and the other for the higher temperature range. For this reason, the decision was made to also include the substances with a boiling temperature above 16 °C and a high critical temperature. For this reason eight of the previously eliminated substances could be added to the list again and brings the total back to 27. The final selection is noted down in Table 3 and a complete overview (including the safety criteria) can be found in **Appendix C**.

Table 3 Selection of suitable refrigerants

Number	Name	Type	Zeotropic*	GWP	ODP	Tcrit (C)	Tboil (C)
R-152a	1,1-Difluoroethane	HFC	no	138	0	113,26	-24,00
R-161	Fluorethane	HFC	no	4	0	102,22	-37,1
R-170	Ethane	HC	no	6	0	32,17	-88,58
R-290	Propane	HC	no	3	0	96,74	-42,11
R-444A	AC5	HFO/HFC	yes	93	0	106,00	-35,70
R-451A	-	HFO	yes	140	0	95,40	-30,80
R-468A	-	HFO/HFC	yes	148	0	84,00	-51,20
R-471A	-	HFO/HFC	yes	148	0	112,00	-16,90
R-516A	ARM-42	HFO/HFC	yes	131	0	97,00	-29,40
R-454C	Opteon XL20	HFO	yes	148	0	82,40	-45,90
R-455A	Solstice L40X	HFO	yes	148	0	85,60	-52,10
R-600	Butane	HC	no	6,6	0	152,01	0
R-600a	Isobutane	HC	no	3	0	134,66	-11,75
R-601	Pentane	HC	no	4	0	196,56	36,10
R-601a	Isopentane	HC	no	4	0	187,78	27,70
R-610	Ethyl ether	HC	no	4	0	193,65	34,60
R-611	Methyl formate	HC	no	0	0	213,55	32,00
R-631	Ethylamine		no	?	0	183	16,60
R-717	Ammonia		no	0	0	132,25	-33,30
R-718	Water		no	0,2	0	373,95	100,00
R-744	Carbon dioxide		no	1	0	31,98	-78,46
R-1233zd(E)	Trans-1-Chloro-3,3,3-Trifluoropropene	HFO	no	1	0,00034	165,5	18,26
R-1234yf	2,3,3,3-Tetrafluoropropene	HFO	no	4	0	94,70	-29,40
R-1234ze(E)	Solstice ze	HFO	no	7	0	109,37	-19,00
R-1270	Propylene	HO	no	1,8	0	92,42	-47,60
R-1336mzz(E)	Trans-1,1,1,4,4,4-Hexafluoro-2-butene	HFO	no	18	0	137,7	7,50
R-1336mzz(Z)	Cis-1,1,1,4,4,4-Hexafluoro-2-butene	HFO	no	2	0	171,3	33,4

3.1.2 Compressors

As mentioned in chapter 2.1.2 (Components and Functions), a compressor is used to increase the pressure and subsequently the temperature of a refrigerant in gaseous state. But, to understand the working principle behind this device, this section will take a more detailed look at the mechanics of some of the most used compressor types and explains their design characteristics. Then, later on, this information can be used to determine which compressor is most suitable for the design of the new heat pump water boiler.

The compressor types that will be discussed in this section are the ones that are suitable for refrigeration and heat pump cycles. These type of compressors work by letting in low pressure gas at the inlet, then compressing the gas mechanically and letting pressurized gas out at the other side. There are several types of compressors that can do this and they are categorized by their compression mechanisms (Engineering360, n.d.). The compression mechanisms can be divided into two main categories, which are the 'positive displacement' compressors and 'dynamic displacement' compressors and for each of the two categories there are several types of compressors that work according to the corresponding principle (BigRentz, 2020).

3.1.2.1 Positive Displacement

The first compressor category is the positive displacement mechanism. This principle works by forcing a gas into a chamber, then decreasing the volume of that chamber by using a mechanical linkage to compress the gas and force it to exit via the outlet (BigRentz, 2020). Depending on the type of implementation, some positive displacement compressors are more suitable for industrial workloads and others are more suitable for consumer products or private projects. The four most used positive displacement compressors, for refrigeration and heat pump cycles, are: reciprocating, rotary-vane, rotary-screw and rotary-scroll compressors (BigRentz, 2020; Bob, 2019; Engineering360, n.d.).

Reciprocating compressor

A reciprocating compressor is a piston compressor. The internals of this type of compressor can be compared to that of a combustion engine because it also uses a piston and crankshaft in its mechanism. By rotating the crankshaft, the piston moves up and down and as the piston moves down, gas is drawn into the chamber and by moving the piston up again, the gas is compressed and forced out through the exit of the chamber. This type of compressor can deliver high pressure and is most of the time used for smaller applications because of its low initial costs and simple design, but some downsides are that it is not suitable for running continuously, it comes with potential vibrational issues and the cost of maintenance can be high.

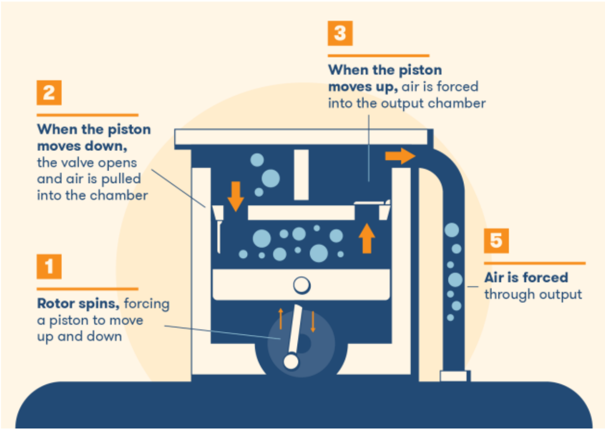

Figure 13 Reciprocating compressor diagram (BigRentz, 2020)

Rotary-vane compressor

There are two types of rotary-vane compressors, but they both consist of the same type of parts, namely a rotating cylinder and retractable vanes. The difference between the two is that one type has multiple vanes mounted onto the cylinder itself and the other type uses a single vane which is mounted onto the inside of the housing (also known as a rolling-piston compressor). A rotary-vane compressor works by rotating an offset cylinder and allowing vanes to retract and in this way decrease the volume of the chamber and compress the gas that is trapped in between. Similarly to the reciprocating compressor, this type of compressor has low initial costs and a simple design which makes it suitable for small scale applications, but because of the smaller chamber size it cannot deliver the same high pressure compared to other compressors. On the other hand, this compressor is very efficient because the process of taking in gas and compressing happens simultaneously, so it is able to run continuously.

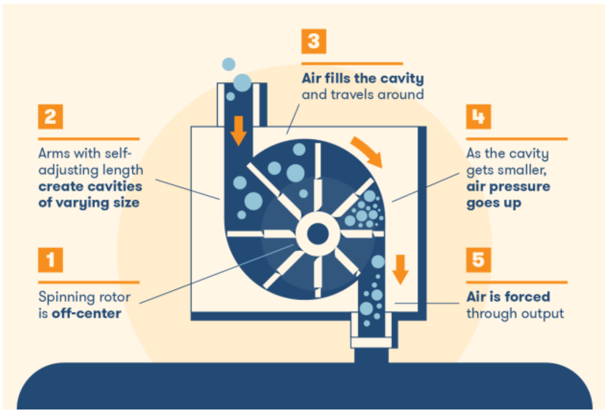

Figure 14 Rotary-vane compressor diagram (BigRentz, 2020)

Rotary-screw compressor

This type of compressor consists of two internal helical screws (one male and one female) that, when put together, create a tight fit in between. The mechanism works by rotating the two screws in opposite direction in relation to each other. Then, because the volume decreases when the gas travels along the shaft, the gas is compressed when moving towards the exit of the chamber. This type of compressor is one of the easiest to maintain, it is suitable for creating a high pressure, it can run continuously and it consumes less power compared to other compressor types. However, because of the higher initial costs, this type of compressor is mainly found in industrial applications and it also has a shorter life expectancy than other compressor types.

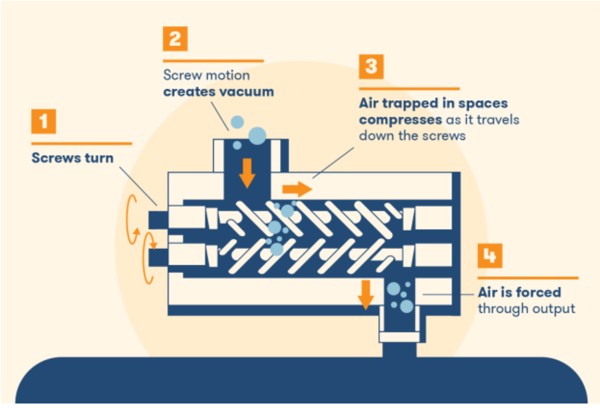

Figure 15 Rotary-screw compressor diagram (BigRentz, 2020)

Rotary-scroll compressor

Another type of rotary compressor is the scroll compressor (also sometimes called a spiral compressor). The scroll compressor consists of two offset spiral disks that are nested together. By keeping one spiral disk stationary and rotating the other in an orbital way, the volume of the space in between the spiral disks decreases the closer it gets to the centre of the chamber and this causes the trapped gas to get compressed. This type of compressor can deliver a medium to high pressure, is suitable for running continuously and, compared to other compressor types, has the highest efficiency ratio and it also has low initial costs. This is the main reason it is primarily used in small scale applications. The maintenance on the other hand is sometimes more difficult (especially when it is a fully hermetic design) and it can be expensive.

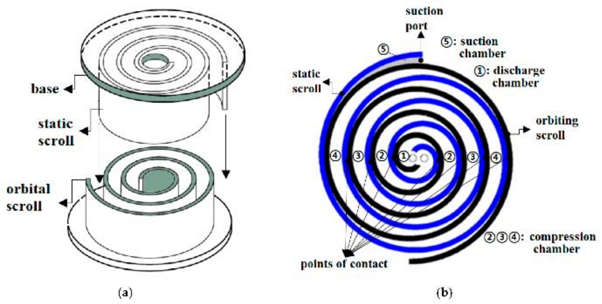

Figure 16 Rotary-scroll compressor diagram (Sung, Boo, & Jung, 2020)

3.1.2.2 Dynamic Displacement

The second compressor category is the dynamic displacement mechanism. This principle works by rotating blades to generate a gas flow. Due to the high kinetic energy of the particles and the fact that gas is restricted by the flow rate and limited space inside the system, the gas is pressurised at the exit (BigRentz, 2020). These type of compressors are mainly used in big industrial plants, but now and then also find their way into smaller applications. The two most used dynamic displacement compressors, for refrigeration and heat pump cycles, are centrifugal and axial compressors (BigRentz, 2020).

Centrifugal

A centrifugal or turbo/radial compressor consists of an impeller that rotates fast to draw in gas through its chamber. By increasing the speed of the impeller, the centrifugal force increases and by decreasing the flow at the exit (with a diffuser), the gas is compressed and pressurised. This type of compressor is suitable for high volumetric flow rates, but it can only deliver a low pressure at the exit. For higher pressure levels, multiple centrifugal compressors need to be installed in series and this makes this type of compressor less suitable for smaller applications. But, when operated with multiple stages, the simple design makes this compressor easy to install and it provides an energy efficient way of compressing gas.

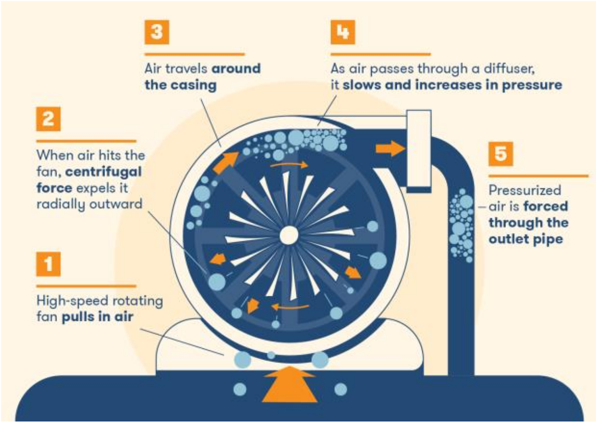

Figure 17 Centrifugal compressor diagram (BigRentz, 2020)

Axial

Similarly to the centrifugal compressor, the axial compressor also uses an impeller to draw a gas through its chamber. But, instead of using a diffuser at the end, the axial compressor uses stationary blades in between to decrease the volume and the flow. In this way the high kinetic energy of the gas helps to compress it. This type is rarely seen in small scale applications and it is also not commonly used in industrial applications because of its limited functionality, higher initial cost and high maintenance costs. But they are sometimes used in big refrigeration systems.

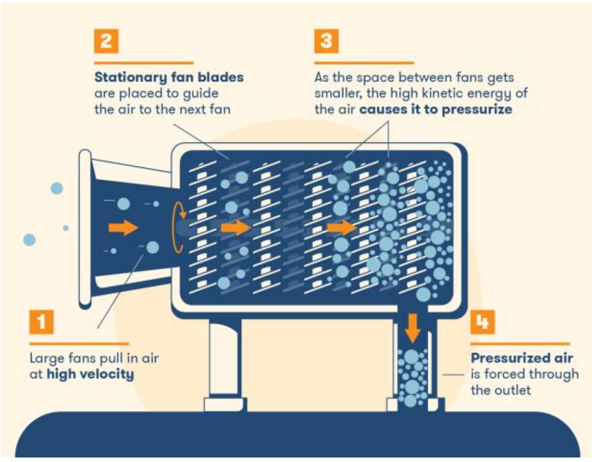

Figure 18 Axial compressor diagram (BigRentz, 2020)

3.1.2.3 Overall Features

Besides the classification according to the different types of compressors, each compressor can also be classified according to their design features. For example, all reciprocating compressors work according to the same mechanism, but they can have different kind of features that makes each type suitable for a different refrigerant and application. Next up, the most important features are noted down and explained briefly (Dell, Moseley, & Rand, 2014; Dincer, 2018; Engineering360, n.d.; Senay, 2021).

- *Compression ratio:* the compression ratio of a compressor is the ratio between the inlet pressure and the discharge pressure. The discharge pressure is dependent on the change in compression chamber volume at the start and at the end of the compression. So, to decrease this ratio, the discharge pressure needs to go down by adjusting the volumetric change.
- *Isentropic efficiency:* the ratio between the ideal work and the actual work is called the isentropic efficiency and it determines the efficiency of a compressor (and subsequently

influences the COP value of a system). Many factors play a role in how efficient a compressor is. For example, the type of motor, lubrication oil, size of the compression chamber, etc. can have an influence on the efficiency.

- *Power:* to make sure that the compressor motor can run at the specific operating point, the required compressor power needs to be known. To find out the amount of compressor power that is needed, the type of refrigerant and the amount of pressure that is required needs to be known. To increase the compressor output power, either the inlet power needs to be increased by using a more powerful electric motor, or the isentropic efficiency of the compressor needs to improve.
- *Flow rate:* the rate at which mass of a certain fluid passes through the compressor is called the flow rate. The flow rate is strongly dependant on the speed of the compressor motor and the volumetric change of the compressor chamber. So, if a certain refrigerant requires a high flow rate, the motor power needs to increase, or the compression ratio of the internal chamber needs to increase.
- *Thermal safety:* some compressors have to deal with extreme temperatures, which means that the housing material, internal components and the lubrication oil need to be able to withstand these harsh conditions for a prolonged amount of time. On the other hand, it can also happen that the compressor malfunctions and when this happens, a “thermal shut off” control is used. This feature is included in some compressors, to improve the safety, by turning off the compressor when it is overheating. Next to this, an automatic restart (when the compressor has cooled down to a certain temperature) can also be incorporated in the control.
- *Sealing:* the way a compressor is sealed is determined by how the internal components (e.g. the compressor, motor and gears) are located, in relation to the operating gas. There are three types of sealing levels, these are: open, hermetic and semi-hermetic. In an open system, the compressor and motor each have their own housing and to prevent leakage between the two, the sealing between parts relies solemnly on the lubrication oils. For the hermetic system type, the opposite is the case, namely the motor and compressor are located in the same completely closed housing and that provides a reliable leak-free system. On the other hand, a hermetic system makes it harder (or sometimes impossible) to maintain and repair the device. And finally, the semi-hermetic system, this type is comparable to the hermetic one, but the difference is that the housing is not completely closed, but it is kept together with fasteners and a seal in between the housing parts, which allows for taking the system apart when maintenance or a repair is needed.
- *Noise level:* the amount of noise a compressor makes should sometimes be limited. To limit this, the type of compressor that is used plays an important role. When the option to choose between compressors types is not present, some design features can be implemented to reduce the noise level. For example, the type of lubrication can help in reducing the sound that is created between parts or when that does not help, the compressor can be wrapped in noise insulating material (when space is limited or when temperatures are extremely high, this will not be an option).
- *Variable speed:* to be able to adjust the flow rate of the operating gas, the compressor can be an inverter type that is able to regulate the speed of the AC motor. This feature can be implemented by using the right type of motor together with a suitable control system. This type of control can be implemented in every type of compressor.
- *Lubrication type:* lubrication oils in compressors are used for a couple of reasons. The first one is preventing the internal components from wearing out and preventing them from overheating. The second one is preventing leakage to and from the outside of the housing and to provide a seal between the internal compression chambers. And the last one is to keep the compressor clean by carrying dust to the oil filter and removing

it from the system. When selecting a lubrication oil, it is important to take into account the type of compressor for which it will be used. Many times the lubrication oil has already been preselected because the compressor already has a lubrication oil specifically developed and tested for the refrigerant and temperature range that is used.

3.1.3 Heat Exchangers

Heat exchangers are components that are used to transfer thermal energy from one substance to another. This transferring process can be liquid-to-liquid, liquid-to-gas or gas-to-gas and most of the time occurs through a solid separator. Depending on the type of process, different types of heat exchangers are available. To determine which heat exchangers should be used in the case of the heat pump water boiler, this section looks at some of the most used heat exchangers and explains their design characteristics (for a better understanding of the underlying thermodynamic principles, see **Appendix D**).

3.1.3.2 Design Characteristics

All of the heat exchangers types operate under the same heat transfer principles, which means that they cannot be categorized in this way. But, by using design characteristics, it is possible to put them into categories. The heat exchangers can be characterized by their flow configuration, construction method and heat transfer mechanism (Ronquillo, 2021). Depending on the type of system, the characteristics can most of the time be used for selecting the most suitable type of heat exchangers.

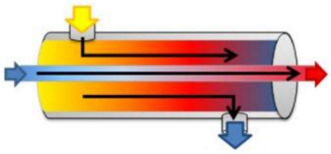

Figure 19 Cocurrent heat exchanger flow configuration (Ronquillo, 2021)

Flow configuration

The first characteristic is the flow configuration and it refers to the direction in which the substances are moving in relation to each other. The four main flow configuration are:

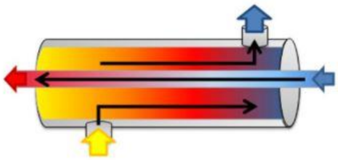

Figure 20 Countercurrent heat exchanger flow configuration (Ronquillo, 2021)

- *Cocurrent flow:* exchange of thermal energy by moving two substances parallel and in the same direction.
- *Countercurrent flow:* exchange of thermal energy by moving two substances parallel and in the opposite direction.
- *Crosscurrent flow:* exchange of thermal energy by moving two substances perpendicular to each other.
- *Hybrid flow:* exchange of thermal energy by using a combination of the previously mentioned flow directions.

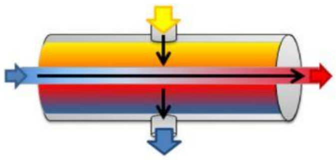

Figure 21 Crosscurrent heat exchanger flow configuration (Ronquillo, 2021)

The most used flow configuration is the countercurrent flow. The reason for this is because it yields the highest heat transfer efficiency. But, because some systems have a limited amount of space, it is sometimes not possible to use this type of configuration and a cocurrent or crossflow fits better or, to safe space, the hybrid flow configuration can be used to combine flow passes and arrangements in a single heat exchanger. Also, when for example the heat exchanger needs a high thermal uniformity across the heat exchanger, then the cocurrent flow is a better option.

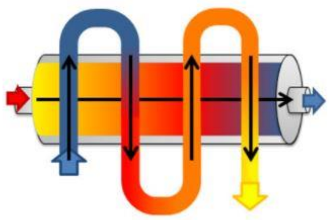

Figure 22 Hybrid heat exchanger flow configuration (Ronquillo, 2021)

Heat transfer method

The second characteristic is the heat transfer method, this one refers to how the heat exchanger components are used to transfer the heat. The construction method is either classified as a direct or indirect recuperative heat exchangers, or a static or dynamic regenerative heat exchanger (Ronquillo, 2021).

- *Recuperative heat exchanger:* a heat exchanger is called recuperative when the substances flow simultaneously through the channel or channels.
    - *Direct:* in a direct recuperator the substances come in contact with each other without some type of separation in between (e.g. oil and water).
    - *Indirect:* in an indirect recuperator the substances do not come in contact with each other, but are separated by a solid medium (a thermally conductive component).
- *Regenerative heat exchanger:* a heat exchanger is called regenerative when the substances flow alternately through the same channel.
    - *Static:* in a static regenerator the components remain stationary during the heat transferring process.
    - *Dynamic:* in a dynamic regenerator the components move during the heat transferring process.

The most commonly used construction method is the indirect recuperative heat exchanger. The reason for this is because most processes require the substances to flow simultaneously through the channels and stay separated by means of a thermally conductive solid medium. All of the previously mentioned construction methods can consist of a variety of different construction materials. Most of the time metals like copper or stainless steel are used, because of their high thermal conductivity. But in some cases, other materials like ceramics or plastics are more suitable (for example when refrigerants are aggressive or corrosive).

3.1.3.3 Construction Type

The purpose of the heat exchanger construction is to let two substances flow close to each other while also keeping them separated. This is done, to transfer the heat from the higher temperature substance onto the colder one, as efficient as possible. Most of the construction types consist of off-the-shelve components like tubes or plates and are arranged in such a way to allow for single or multi flow passes. The six main construction types are shell and tube, double pipe, plate and frame, finned tube, spiral plate and rotary wheel heat exchangers (EnggCyclopedia, 2022a; GoochThermalSystems, 2021; Ronquillo, 2021).

Shell and tube

The shell and tube heat exchanger is the most common type of heat exchanger in industry and is mostly used for preheating, oil cooling and steam generation. Its construction is made out of a cylindrical shell through which tubes run from one side to the other. One of the substances flows through the tubes and the other through the cylinder and in this way the substances do not come in contact with each other, but still have a big surface area for transferring heat. It

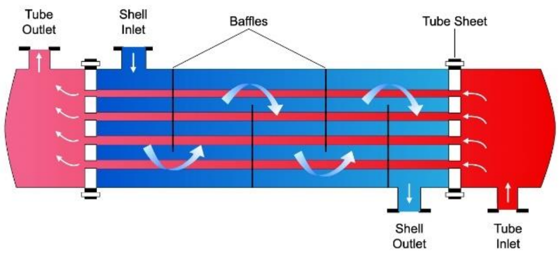

Figure 23 Shell & tube heat exchanger (Jawad, 2018)

is mostly used as an intermediate single-phase heat exchanger, but it can also be used for two-phase heat transfer. The flow configuration can be cocurrent, countercurrent, crosscurrent or hybrid, and it is also suitable for multi pass flow configurations.

Double pipe

The double pipe heat exchanger resembles the shell and tube heat exchanger, but it is basically a simpler version. Its construction is made out of two concentric pipes, with a bigger pipe through which one of the substances flows and a smaller pipe (in the centre) through which the other substance flows. It is mostly used as an intermediate single-phase heat exchanger, but it can also be used for two-phase heat transfer. The flow configuration can be cocurrent, countercurrent, crosscurrent or hybrid, and it is also suitable for multi pass flow configurations. Compared to a shell and tube heat exchanger, the double pipe heat exchanger is most of the time less efficient, but in small scale systems this difference becomes less significant.

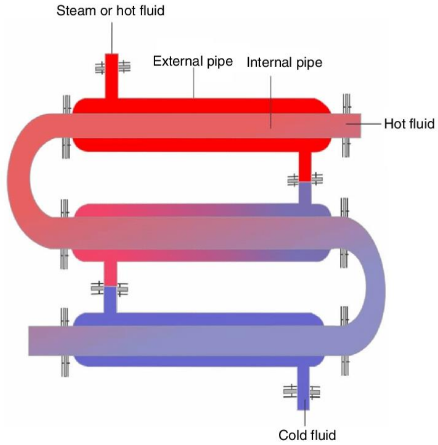

Figure 24 Double pipe heat exchanger (Subramanian, Senthil Kumar, Vinayagar, & Muthusamy, 2020)

Plate and frame

The plate and frame heat exchanger is also a type of intermediate heat exchanger, mostly used for liquid-to-liquid heat transfer. Its construction consists of several corrugated metal plates that, when stacked together, form channels in between. By bolting or welding them in a certain way, the flow of the two substances is separated but stays as close as possible to each other. This provides a big surface area through which heat can be transferred and that increases the heat exchanger efficiency. It is mostly used as an intermediate single-phase heat exchanger, but it can also be used for two-phase heat transfer. The flow configuration can be cocurrent or countercurrent.

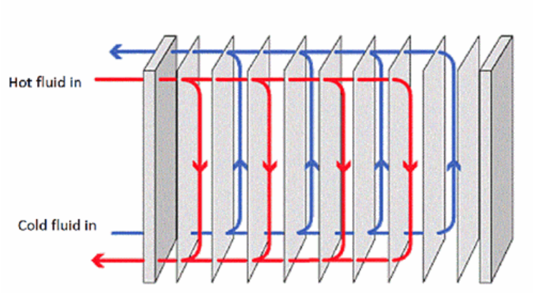

Figure 25 Plate & frame heat exchanger (Ipieca, 2014)

Finned tube

The finned tube heat exchanger is used for gas-to-liquid heat transfer and is most of the time used as an external heat exchanger, to transfer heat from the outside to the inside of a system. Its construction consists of a row of plates (fins) with small spaces in between and perpendicular through these plates a hollow tube (coil) is placed. By forcing a gas through the fins, heat can be transferred to the liquid substance inside the tube coil. This type of heat exchanger can both serve as a single-phase heat exchanger, but it can also be used for two-phase heat transfer (like in a condenser and evaporator). The flow configuration can be cocurrent, countercurrent, crosscurrent and hybrid, and it is also suitable for multiple pass flow configurations.

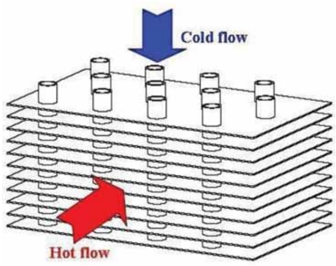

Figure 26 Finned tube heat exchanger (Ghoochani, Dehghan, Hasanvand, Jelvani, & Montazerolghaem, 2014)

Spiral plate

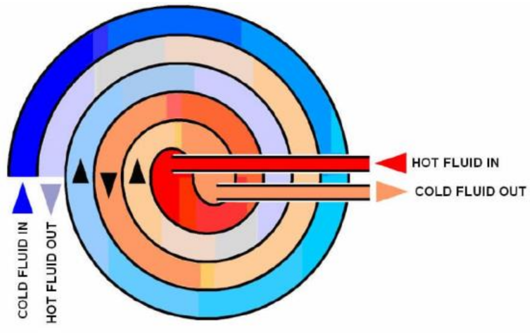

Figure 27 Spiral plate heat exchanger (EnggCyclopedia, 2022b)

The spiral plate heat exchanger is used in big scale systems and mainly works with liquid-to-liquid heat transfer. Its construction consists of two long sheets of metal that are rolled around a core, to create two concentric flow passages that are suitable for running two separated, but closely located, substances through them. It is a very efficient heat exchanger, but it is costly to manufacture. This type of heat exchanger can both serve as a single-phase heat exchanger, but it can also be used for two-phase heat transfer. The flow configuration can be cocurrent, countercurrent or crosscurrent, a hybrid flow configuration on the other hand is too costly and hard to implement.

Rotary wheel

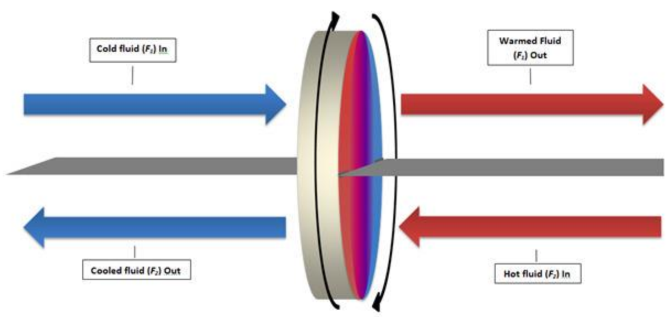

Figure 28 Rotary wheel heat exchanger (Ronquillo, 2021)

The rotary wheel heat exchanger is a dynamic type of heat exchanger and mostly used in big air-conditioning systems to support a gas-to-gas heat transfer. It is a costly installation, requires constant movement and its efficiency differs a lot between systems. Its construction is made out of two compartments which are separated from each other and connected with a rotary drum in between. By rotating the drum, warmer and colder substances can come in contact with each other to exchange heat. The flow configuration is countercurrent and it is not suitable for multiple passes.

Together with the preliminary research results in chapter 2, the information in chapter 3.1 can be used to complete the list of requirements. With these requirements the next section continues with the ideation phase and starts by introducing configuration ideas for the heat pump water boiler.

3.2 System Configuration and Deployment Combinations

Resulting from chapter 2.4 (System Configurations), there are a number of heat pump system configurations that can be used. Depending on the type of application and the external factors (e.g. outside temperature, humidity and temperature range), one is more suitable than the other. The three configurations most commonly used are the single-stage, multi-stage, and cascaded systems.

In addition to the difference in system configurations, as seen in chapter 2.5 (Deployment Methods), the way in which the heat pump is deployed can also be different. The heat pump can have a 'monovalent', 'bivalent-parallel' or 'bivalent-alternative' deployment method and these options are also each suitable for different situations and applications. The heat pump types, their functions, benefits and feasibility, with regard to the new applications, are discussed in this section.

3.2.1 Monovalent Heat Pump

function: a monovalent system uses 1 refrigerant and 1 compressor in a single closed cycle (belongs to the 'single-stage' heat pump systems).

Advantages: due to the simple design of this type of system (compared to the others), the installation costs are low and because it uses a minimum number of parts, the system is more reliable and the maintenance costs are also lower.

Feasibility: not suitable for the boiling water system, because from a physics stand point it is not possible to get from room temperature to the minimum required temperature of 100 °C with a single refrigerant and a single compressor, while still being efficient.

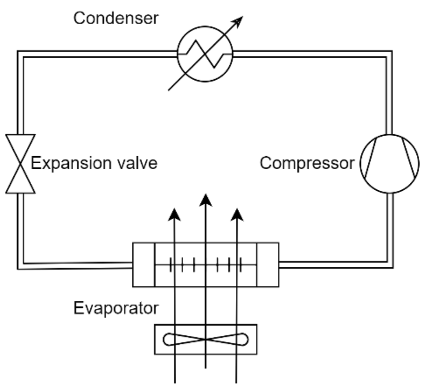

Figure 29 Monovalent heat pump system

3.2.2 Bivalent-Parallel Heat Pump

Function: a bivalent-parallel system uses 1 refrigerant and 1 compressor, but can be supported with an additional heat generator (e.g. electric element or gas-fired central heating).

Advantages: if the external factors are not optimal, or if the temperature range cannot be achieved an additional heat generator can supply extra thermal energy and the performance and capacity of the system can be improved.

Feasibility: possible, but not efficient, as most of the required temperature range (16 to 100 °C) has to be supported with an additional heat generator.

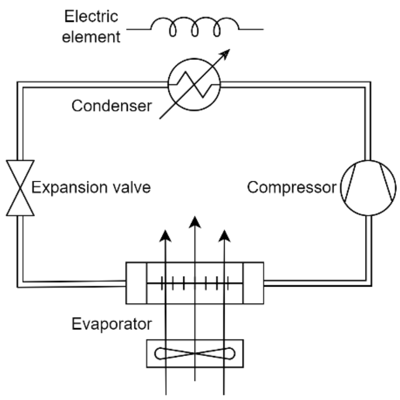

Figure 30 Bivalent-parallel heat pump system

3.2.3 Bivalent-Alternative Heat Pump

Function: a bivalent-alternative system uses (just like the bivalent-parallel system) 1 refrigerant and 1 compressor, but instead of using an additional heat generator as support, it is possible to switch between the heat pump system and the heat generator.

Advantages: if the temperature drops below a certain level, the COP value of a system can drop drastically, so it is sometimes wiser to switch to a completely different system (e.g. gas boiler), which works more efficiently in that situation.

Feasibility: not possible, because you have to switch to a completely different system at higher temperatures, thus also at temperatures up to 100 °C.

3.2.4 Cascaded Heat Pump

Function: a cascaded system works with multiple closed cycles, 2 or more compressors and 1 or more refrigerants. Thermal energy is transferred in this system by means of 1 or more intermediate heat exchangers.

Advantages: by using multiple cycles, the required individual compressor power can be reduced and the condenser mass flow can be improved (this increases the efficiency of the system). And, by using multiple refrigerants, a wider temperature range can be reached, making the system suitable for a wider range of applications.

Feasibility: possible for a temperature range of around 100 °C. But for the really high temperature ranges, of above 200 °C, there is only 1 type of refrigerant (water: R-718) that can reach the required minimum temperature, but it needs a high volumetric flow rate to compensate for its low volumetric heating capacity and the currently available small-scale compressors are not suitable for this.

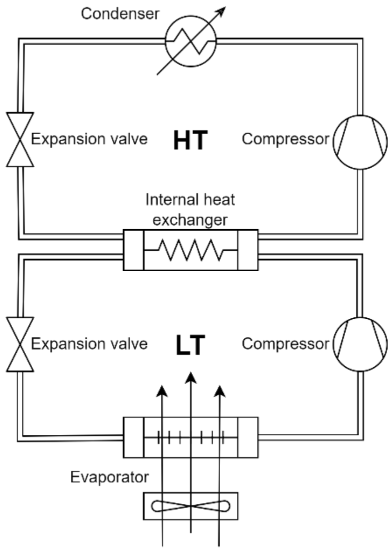

Figure 31 Cascade heat pump system

3.2.4 Multi-Compression Heat Pump

Function: a multi-compression system uses 1 refrigerant which is compressed in steps by several compressors in a single cycle.

Advantages: compressing a refrigerant in multiple steps in the same cycle can reduce the individual compressor power required and increase the efficiency of a system.

Feasibility: possible, but from a physics stand point it is still not possible to get from room temperature to the required minimum temperature with a single refrigerant, while being more efficient than traditional heating systems.

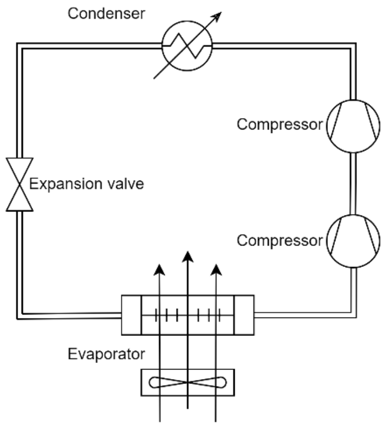

Figure 32 Multi-compression heat pump system

3.2.5 Cascaded Bivalent-Parallel Heat Pump

Function: a cascaded bivalent-parallel system is a combination of two of the aforementioned systems and works with multiple cycles, 2 or more compressors and 1 or more refrigerants, with the possibility to be supported with an additional heat generator.

Benefits: by using multiple refrigerants and cycles, the efficiency of a system for the lower temperature range can be increased and by combining this with the support of an additional heat generator an even higher temperature can be achieved.

Feasibility: possible, but it depends on the type of application and the required temperature range, how efficient the system will be and thus how much energy it could save.

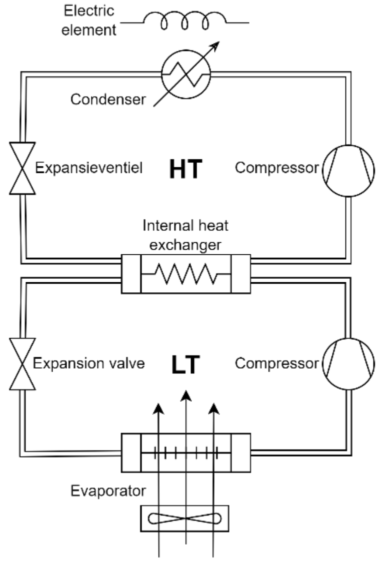

Figure 33 Cascade bivalent-parallel heat pump system

3.2.6 Multi-Compression Bivalent-Parallel Heat Pump

Function: a multi-compression bivalent system is also a combination of two of the aforementioned systems and works with 1 refrigerant, compressed in the same cycle by several compressors, with the possibility to be supported with an additional heat generator.

Benefits: by using multiple compressors, the efficiency of a system for the lower temperature range can be increased and, in combination with an additional heat generator, the system can be supported when a higher temperature is required.

Feasibility: possible, but not efficient because for a higher temperature range of around 100 °C the COP quickly goes towards a negligible low value.

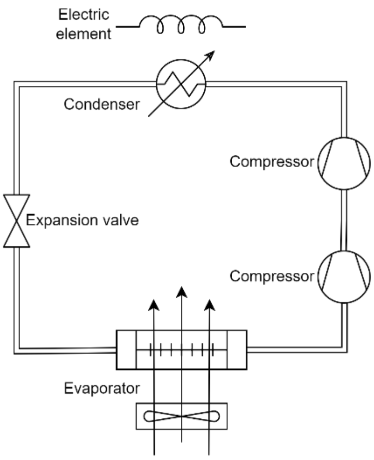

Figure 34 Multi-compression bivalent-parallel heat pump system

3.2.7 Chosen System

As explained in chapter 2.2.4 (Chosen Heat Pump Application), the best application for implementing heat pump technology is the kitchen boiler. The required temperature range for this device is from 16 °C (room temperature) to 100 °C (boiling water). Looking at the seven previously explained configuration combinations, the most promising one is the cascaded heat pump system. The reason for this is that the temperature difference is too big for a single stage heat pump system and in the other configurations the system would just not be more efficient (or even less efficient) than the currently used electric boilers. This is why a cascaded system could be a viable option, because in this type of system the temperature range can be divided over two or more refrigerants in two or more cycles and this will decrease the required mass flowrate and maximum pressure values (thus decreasing the required amount of total compressor power).

As mentioned before, for certain temperature ranges and applications, this system is also not an option. This because for the really high temperature range of above 200 °C there is only 1 type of refrigerant (R-718: water) that is able to reach the required minimum temperature. But the problem with this substance is that it needs a high volumetric flowrate to compensate for its low volumetric heating capacity and the currently available small-scale compressors are not suitable for this. But, because the kitchen boiler will operate at a much lower temperature of 100 °C, there are still 16 suitable refrigerants (see Table 3) with a critical temperature higher than 100 °C.

3.3 Thermodynamic Analysis of the System

For the heat pump application, regarding the kitchen boiler, the system needs to be able to get from 16 ^{o}C (room temperature) to a temperature of 100 ^{o}C (boiling water). The only way to achieve this (while being more efficient than traditional devices) is to use a cascaded heat pump system. But, since heat exchangers are never a hundred percent efficient (the lower temperature substance at the output of the heat exchanger can never reach the exact temperature of the higher temperature substance at the inlet), the temperature of the refrigerant needs to be higher than 100 ^{o}C to be able to heat up the water to the same temperature. For this reason a margin of 10 ^{o}C was added to the current temperature range, which means an adjustment of the output temperature from 100 ^{o}C to 110 ^{o}C.

The goal of this section is to find the most efficient refrigerant combination, by combining the most suitable refrigerants (found in Table 3), calculating the coefficient of performance of the system and finally check if the required pressure and volumetric flowrate are within reasonable values. An explanation of the refrigerant selection can be found in **Appendix C** and the refrigerant types used for this experiment are:

- R-600 (Butane)
- R-600a (Isobutane)
- R-601 (Pentane)
- R-601a (Isopentane)
- R-1233zd(E) (Trans-1-Chloro-3,3,3-Trifluoropropene)
- R-1234ze(E) (Solstice ze)
- R-1234yf (2,3,3,3-Tetrafluoropropene)
- R-1336mzz(Z) (Cis-1,1,1,4,4,4-Hexafluoro-2-butene)

Materials

The materials used for conducting this research are:

Calculation software:

- MATLAB R2022a
- Microsoft Excel

Thermodynamic property datasheets:

- ASHRAE Handbook - Fundamentals 2021 – SI
- NIST Reference Fluid Thermodynamic and Transport Properties Database (REFPROP): Version 10

Diagram of Setup

A diagram of the cascaded heat pump system configuration can be found in Figure 35 and the explanation of the units are noted down to the left of it.

HT = High Temperature cycle

LT = Low Temperature cycle

$\dot{Q}_e$ (Watt) = evaporator input capacity

$\dot{Q}_{IHE}$ (Watt) = intermediate heat exchanger capacity

$\dot{Q}_c$ (Watt) = condenser output capacity

T_{IHE} (Celsius) = intermediate heat exchanger temperature

W_1 (Watt) = LT compressor power

W_2 (Watt) = HT compressor power

P_1 (bar) = LT compressor pressure

P_2 (bar) = HT compressor pressure

$\dot{m}_1$ (kg/s) = LT mass flowrate

$\dot{m}_2$ (kg/s) = HT mass flowrate

$\dot{V}_1$ (m^3/s) = LT volumetric flowrate

$\dot{V}_2$ (m^3/s) = HT volumetric flowrate

H (J/kg) = enthalpy

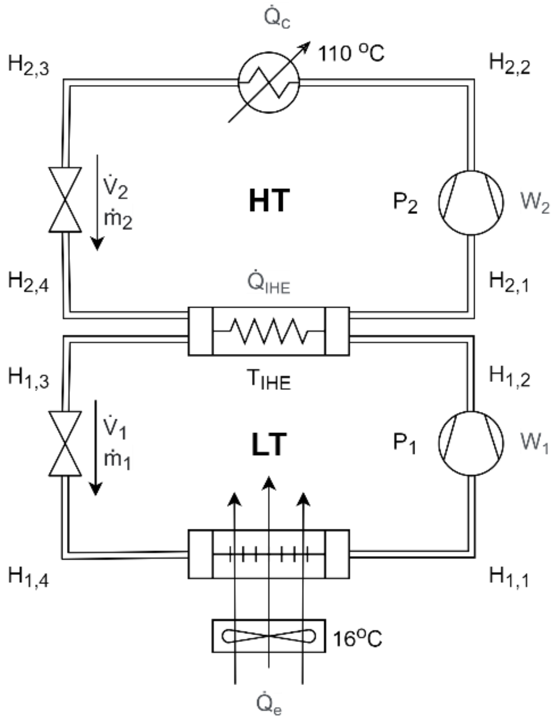

Figure 35 Cascaded heat pump schematics and units

Steps Taken

The coefficient of performance (COP) was used to find out what the most efficient refrigerant combination and temperature ranges are for the cascade heat pump system.

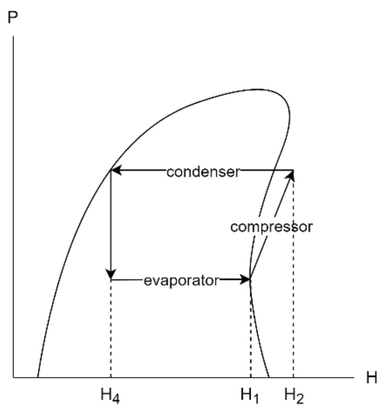

Figure 36 Pressure-enthalpy diagram of a single stage heat pump system

The COP value of the cascade heat pump system can be calculated by dividing the condenser output capacity by the total amount of required compressor power:

$$COP = \frac{\dot{Q}_c}{W_1 + W_2} = \frac{\dot{m}_2\left(H_{2.2} - H_{2,4}\right)}{\dot{m}_1(H_{1.2} - H_{1.1}) + \dot{m}_2\left(H_{2.2} - H_{2,1}\right)}$$

The preferred condenser output capacity is 2200 Watts which means that:

$$\dot{Q}_c = 2200W = 2200\,J/s$$

The following steps were used to calculate the COP value for each separate combination:

1. First the mass flowrate of the high temperature cycle was calculated with the equation:

$$\dot{Q}_c = 2200W = \dot{m}_2(H_{2.2} - H_{2,4}) \rightarrow \dot{m}_2 = 2200/(H_{2.2} - H_{2,4})$$

2. Then, with the calculated high temperature cycle mass flow rate, the intermediate heat exchanger thermal energy was calculated:

$$\dot{Q}_{IHE} = \dot{m}_2(H_{2.1} - H_{2,4})$$

3. Because the intermediate heat exchanger is the evaporator for the high temperature cycle and the condenser for the low temperature cycle, the following equation was used to calculate the mass flowrate of the low temperature cycle:

$$\dot{Q}_{IHE} = \dot{m}_1(H_{1.2} - H_{1,4}) \rightarrow \dot{m}_1 = \dot{Q}_{IHE}/(H_{1.2} - H_{1,4})$$

4. Then, with the calculated low temperature cycle mass flow rate and the high temperature cycle mass flow rate, the COP equation can be filled in to calculate the efficiency of the system:

$$COP = \frac{\dot{m}_2(H_{2.2} - H_{2,4})}{\dot{m}_1(H_{1.2} - H_{1.1}) + \dot{m}_2(H_{2.2} - H_{2,1})}$$

5. To find out the optimal COP value, step 1 to 4 was repeated for the following intermediate heat exchanger transition temperatures: 50, 60, 70, 80, 90, 100 ^oC and the following refrigerant combinations:

Table 4 Cascade heat pump refrigerant combinations

	R-600	R-600a	R1234ze(E)	R1234yf
R-600	LT: R600 HT: R600	LT: R600a HT: R600	LT: R1234ze(E) HT: R600	LT: R1234yf HT: R600
R-601	LT: R600 HT: R601	LT: R600a HT: R601	LT: R1234ze(E) HT: R601	LT: R1234yf HT: R601
R-601a	LT: R600 HT: R601a	LT: R600a HT: R601a	LT: R1234ze(E) HT: R601a	LT: R1234yf HT: R601a
R-1233zd(E)	LT: R600 HT: R1233zd(E)	LT: R600a HT: R1233zd(E)	LT: R1234ze(E) HT: R1233zd(E)	LT: R1234yf HT: R1233zd(E)
R-1336mzz(Z)	LT: R600 HT: R1336mzz(Z)	LT: R600a HT: R1336mzz(Z)	LT: R1234ze(E) HT: R1336mzz(Z)	LT: R1234yf HT: R1336mzz(Z)

6. Finally, after establishing the best combination, the required compressor pressure was noted down and the corresponding volumetric flow rate was calculated. These values were then used to evaluate if the required pressure and volumetric flowrate are within the acceptable range, if this was not the case, the next best combination needed to be checked or the heat pump system needs to be adjusted.

Note: ideal heat pump system conditions were used for calculating the COP values. The reason for this is that for determining the most efficient combination, it is not necessary to include the compressor efficiency, heat exchanger efficiency, heat losses and fan work, because these will roughly be in the same range for every combination, thus the result (the combination that yields the highest COP value) will not vary much. But, for the best and final combination, these factors should be taken into account.

After executing the previously described steps for every refrigerant combination, the resulting COP values can be found in Table 5 and the MATLAB script can be found in **Appendix E**.

Table 5 Cascade heat pump COP values

Temperature range (C):	16-110								
Temperature IHE (C):	40	50	60	70	80	90	100	Max COP	T (C)
R-600 & R-600	2.278382	2.40029	2.482699	2.508433	2.464155	2.345287	2.150694	2.50886	69
R-600 & R-601	2.219028	2.320298	2.390049	2.414843	2.383044	2.288105	2.12354	2.41485	69.3
R-600 & R-601a	2.111384	2.223607	2.308985	2.353067	2.341755	2.265554	2.115246	2.35597	73.4
R-600 & R-1233zd(E)	2.552175	2.638505	2.673428	2.645393	2.548126	2.386353	2.163523	2.67362	60.6
R-600 & R-1336mzz(Z)	2.042316	2.172203	2.275867	2.336519	2.337628	2.267917	2.118144	2.34532	75.5
R-600a & R-600	2.266477	2.376669	2.44131	2.442765	2.368647	2.215542	1.990994	2.45071	66
R-600a & R-601	2.207969	2.298756	2.352656	2.355451	2.295609	2.166619	1.969307	2.36128	65.9
R-600a & R-601a	2.101786	2.204462	2.274936	2.297662	2.258309	2.147261	1.962668	2.29794	69.3
R-600a & R-1233zd(E)	2.536002	2.608173	2.623234	2.570031	2.443931	2.250536	2.001213	2.62547	57.7
R-600a & R-1336mzz(Z)	2.033607	2.15428	2.243143	2.28216	2.254576	2.149291	1.964988	2.28265	71.4
R-1234ze(E) & R-600	2.287572	2.417942	2.511897	2.549113	2.510994	2.3817	2.146927	2.54911	70
R-1234ze(E) & R-601	2.227562	2.33638	2.416382	2.451539	2.425787	2.322099	x	2.45197	71.4
R-1234ze(E) & R-601a	2.118784	2.237882	2.332926	2.38724	2.382482	2.298614	x	2.3935	74.8
R-1234ze(E) & R-1233zd(E)	2.564686	2.661237	2.708968	2.692258	2.599395	2.424554	x	2.71127	63.3
R-1234ze(E) & R-1336mzz(Z)	2.049028	2.185559	2.298861	2.37003	2.378155	2.301074	x	2.38387	76.2
R-1234yf & R-601	2.262857	2.372179	2.436423	2.436444	2.358015	2.220723	x	2.44583	65
R-1234yf & R-601	2.204605	2.294659	2.348236	2.349724	2.285853	x	x	2.35639	65.5
R-1234yf & R-601a	2.098865	2.200817	2.270907	2.292312	2.248986	x	x	2.29308	68.5
R-1234yf & R-1233zd(E)	2.531091	2.602418	2.617322	2.562795	2.432361	x	x	2.61955	57.2
R-1234yf & R-1336mzz(Z)	2.030955	2.150866	2.239269	2.27691	2.245296	x	x	2.27696	70.2

Table 6 Pressure vs temperature results for selected refrigerants (in bar)

Temperature (C):	40	50	60	70	80	90	100	110
R-600	3.78	4.96	6.38	8.09	10.1	12.5	15.3	18.5
R-600a	5.31	6.85	8.69	10.9	13.4	16.4	19.9	23.8
R-601	1.16	1.59	2.15	2.84	3.68	4.71	5.93	7.38
R-601a	1.52	2.06	2.73	3.56	4.57	5.79	7.22	8.91
R-1233zd(E)	2.16	2.93	3.91	5.11	6.58	8.33	10.4	12.9
R-1336mzz(Z)	1.28	1.79	2.45	3.27	4.29	5.55	7.06	8.87
R-1234ze(E)	7.66	9.97	12.8	16.1	20.1	24.8	30.3	x
R-1234yf	10.2	13	16.4	20.4	25.2	30.8	x	x
R-717	15.6	20.3	26.2	33.1	41.4	51.2	62.6	75.8

Figure 37 shows the COP values of all the combinations (see Table 5), against the temperature of the intermediate heat exchanger. The conclusion that can be drawn from this diagram that the combinations with R1233zd(e) deliver the highest COP values. But, although R1233zd(e) yields good results and is currently still being used, it turns out that it does have a low ODP value of 0.00034. This makes it uncertain if this substance can still be used in the near future. Also there have already been a couple of organisations that have tried to ban this substance, an example of this is the German Federal Environment Agency (UBA) (CoolingPost, 2017).

Because of the previously mentioned reasons it is wiser to go for the next best option, which is the combination R1234ze and R600. R1234ze (Solstice ze) is already used for refrigeration cycles and thus can be easily implemented for heat pump applications. And R600 (n-Butane) is a well-known hydrocarbon and widely available. On the other hand it has not been used much in refrigeration or heat pump applications, so this makes it harder to implement.

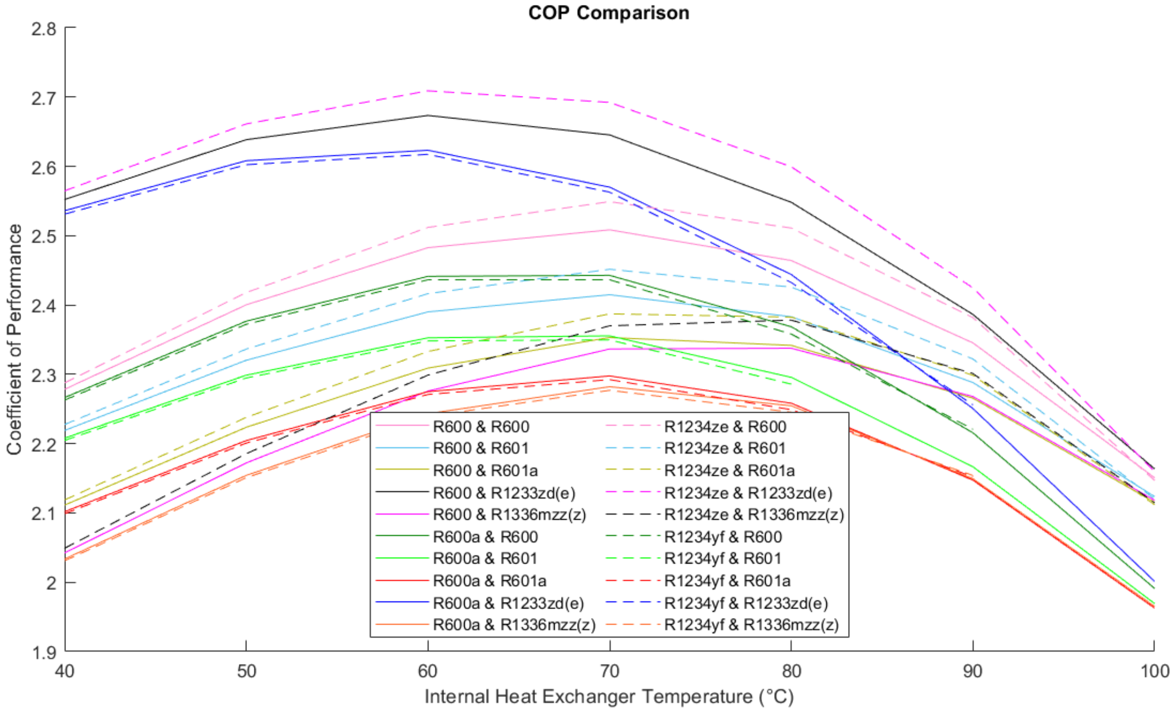

Figure 37 Refrigerant combinations & COP comparison

3.4 Remarks

From the configuration and deployment combinations in Chapter 3.2 the conclusion can be drawn that the cascaded heat pump system is the most promising type for the kitchen boiler application. This because the temperature range can be divided over two or more refrigerants, in two or more cycles, and that will decrease the required mass flowrate and maximum pressure values (thus decreasing the required amount of total compressor power).

Secondly, according to Chapter 3.1.2 (Compressors), the positive displacement compressor type is more suitable for small scale domestic applications, than the dynamic compressor type. And, out of these compressor type, the rotary-scroll compressor is most suitable because it can deliver a high pressure, is able to run continuously, has the highest efficiency ratio and a relatively low initial cost. For the heat exchangers, these will be explained in more detail in the next chapter, because these are strongly dependant on the type of refrigerants used and the application.

And for the refrigerant, there are a total of 27 substances suitable for the required temperature range, while also in accordance with the European rules and regulations (see **Appendix C**). And, concluding from Chapter 3.3 (Thermodynamic Analysis of the System), the best refrigerant pair, for the cascaded heat pump system (looking at the COP value, required maximum pressure and volumetric flowrate), is the combination with R1234ze(e) (Solstice ze) in the lower temperature cycle and R600 (n-Butane) in the higher temperature cycle.

3.5 Modelling of the System

According to the previous research results, the best configuration for the boiler heat pump system is the cascaded system in which two separate heat pump cycles are used. The best refrigeration combination for such a system (which also meets the requirements in **Appendix F**) has proven to be the one with R1234ze (Solstice ze) in the lower temperature cycle and R600 (Butane) in the higher temperature cycle. This chapter will go deeper into the chosen concept by using Chapter 2.1.2 (Components and Functions), 3.1.2 (Compressors) and 3.1.3 (Heat Exchangers) to select the right type for each component.

3.5.1 System Component Selection

In Figure 35 a schematic overview of a cascaded heat pump system can already be seen. But, to give an even better impression of the system layout, the figure down below also shows the outline of the required components, how the components are connected to each other, where the temperature sensors for the expansion valves are placed, what the lower temperature cycle is, what the higher temperature cycle is and what the flow direction of the refrigerant within the system is.

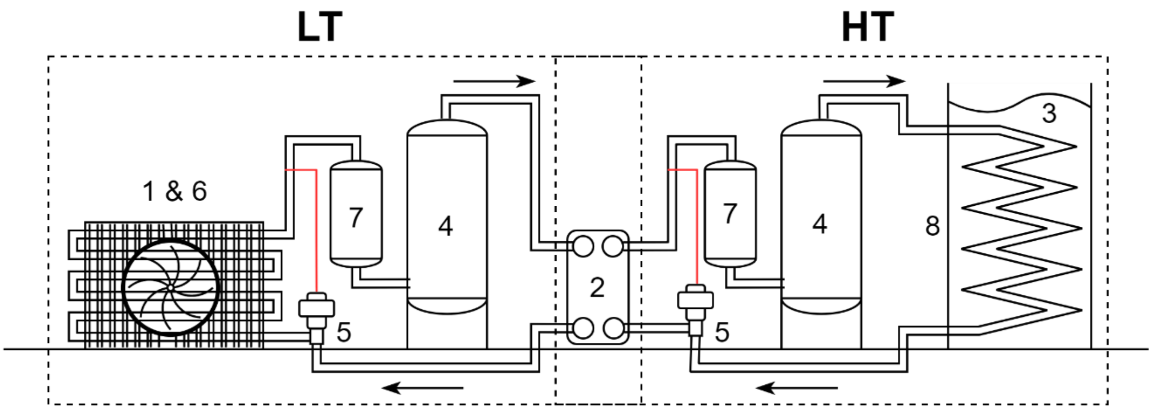

Figure 38 Schematic overview of the cascade heat pump system set-up

Evaporator (number 1 in Figure 38)

The first component is the evaporator. As explained at the end of Chapter 2.1.1, the air source heat pump is the most suitable option. To be able to extract the thermal energy from the air, heat transfer by convection is used. According to Chapter 3.1.3 the most suitable type of heat exchanger for this type of gas-to-liquid heat transfer is the finned tube heat exchanger and the most efficient flow configuration for this is the crosscurrent one. The construction related to this configuration consists of a row of plates (fins) with small spaces in between and perpendicular through these plates a tube (coil) is placed. Then, by using a fan, the air can be guided through the fins and over the tubes, and by means of forced convection the thermal energy from the air is transferred onto the refrigerant.

Intermediate heat exchanger (number 2 in Figure 38)

The intermediate heat exchanger can be found in between the lower and higher temperature cycle. According to the findings in Chapter 3.1.3, the most efficient heat exchanger for this is the plate heat exchanger. The reason for this is because it is the most compact heat exchanger type, with the biggest possible surface area compared to its size. This type of heat exchanger consists of several corrugated plates which are stacked together to form channels in between and it can serve both as an evaporator and as a condenser, which makes it perfect for two-phase heat transfer. Since the flow configuration can be either cocurrent or countercurrent, it makes most sense to choose the most effective one, which is the countercurrent flow configuration.

Condenser (number 3 in Figure 38)

The component located at the end of the system is the condenser. In the case of the kitchen boiler it needs to transfer the thermal energy from the refrigerant onto the water inside the tank. This type of heat transfer is called gas-to-liquid. Since the water is only moving by means of natural convection and the refrigerant is moving by forcing it through the tubes, the most suitable type of heat exchanger for this case is the shell and tube heat exchanger (according to Chapter 3.1.3). In the case of the boiler, the boiler tank itself then functions as the shell and the helical coil is the tube through which the refrigerant runs. To increase the heat transfer capacity, the flow configuration needs to be countercurrent. And, because the water rises from the bottom of the tank towards the top when heated (due to the buoyancy force in natural convection), the refrigerant needs to flow from the top of the tank towards the bottom.

Compressor (number 4 in Figure 38)

The system contains two compressors, one for the lower temperature cycle and one for the higher temperature cycle. According to Chapter 3.1.2, for small scale (non-industrial) applications, the positive displacement compressor types are more suitable than the dynamic compressors. Out of the positive displacement compressor types, the rotary vane and rotary scroll compressors are most suitable because they are able to run continuously and, compared to the other types, also have the lowest initial and maintenance costs. Looking at the efficiency, the rotary scroll compressor has a slightly better performance, but the rotary vane compressor is still more efficient than the reciprocating or screw compressors, so both types can be used.

Expansion valve (number 5 in Figure 38)

The system requires two expansion valves, one for the lower temperature cycle and one for the higher temperature cycle. As stated in Chapter 2.1.1 there are two types of expansion valves, thermal expansion valves and electronic expansion valves. Thermal expansion valves are completely mechanical, while electronic expansion valves can be controlled electronically with a programmed controller. Because of the more precise control of an electronic expansion valve, it allows to have a more optimized performance and efficiency. Although the electronic expansion valve is more expensive, in the case of the cascade heat pump system, it is still better to go for this valve type because with two thermal expansion valves it is harder to accurately regulate the whole system.

Air fan (number 6 in Figure 38)

To be able to generate forced convection through the evaporator, an air fan is needed. There are many types of fans available, but the most important aspect for selecting one is the orientation the air stream needs to have within the system. The air flow can namely be increased or decreased for all types of fans (by for example changing the motor power or the total amount of blades). In the case of the heat pump boiler, the system will be placed underneath a kitchen cabinet and because there is only a limited amount of space available, it is best to use a centrifugal fan. With this type of fan the air is drawn in from the front and the outlet is located perpendicular to the inlet. Also, compared to other types of fans, this fan makes less noise when operated at a moderate speed.

Liquid accumulator (number 7 in Figure 38)

The liquid accumulators are placed in front of the compressors. They are used as a safety measure, to prevent liquid refrigerant and an abundance of lubricating oil from entering the compressor compression chamber. All liquid accumulators basically function the same and they most of the time are already preassembled in combination with the compressor. That is why the type of liquid accumulator does not have to be selected individually. The size of the liquid accumulator does have to be selected. But this depends on the total amount of refrigerant volume (in liquid state) in the system.

Boiler tank (number 8 in Figure 38)

To be able to store the water safely and maintain it at a certain temperature, a boiler tank should be used. The boiler tank has not been introduced in the previous chapters, but basically the main thing that distinguishes certain boiler tanks is the type of insulation that is used. This can either be some kind of insulation material (e.g. expanded polypropylene) or a vacuum seal (like in a thermos flask). The second option is more expensive, but has proven to be the most effective and since it will be a small tank, the vacuum insulation option is selected.

3.5.2 System Component Sizing

After having selected the most suitable component types, the components need to be sized to fit the required performance. First of all, to make sure the components are up to standards, the requirements in **Appendix F** are used. Secondly, it is also important that the amount of available space underneath a kitchen sink is taken into account and that a first thought is given about what the component layout will look like inside the kitchen cabinet. This chapter will provide an explanation for each aspects of the components.

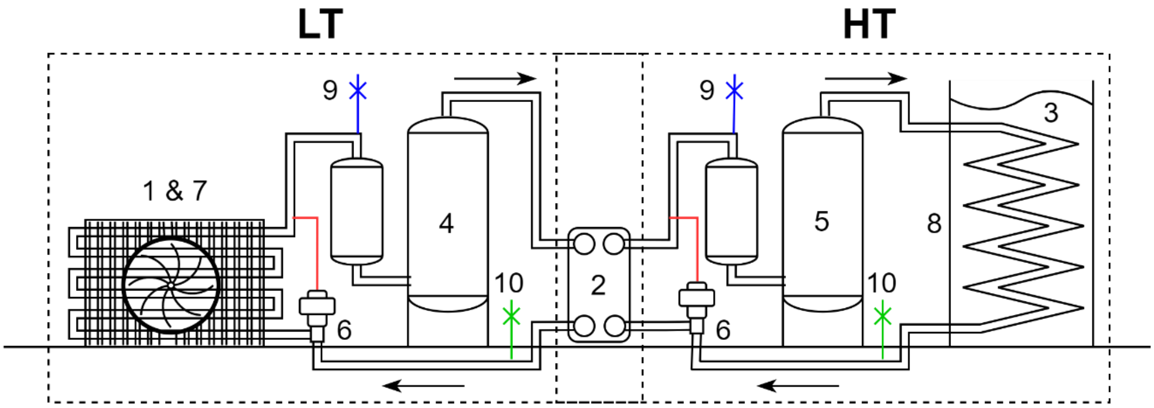

Figure 39 Schematic overview of the cascade heat pump system components

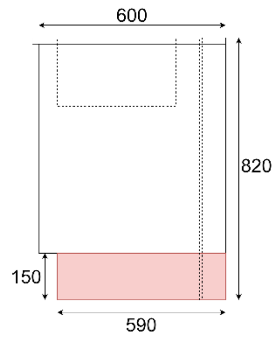

Figure 40 Average kitchen cabinet measurements

Finned tube HE (number 1 in Figure 39)

- *Dimensions: 300 (l) x 155 (h) x 50 (w) mm*

The finned tube heat exchanger has to be placed in the space below the kitchen sink and the decision was made to place it underneath the bottom plate of the cabinet (see highlighted section in the figure on the right). In this way, the appearance of the door does not have to be altered. So, to determine the size of the heat exchanger, the average available space was taken into account.

- *Material: copper tubes (10 mm outer diameter), aluminium fins (0.115 mm thick)*

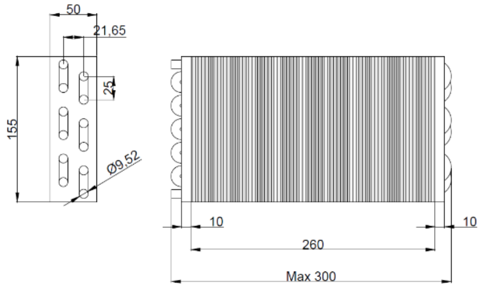

Figure 41 Finned tube heat exchanger technical drawing

The average finned tube heat exchanger uses copper for the tubes, because this material has a high thermal conductivity, is resistant to atmospheric and water corrosion, can be easily sealed by soldering, can be easily bend into the required shape and it has a high mechanical strength.

And, for the fins, aluminium is most of the time used. The reason for using this material is also because of its high thermal conductivity, high mechanical strength and its corrosion resistance (when a hydrophobic protection layer is applied). But, because the required amount of material for the fins is much higher than for the tubes, the weight and material price is also important and compared to copper, aluminium has a much lower density and is also much cheaper.

- *Tube amount: 12 (2 tube rows)*
- *Tube inner diameter: 9.52 mm*
- *Fin spacing: 1.8 mm*

For more insights into the required tube amount, tube diameter and the fin spacing a manufacturer of finned tube heat exchangers was contacted. The standard tube inner diameter for small scale application is 9.52 millimetre and looking at the available space, the optimal tube amount is 12 tubes and these are divided over 2 rows.

The flow configuration was already discussed and can be found in Chapter 3.5.1.

Brazed plate HE (number 2 in Figure 39)

- *Dimensions: 111 (l) x 310 (h) x 52 ± 3% (w) mm*

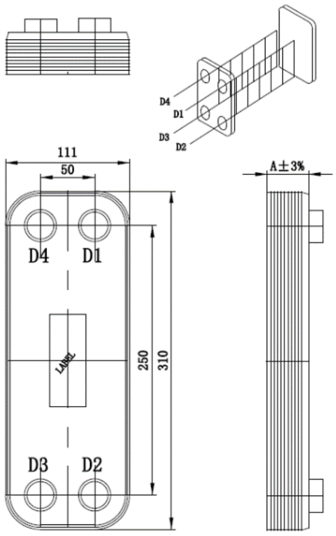

Figure 42 Brazed plate heat exchanger technical drawing

To determine the dimensions of the brazed plate heat exchanger, the required amount of heat exchange area needed to be calculated. The calculations were done with a software from SWEP (called SSP G8) and is based on the logarithmic mean temperature difference model for 2 phase heat transfer (see **Appendix G** for a complete overview). The outcome of these calculations were compared to the MATLAB calculations in Chapter 3.3. The outcome of both calculations turned out to be roughly the same and the required amount of heat exchange surface area is around 0.322 square metres. But, to be completely sure that the thermal energy can efficiently be transferred, a rule of thumb is to take 15 percent more than the calculated value. That changes the required amount of surface area to 0.3703 square metres. Looking at the available space, the height was first selected and the length and width were changed accordingly.

- *Material: stainless steel 304 plates, copper brazing*

The reason for using stainless steel, instead of the higher thermal conducting materials like copper or aluminium, is because of its strength and rigidity. This makes it perfectly suited for long-run installations and high pressure situations. Also, stainless steel requires less support than copper, so the plates can be thinner and this makes the overall component lighter and more thermally conducting.

- *Plate amount: 18*
- *Plate thickness: 0.38 mm*
- *Heat exchange area: 0.026 m^2/plate (Total: 0.375 m^2)*

To determine the required plate amounts and plate thickness, the required heat exchange area is again the most important factor. As mentioned before, the total heat transfer area is 0.3703 square metres. When looking at existing brazed plate heat exchanger catalogues, the most suitable heat exchange area per plate is 0.026 square metres. The reason for this is because the amount of plates can then be 18. Also, with this surface area per plate, the dimensions of the complete heat exchanger is able to fit snuggly inside the kitchen cabinet.

- *Flow configuration: counter flow*

The flow configuration is already discussed and can be found in Chapter 3.5.1.

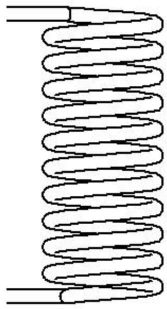

Figure 43 Helical coil heat exchanger drawing

Helical coil HE (number 3 in Figure 39)

- *Dimensions: 4480 (l), 75 (w) x 210 (h) mm*

The bigger the coil the bigger the heat transfer area and since the space inside the tank is limited, the coil length is sized to fit perfectly inside the tank.

- *Material: copper tube, 9.52 – 10 mm (inner and outer diameter)*

The helical coil heat exchanger uses a copper tube, because this material has a high thermal conductivity, is resistant to atmospheric and water corrosion, can be easily sealed by soldering, can be easily bend into the required shape and it has a high mechanical strength.

- *Flow configuration: counter flow*

The flow configuration is already discussed and the reasoning can be found in Chapter 3.5.1.

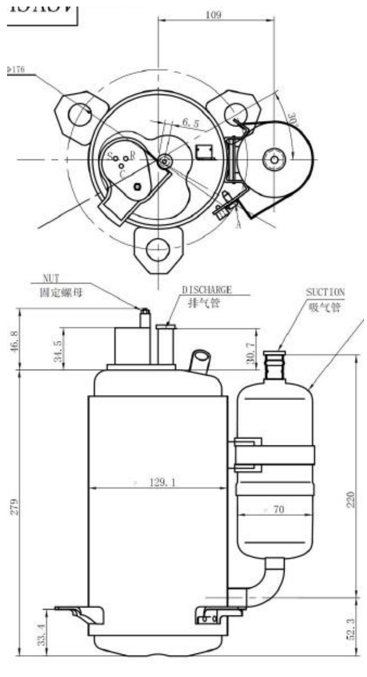

Figure 44 R-1234ze compressor technical drawing

R-1234ze compressor (number 4 in Figure 39)

- *Rated capacity: 1.8 kW (required), 2.24 kW (system)*

According to Chapter 3.3 the R-1234ze cycle needs a capacity of 1800 Watt. For this refrigerant type there are already some compressors available, but the one that comes closest to the required capacity is the WHP02830VUX-C7LG from Highly and has a rated capacity of 2240 Watt.

- *Dimensions: 176 (diameter) x 279 + 46.8 (h) mm*
- *Type: hermetic, rotary*
- *Operating mode: fixed speed*
- *Motor speed: 50 Hz*
- *Displacement: 18 ml/rev*
- *Power consumption: 540 W*

R-600 compressor (number 5 in Figure 39)

- *Rated capacity: 2.2 kW (required), 2.61 kW (system)*

According to Chapter 3.3 the R-600 cycle needs a capacity of 2200 Watt. For this refrigerant type there are currently no compressors available, so the decision was made to look at compressors for the refrigerant type that comes closest to the chemical properties of R-600 and that is R-290 (propane). For R-290 there are compressors available and the one that comes the closest to the required capacity is the WHP02600PSV-H3BUN from Highly and has a rated capacity of 2610 Watt.

- *Dimensions: 112.2 (diameter) x 225 + 43.2 (h) mm*
- *Type: hermetic, rotary*
- *Operating mode: fixed speed*
- *Motor speed: 50 Hz*
- *Displacement: 13.5 ml/rev*
- *Power consumption: 675 W*

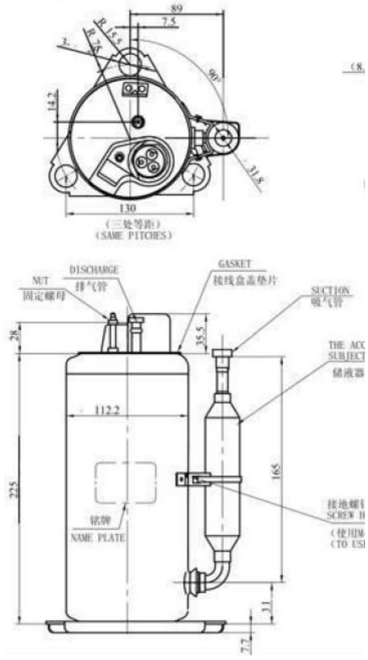

Figure 45 R-600 compressor technical drawing

Electronic expansion valve (number 6 in Figure 39)

- *Capacity: max. 2.5 kW (for R-1234ze), max. 4.2 kW (for R-290)*

As mentioned before, the R-1234ze cycle will have a rated capacity of around 2240 Watt and the R-600 cycle around 2610 Watt. This means that an electronic expansion valve should be selected which can handle at least these capacities. For both refrigerant types, the same type of expansion valve can be used, which is the DPF(TS1)1.0C-15 from Sanhua.

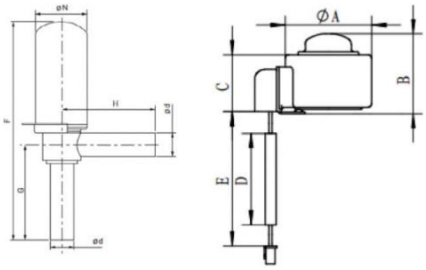

Figure 46 Electronic expansion valve technical drawing

- *Dimensions: 49,25 (l) x 78 (h) x 38,5 (w) mm*
- *Tube diameter: 6,35 mm*
- *Actuating mode: 4-phase-8-step*

Centrifugal fan (number 7 in Figure 39)

- *Dimensions: 133 (diameter) x 61 + 49 (h) mm*

For establishing the size of the centrifugal fan, the average available space underneath the kitchen cabinet behind the finned tube heat exchanger was taken into account. Since the maximum height is 150 mm, the HB133-072E230H model from HEKO, with a diameter of 133 mm, is the most suitable one.

- *Material: polypropylene with glass-fibre (Impeller)*

The impeller of the centrifugal fan is made out of glass fibre reinforced polypropylene. Polypropylene is used because it is lightweight (which requires less motor power to move the impeller), it improves the dimensional stability (resistance to warpage) and it is a cheap material.

- *Operating mode: variable speed*

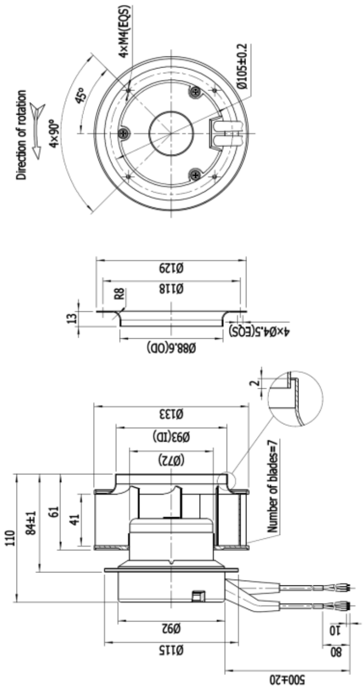

Figure 47 Centrifugal fan technical drawing

- *Airflow: 440 m^3/h*
- *Noise level: 75 dBA*
- *Motor speed: 4480 RPM*
- *Power consumption: 45 W*

Boiler tank (number 8 in Figure 39)

- *Dimensions: 150 (diameter) x 300 (h) mm*
- *Volume: 5 Litres*

The chosen boiler tank volume is 5 Litres and since it is preferred that the whole system fits into a single housing, the height of the tank is limited to the height of the highest component (to make the system as compact as possible). The chosen height is 300 mm and, to be able to withstand the high pressure inside the tank, the strongest shape is a cylinder, so the calculated diameter of the tank will be approximately 150 mm.

- *Material: Stainless steel*

The reason for using stainless steel is because it is a strong and rigid material, it is corrosion resistant and it is relatively cheap compared to other metals.

- *Type: double wall, vacuum insulated, reflective finish*

Because a near complete vacuum consists of hardly any molecules, conduction and convection are limited. The only way of transferring thermal energy is by means of radiation and this makes a vacuum layer around the tank, compared to other types of insulation, a better insulator. And, to limit the heat loss through radiation, a reflective finish could also be incorporated.

Service valves (number 9 and 10 in Figure 39)

- *Vacuumizing valves (number 9 and 10 in* Figure 39*)*

To get rid of air and other unwanted fluids before filling the system, a vacuum pump has to pull the system vacuum. To make sure the complete system is empty, a valve between the evaporator and the compressor, and a valve between the condenser and expansion valve, needs to be installed (a total of four valves, because there are two refrigerant cycles).

- *Filling valves (number 9 in* Figure 39*)*

To load the refrigerant into the system, the valve between the evaporator and compressor can be used (two valves in total, because there are two refrigerant cycles).

Control system (connected to compressors, expansion valves and fan)

- Customized printed circuit board (PCB)
- 2 x pressure sensor
- 3 x temperature sensor

The system needs to be able to automatically switch on when the temperature of the water in the boiler tank is under a certain threshold. The fan and compressors are simply switches on and off, and the opening of the expansion valves are controlled by measuring the pressure and temperature at the evaporator outputs and calculating the amount of superheat. Then, with these superheat values, the opening of the valves can be adjusted accordingly.

3.6 Prototype Development

Finally, with all the components selected, and sized according to their specifications, a 3D CAD model was created. According to this layout, the prototype could be constructed later on.

3.6.1 System 3D Model

First the STEP files for most of the components were collected and with these, the layout and configuration of the system, could be established. To make sure the system fitted inside the space underneath the kitchen sink, a model of the kitchen cabinet (including the sink and faucet) was constructed. Then, after trying out multiple configurations, the most suitable one was the one in the picture on the right. This was the best way to get all the components as compact as possible together. Also, this is the configuration in which the pipes can be as short as possible. This reduces the amount of required refrigerant and it limits the maximum amount of pressure drop inside the system.

Figure 48 3D representation of the complete system configuration inside the kitchen cabinet

While figuring out the system configuration, the decision was made to exclude some components. These components are the sensors, printed circuit board, charging valves, insulation and system housing. The reason for not including these components is because they can be placed almost everywhere, so they do not influence the overall shape of the system. A better overview of the system configuration can be found in the pictures underneath.

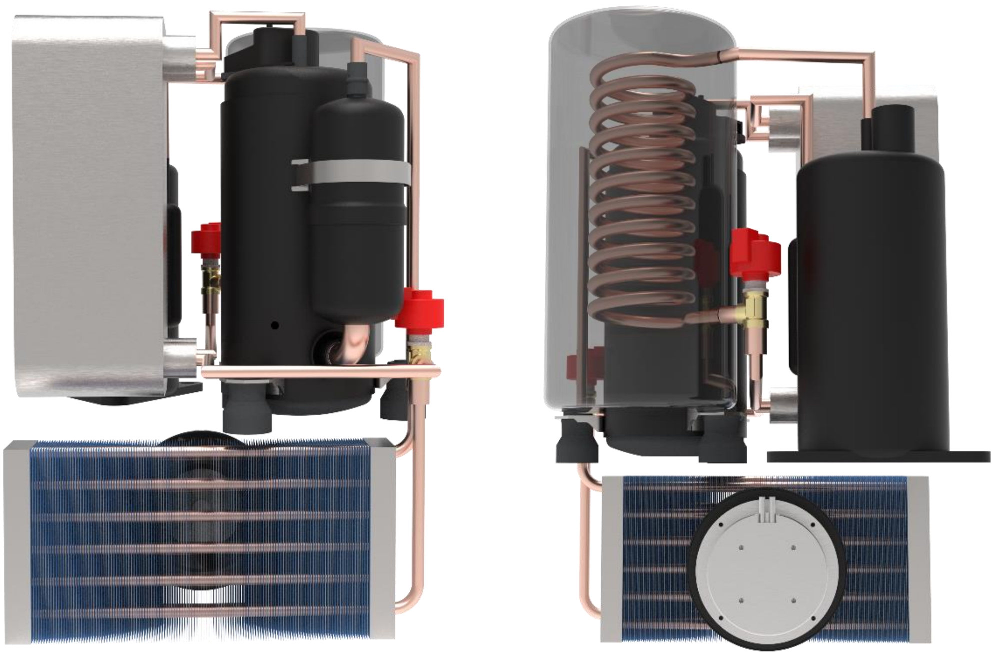

Figure 49 Front view (left) and back view (right) of the final system configuration, with from the front a clear view of the low temperature cycle and from the back a clear view of the high temperature cycle.

3.6.2 System Test Configuration

For the experimental setup it is important to be able to easily reach, and also see, all the system components. For this reason the decision was made to use a different configuration than the one shown in the previous chapter. The layout of the prototype will be more spread out horizontally, instead of stacking some of the components. Regarding the differences in pipe length, compared to the actual system configuration, the pipes will be a bit shorter in some places. But, because this is only a minor difference, the pressure drop will not increase much and the prototype can still be used to answer all the research questions. Figure 50 shows the configuration of the test setup.

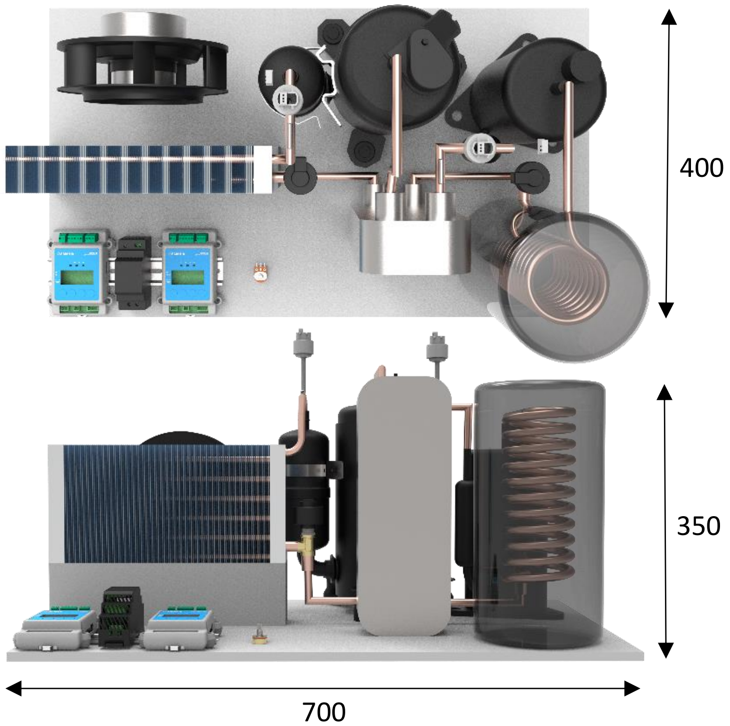

Figure 50 Test setup configuration and measurements

Control structure

Compared to the final system setup, the way the prototype will be controlled is also a bit different. For the final system a single integrated printed circuit board will be used to control each component, but for the prototype some of the components will be controlled manually and some automatically.

The most important part of controlling the system is regulating the superheat for each individual cycle, the superheat should namely be controlled automatically. And, since the fan speed can be adjusted with a potentiometer and the compressors with an "on and off" type of control, these can be controlled manually. The diagram in Figure 51 shows the superheat controllers (and the location of where they are connected to the system), the fan variable resistance control and the compressor relays.

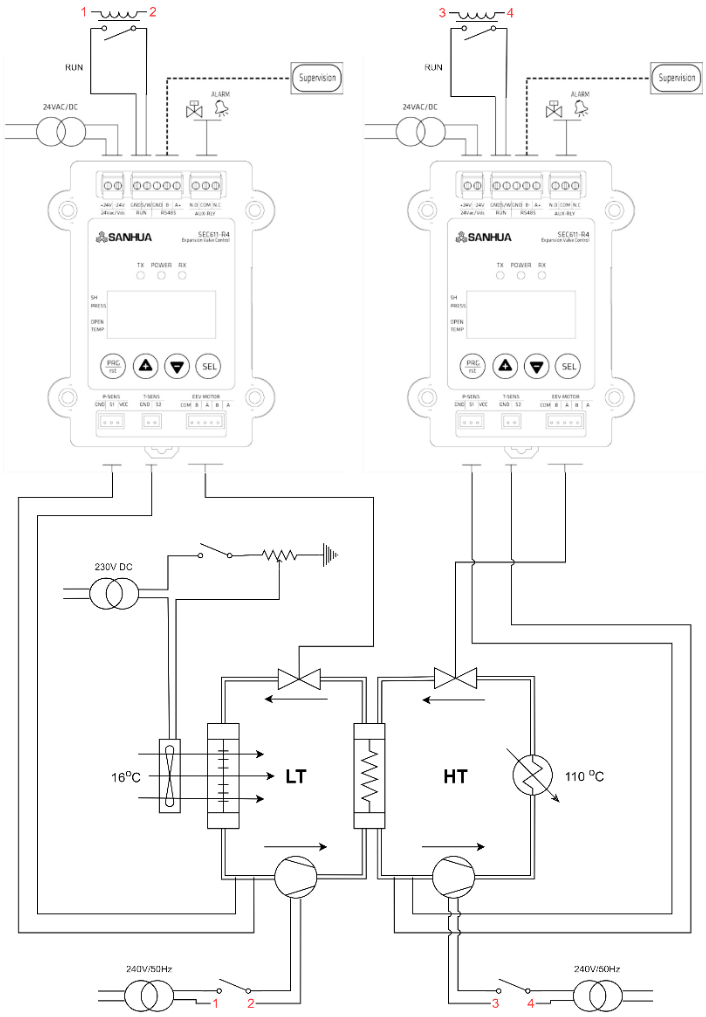

Figure 51 Test setup control structure diagram

Fan speed control

The type of fan that will be used is an electronically commutated (EC) fan, this fan has a three-phase linear motor and to generate motion it requires switching between the phases to energize the right windings. This process of switching phases is called electronic commutation. The timing in which this switching occurs determines the speed of the motor. Thus, by integrating a variable resistance in the circuit, the input voltage can be regulated and this determines the speed of the fan. The type of variable resistance that is used is called a rotary potentiometer. This component has a knob which can be turned to set a certain resistance and change the value of the input voltage.

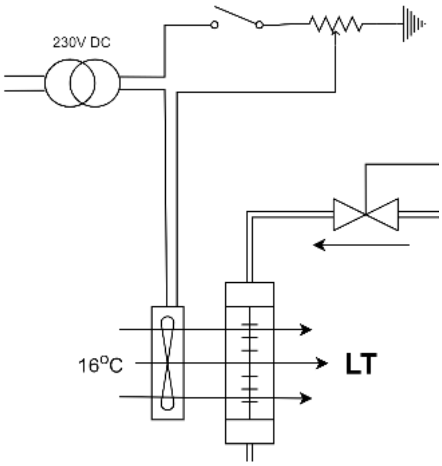

Figure 52 Fan variable resistance control diagram

Superheat controller

The superheat controller uses a PID (proportional integral derivative) algorithm to accurately provide fast automatic adjustment of the superheat. A PID controller consists of a control loop mechanism to provide feedback to the electronic expansion valve. The way in which this controller operates is by measuring the temperature and pressure at the outlet of the evaporator and with these values calculates the superheat. When this value is higher than the set value, the size of the expansion valve opening will increase and, when the measured value is lower, the size of the opening will decrease. In total the system uses two of these devices (one for the lower temperature cycle and one for the higher temperature cycle).

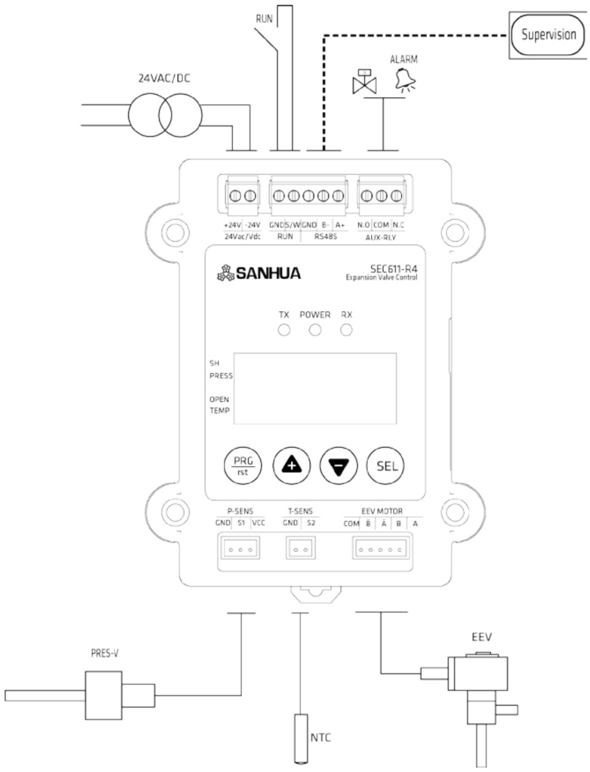

Figure 53 Electronic expansion valve superheat controller (www.SanhuaEurope.com)

Compressor control

The compressor types used in the system contain fixed speed motors. This type of motor does not require a complex control system like the inverter type compressor. The motor on this device is simply turned on and off to control the compressor and this can simply be achieved with a normal switch. The only thing that needs to be incorporated into the circuit is a relay between the compressor and superheat controller, to make sure the superheat controller is simultaneously activated with the compressor.

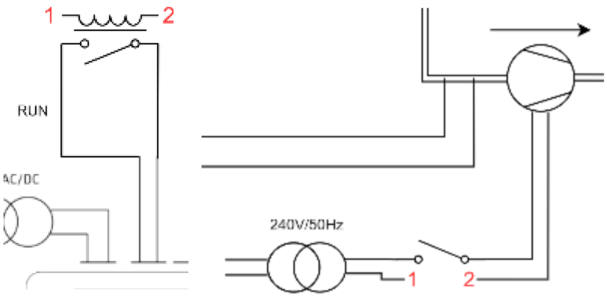

Figure 54 Compressor control diagram (with on the left a relay connected to the superheat controller)

4. Experimental Study

After having selected the right type of components and sizing them according to the requirements and specifications, the cascade heat pump system is ready for testing. This chapter will start with a simulation of the system (to more precisely predict the behaviour of the system in the real life situation) and later on a prototype of the system was built, to be able to test the system physically and compare these results to the expected simulation outcome.

4.1 System Simulation

Now that the components are selected, more parameters are known. This means that the resulting heating capacity and efficiency can be calculated more precisely. The software used for the simulation is called “Genetron Properties Suite v1.4.2”. This program allows to put in all the parameters manually and display the resulting outcomes for each individual component in clear tables. For a full overview of the system input values see **Appendix H**.

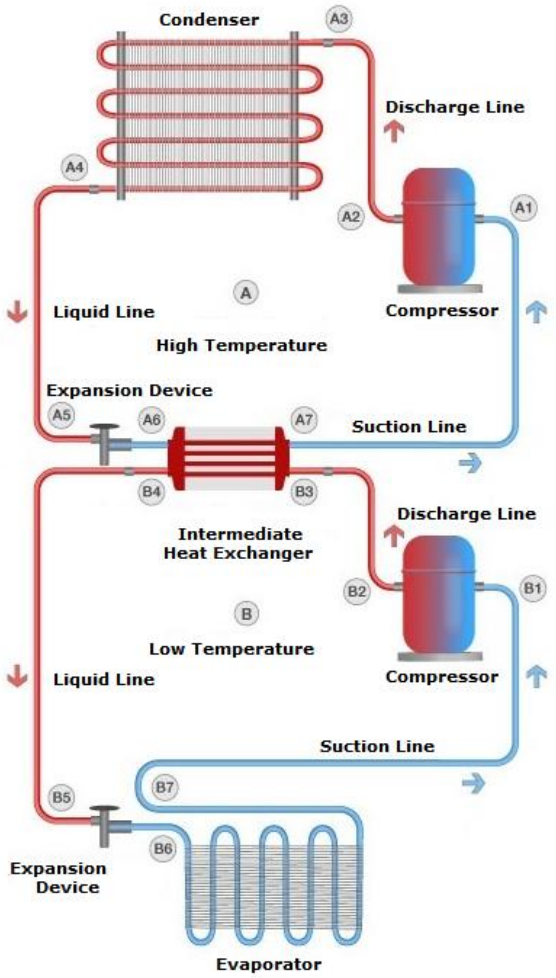

Figure 55 Cascade system simulation diagram

Overall System Performance

With the refrigerant R1234ze(e) in the lower temperature cycle and R600 in the higher temperature cycle, and with the corresponding component parameters from Chapter 3.5.2, the following system performance and efficiency was calculated:

- Temperature range: 11-110 ºC
- LT evaporator capacity: 1500 Watt
- Intermediate HE capacity: 2243 Watt
- HT condenser capacity: 2729 Watt
- Total power consumption: 1229 Watt
- Overall system COP: 2.22

To conclude, the calculated coefficient of performance in the simulation is lower than the one in Chapter 3.3 (2.22 instead of 2.55), but this was expected since the compressor volumetric and isentropic efficiencies where not yet taken into account. But, even though the COP value is lower, the resulting system is still more than two times as efficient as the current systems.

Note: pressure and temperature loss in the pipes were not yet known, so could not be used within the simulation.

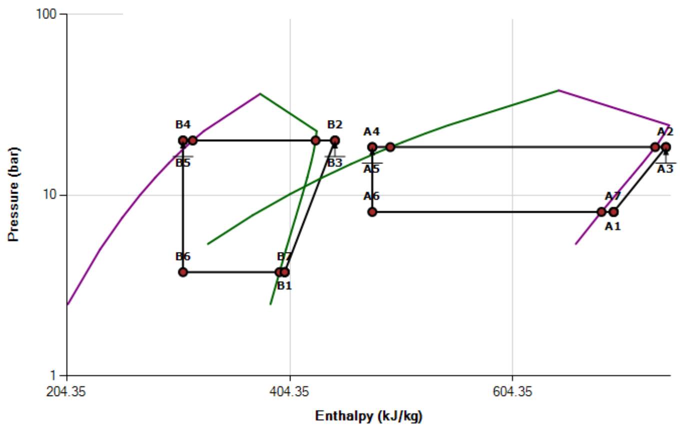

Figure 56 Pressure-enthalpy diagram of the cascade system simulation (Points on the graph correspond to locations within figure 55)

4.2 Experimental Procedure

To be able to test the cascaded heat pump water boiler system and to check if the calculated theoretical values are the same as in the real life situation, a prototype needed to be build. The main goal of the physical tests is to check if it is possible (with the newly designed system) to heat up water from a temperature of 10 °C (tap water) to a temperature of 100 °C (boiling water) in a more efficient way than the traditional systems.

4.2.1 Test Facility

The system was tested by means of a physical prototype and with test equipment (e.g. sensors and data logger). First, the system was switched on (according to the control structure in **Appendix I**), to test if it is able to heat up water from room temperature to 100 °C. If this was possible, the coefficient of performance could be calculated to see how efficient the device actually is. But, if the system does not cohere with the expected efficiency, the pressure and temperature sensors could be used to find out where the system can be optimized and possibly improved.

Materials

The materials needed to conduct this experiment are:

- System prototype/test rig (see Chapter 3.6.2)
- Refrigerants:
    - R-1234ze(E) (Solstice ze)
    - R-600 (n-Butane)
- Measuring equipment:
    - Temperature sensors (7x)
    - Pressure sensors (4x)
- Data logger/processor (Keysight 34972A LXI Data Acquisition)
- Control equipment (Superheat controllers)
- Power supply (230V/ac to 24V/dc transformer)

System Setup

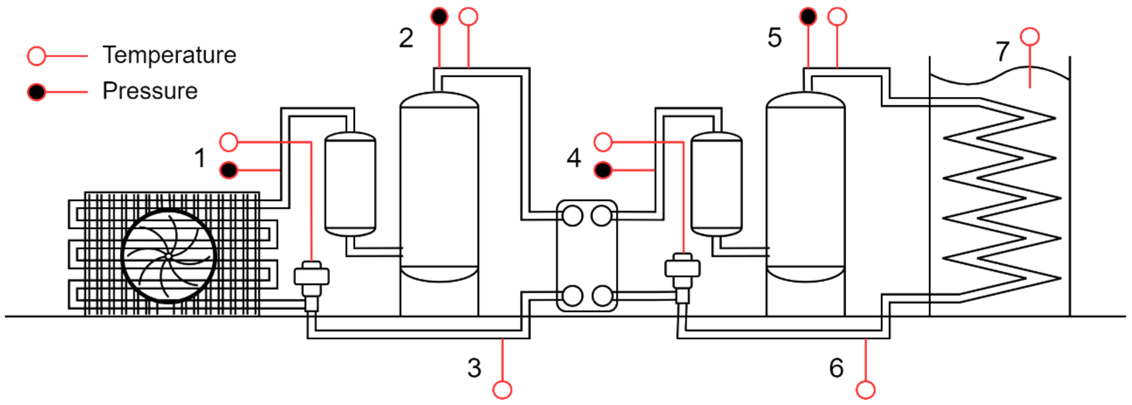

Figure 57 Overview of the sensor placement

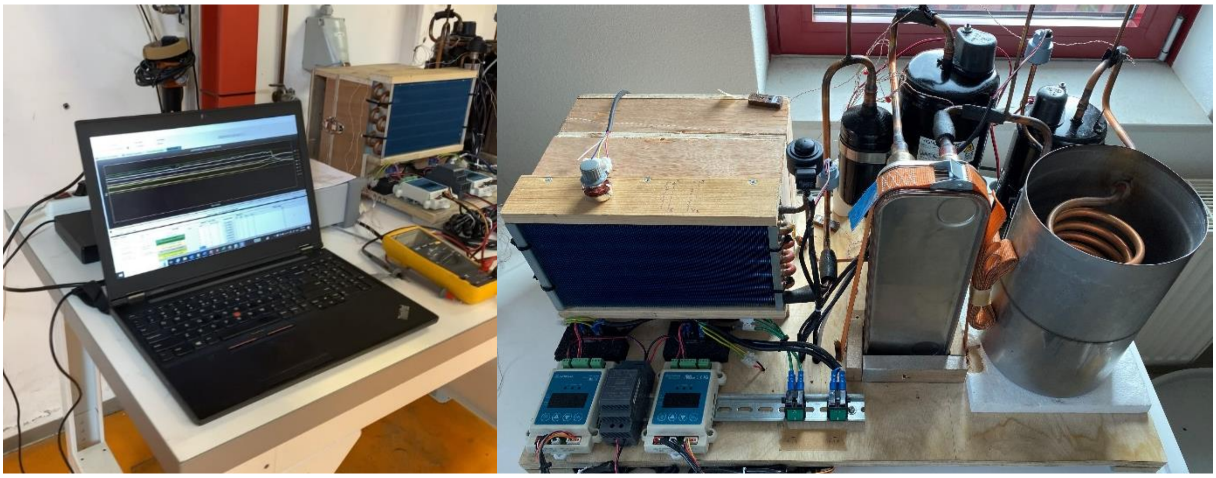

Figure 58 System prototype (right) and laptop with datalogger (left)

Figure 39 already gives a clear overview of the individual components and of the refrigerant flow direction through the system. But, for the test setup, there are still some components that need to be included. These components are the temperature and the pressure sensors. To see where each of these components are placed within the system, Figure 57 provides some more information. Also, for testing the system, the vacuum insulated boiler tank will not yet be included, instead an open container will be used. The reason for this is because in this way a boiler tank does not yet have to be custom made and that makes the system easier to install and it limits the overall cost of the prototype (for an overview of the physical prototype and datalogger see Figure 58).

Experimental steps

The procedures to be followed for the preparation, execution and the shutdown at the completion of the experiment are noted down below.

- *System preparation:*

After the prototype has been assembled, and before it can be tested, the system first needs to be prepared. When the preparation phase is finished, the system can be tested and finally it can be optimized where needed.

Action	Procedure
1.1	If the set-up is not clean, cleaning should be done before performing the preparation.
1.2	Connect a vacuum pump and pull the system vacuum, to get rid of air and other unwanted fluids in the system (repeat for each individual cycle).
1.3	Connect a nitrogen tank and open the main supply line to fill the system with nitrogen gas to check if the system does not contain any leaking parts and if it can withstand a pressure of 30 bar (repeat for each individual cycle).
1.4	Connect the vacuum pump again and pull the system vacuum, to get rid of the unwanted nitrogen and to prepare the system for the refrigerant filling (repeat for each individual cycle).
1.5	Connect the R1234ze(e) tank to the lower temperature cycle and connect the R600 tank to the higher temperature cycle and open the main supply line, to load the refrigerants into the system.

1.6	Weigh the amount of refrigerant that has been loaded into the system (separately for each cycle).
1.7	Connect the sensors at the indicated locations (see Figure 57) and to the datalogger, to be able to retrieve temperature and pressure data within the system.
1.8	Connect the control equipment to the sensors and the electric motors, to manage the movements of the components (compressors, electronic expansion valves and centrifugal fan) within the system.
1.9	Switch on the laboratory ventilation system before conducting the experiment
1.10	Fill the tank with 5 litres of water and completely submerge the helical coil heat exchanger.

- *System testing:*

When the preparation procedure is finished, the setup is ready for the experiment.

Action	Procedure
2.1	If the set-up is not clean, cleaning should be done before performing the experiment.
2.2	First check if all the components are connected the right way.
2.3	Measure the temperature of the water in the tank and note it down.
2.4	Switch on the centrifugal fan.
2.5	Switch on the control system to simultaneously start the compressors and electronic expansion valves.
2.6	While the system is running, start the stop-watch for analysis of the experimental results afterwards.
2.7	Use the data logger to retrieve the temperature and pressure data during the experiment.
2.8	Start the shutdown procedure when water is boiling (roughly 100 ^{o}C).

- *System shutdown:*

Operator should always be present at the setup during the experimental run. To take appropriate action in case of emergency see: 'Emergency Shutdown Procedure' in **Appendix J** (Risk Inventory and Evaluation), a complete overview of the potential hazards that can occur during the experiment and information about the corresponding emergency shutdown procedure can be found there.

Action	Procedure
3.1	Switch off the compressors, stop the time and note down the time of the experiment.
3.2	Switch off the centrifugal fan.
3.3	Stop the data logger and make a copy of the retrieved data.
3.4	Switch off the laboratory ventilation system.
3.5	Clean the setup and surroundings before leaving the lab. Cleaning should be done after performing every experiment.

After repeating the system tests multiple times, with different input parameters, the data can be used to draw a conclusion about the system performance. The input parameters and the corresponding test results are discussed in the next chapter.

4.2.2 Data Reduction and Experimental Error

The test setup uses a total of 7 temperature sensors to be able to analyse the performance of the system. These sensors are connected to a datalogger and a laptop, which is able to store the data. For an accurate measurement throughout the tests, the datalogger was set to a time interval of 1 second. Meaning that every second, 7 data points where logged. So, if a test takes for example 30 minutes, this means that a total of 12600 data points (7 sensors x 60 sec. x 30 min.) per test are saved.

Normally data reduction is used to increase the storage efficiency and performance, but since the data does not take up much storage space (only about 350 KB per test), this is not the reason for reducing the data. The biggest reason for using data reduction is because it is hard to get a clear overview in such a big table. So, by simplifying the data with the use of a graph, it is much easier to get an insight in the results and the correlation between data points.

As for the experimental error, the difference between the measured value and the true value was measured for each individual sensor. This was done by connecting all of the sensors to the datalogger and measuring the temperature in the same location and check how much the sensors differed from each other and the mean temperature. The mean temperature was about 21 ^{o}C and the biggest deviation from this value was a temperature difference of 0,5 ^{o}C. The sensor with the biggest deviation was replaced by a new sensor and that brought the maximum deviation to a value of 0,35 ^{o}C. And, since this uncertainty is only minimal, it does not affect the goal of the experiment and the data points did not have to be adjusted afterwards.

5. Results and Discussion

A total of 13 test runs have been executed. In between each test a waiting time of at least 2 hours was applied, to make sure that the system had sufficient time to cool off. Also, at the start of each new test, the water in the boiler tank was replaced and the EEV's were recalibrated, to make sure that every test started with the same initial conditions. The test parameters consist of constant and variable parameters. The constant parameters remain the same for each test and the variable parameters could be adjusted.

The **constant parameters** are:

- LT refrigerant charge (kg): 1.95
- HT refrigerant charge (kg): 0.6
- Tank volume (L): 5
- LT and HT EEV start open ratio (%): 30
- LT and HT EEV start open duration time (sec.): 10
- LT cycle superheat (°C): 4

The **variable parameters** are:

- HT cycle superheat (°C): {10, 9, 8, 7}
- Fan speed (m^3/h): {600, 500, 400, 300, 200}
- HT cycle IHE start temperature (°C): {18, 62, 43, 38}

The following section first discusses the system simulation validation, by comparing the actual outcome of the physical tests, to the new input parameters. Then, the variable parameters will be discussed in more detail, by showcasing the effect of changing each individual parameter. And finally, the current best result are discussed, together with what should and could be improved within the system.

5.1 Model Validation

Table 7 Model simulation validation data

	Old simulation	Physical test	New simulation
Temperature range (°C)	11-110	0.18-105.56	0.18-105.56
LT sat. temperature (°C)	11	0.18	0.18
LT superheat (°C)	5	9	9
LT eva. capacity (W)	1500	-	331
LT con. temperature (°C)	80	45.05	45.05
HT sat. temperature (°C)	70	33.76	33.76
HT superheat (°C)	5	7	7
IHE capacity (W)	2243	-	658.59
HT con. temperature (°C)	110	105.56	105.56
HT con. capacity (W)	2729	1659.5	1657.28
Total power (W)	1229	1362.24	1326.3
Overall system COP	2.22	1.22	1.25

After the first physical tests were executed, the actual system performance could be measured. So, to validate the model (from Chapter 4.1), the new input data could be used to calculate the new theoretical performance. If these results were in line with the test results, the conclusion can be made that the model is valid. The data in Chapter 4.1, together with the actual physical test data and the new input data are displayed in Table 7, together with the corresponding performance.

To conclude, the calculated COP value from the physical test is in line with the COP value from the new simulation data. The reason that the COP value in the new simulation is slightly higher than the physical test, can be explained. Namely, when calculating the total amount of power for the physical tests, the centrifugal fan has also been taken into account and in the simulation only the LT and HT cycle compressor power is taken into account. The difference in COP value, compared to the old simulation, is explained later on in section 6.3.

5.2 Dependency of Variable Parameters

For each new test, one of the variable parameters was changed, to evaluate the effect on the system performance. The total amount of iterations that could be made with the amount of variable parameters values were 11 tests. A complete overview of the results for all of the test can be found in **Appendix K** and the current optimal outcome (test 5) can be found in Chapter 5.3. The following things are examined in this section: the effect of the HT cycle superheat on the total heat capacity, the effect of the fan speed on the LT cycle evaporator outlet temperature and the effect of the HT cycle IHE start temperature on the total heating time.

HT superheat vs. heat capacity

A total of four superheat values were used to evaluate the effect of the HT cycle superheat on the heat capacity of the total system. The reason for not going lower than a superheat of 7 ºC is because otherwise the risk of liquid compression is too high (which can cause damage to the compressor's internal components).

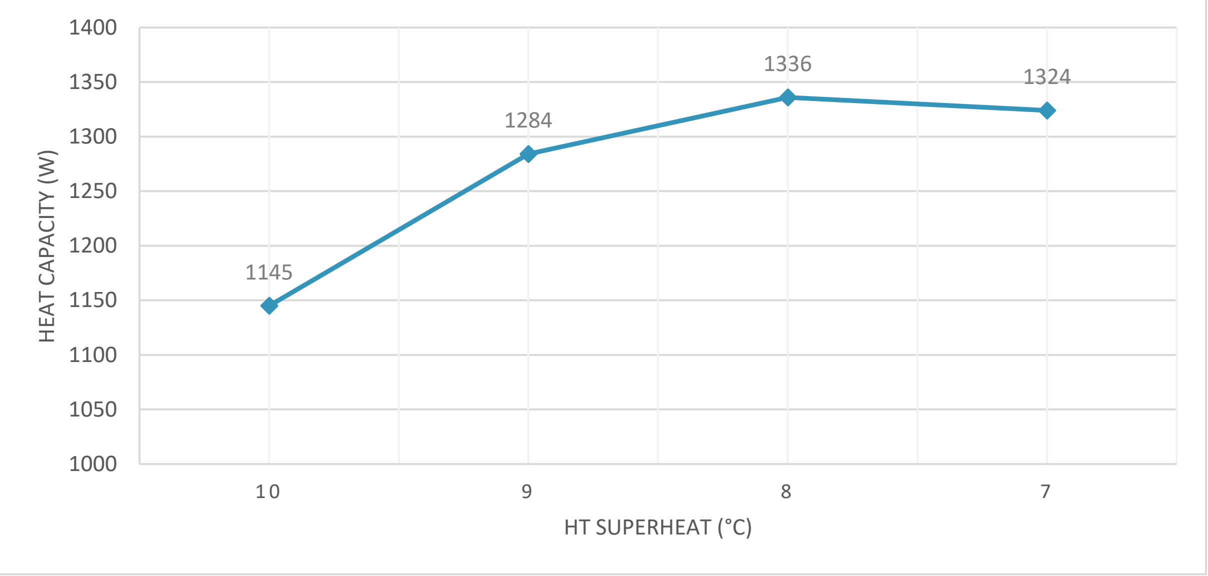

Figure 59 Effect of HT superheat on the total system heat capacity

According to the test results in Figure 59 the best HT superheat value is in between a temperature of 7 ºC and 8 ºC. The reason for going with a superheat of 7 ºC instead of 8 ºC is because the difference between the corresponding superheat values is small. And a lower superheat value increases the overall heat transfer efficiency. Also, the first three tests were executed with a two hour waiting time in between and the fourth test was executed a day later (longer time to cool off), so probably the heat capacity corresponding to the 7 ºC superheat would have been higher when it was also executed two hours after the previous test.

Fan speed vs. LT evaporator outlet temperature

A total of five different air flows where used to evaluate the effect of the fan speed on the LT cycle evaporator outlet temperature. The reason for starting with an airflow of 600m^3/h is because with a higher air flow the noise level became too high (fan speeds above 600m^3/h exceeded the acceptable noise level of 75dBA). For the other air flow values a reduction of 100m^3/h per test was used to evaluate the effect on the LT evaporator outlet temperature.

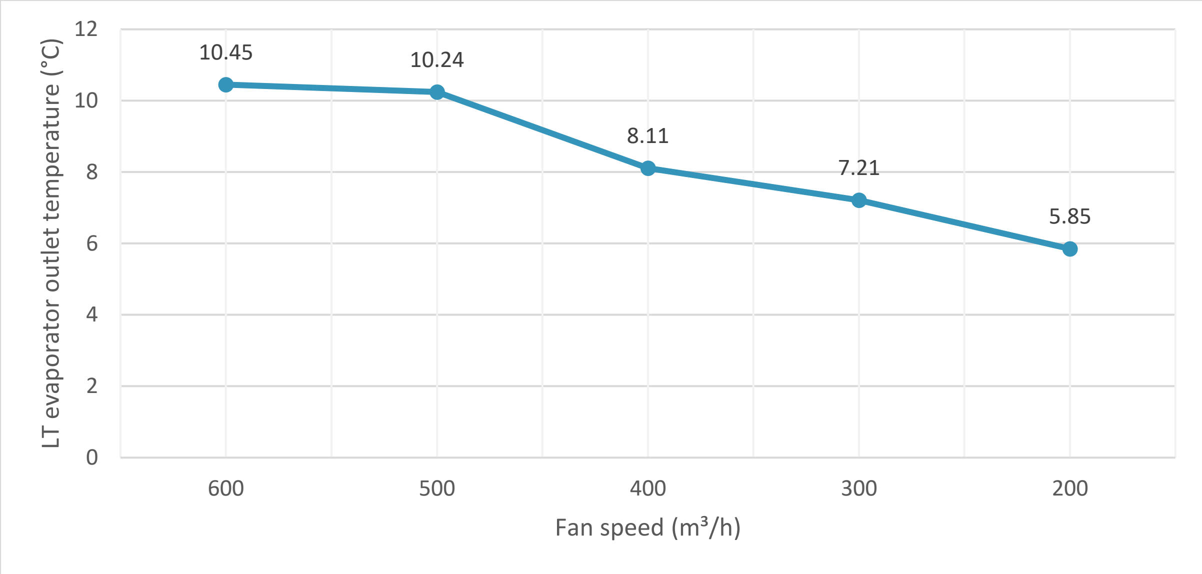

Figure 60 Effect of fan speed on the LT evaporator outlet temperature

By analysing the graph in Figure 60 the observation can be made that the difference in LT evaporator output temperatures between an air flow of 600m^3/h and 500m^3/h is relatively small. The lower fan speeds (400m^3/h, 300m^3/h and 200m^3/h) on the other hand show a much bigger decrease in LT evaporator outlet temperature. So, also taking into account the noise level, the most suitable fan speed is the one corresponding to an airflow of 500m^3/h.

HT cycle IHE start temperature vs. total heating time

The HT cycle IHE start temperature was used as the third variable parameter. The reason for this is to find out if it was more efficient to first allow the LT cycle to heat up the IHE and then turn on the HT cycle. First an IHE temperature of 62 ^{o}C was used, because this is the maximum temperature the LT cycle could reach when operating on its own. Secondly a IHE temperature of 43 ^{o}C was used, because this is the maximum temperature the LT cycle reaches when both the LT and HT cycle are activated. And finally a IHE temperature of 38 ^{o}C was used, because this is the temperature from which the LT cycle compressor first stabilizes when both the LT and HT cycle are activated.

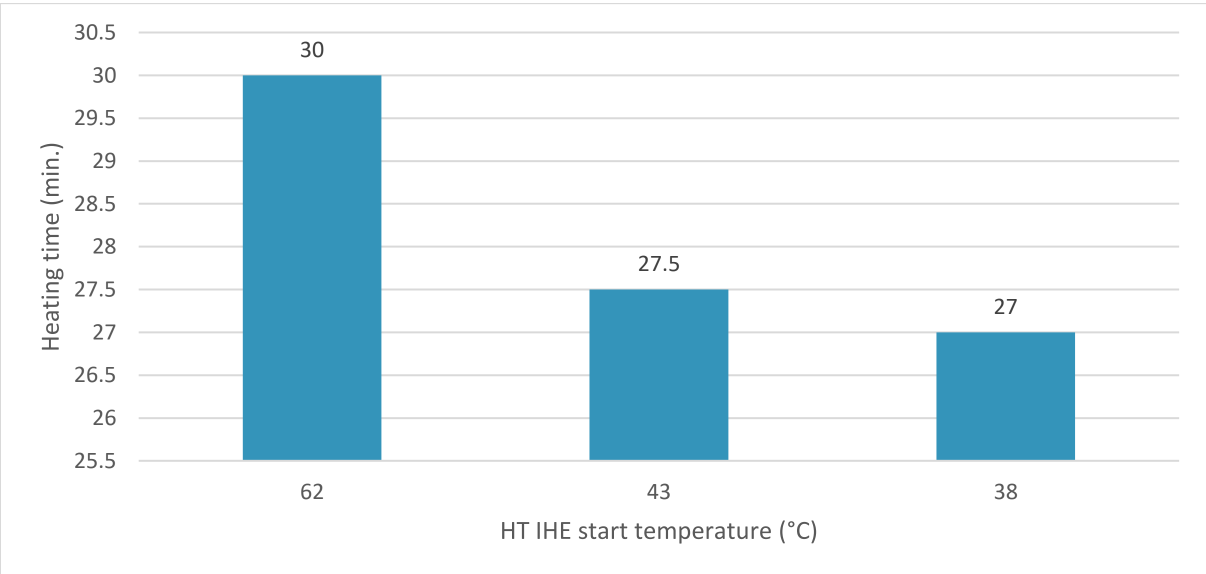

Figure 61 Effect of HT cycle IHE start temperature on the total heating time

Looking at the graph in Figure 61, the conclusion can be made that first starting the LT cycle does not decrease the overall heating time. Even taking into account that the first couple of minutes the HT cycle compressor does not run yet and the LT cycle compressor is the only one that requires power to run, the COP will not be better than when both cycles are started simultaneously. Also, when the HT cycle was activated later than the LT cycle, the HT cycle had more difficulty with controlling the superheat. Which caused the controller to go into the low superheat alarm quite often.

5.3 Proof of Concept

This section contains the current optimal test results. To make sure that the test results were reliable, the test with the most optimal variable parameters was repeated two more times.

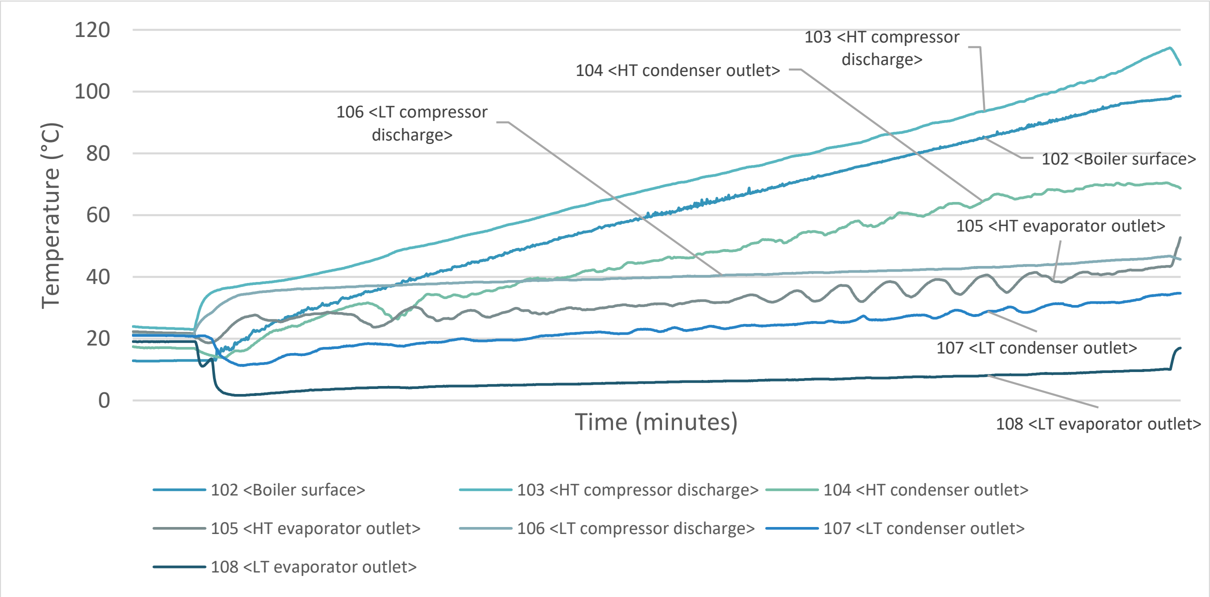

Figure 62 Test run data, with temperature on the Y-axis and time on the X-axis

Figure 62 shows the graph of the best test run result, with each line representing a temperature at a specified location within the system (see Figure 57). The variable parameter settings for this run are: a HT cycle superheat of 7 ºC, a fan speed of 500 m^3/h and the HT cycle is activated simultaneously with the LT cycle (IHE start temperature at room temperature).

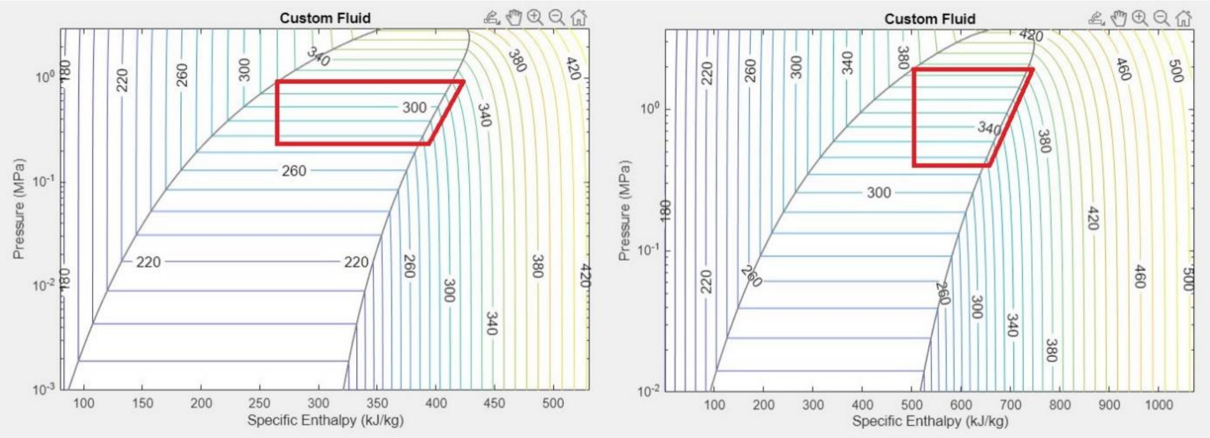

Figure 63 Pressure-enthalpy diagrams of the LT cycle with R1234ze (left) and HT cycle with R600 (right)

Figure 63 displays a simplified version of the pressure-enthalpy diagrams of the LT and HT cycles at the end of the current most optimal test runs. The X-axis shows the enthalpy, the Y-axis the corresponding pressure value and the lines running across the graph are the corresponding temperature values.

5.4 Comparison of Key Performance Indicators

This section discusses the most important data points and the influence on the key performance indicators. First the temperature of the water in the boiler tank is discussed, then the superheat controllers are evaluated, then the efficiency of the heat exchangers is discussed and finally the overall heat capacity (total system performance) is shown.

Boiler tank operating temperature

As can be seen in the graph in Figure 62 and the table in **Appendix K**, the <Boiler surface> temperature reaches close to 100 ^{o}C and by executing a visual check, it was observed that the water was actually boiling. The reason for it being difficult for the water to reach exactly 100 ^{o}C had to do with the fact that the tests were executed with an open boiler tank, which meant that the water stayed under atmospheric pressure the whole time and 100 ^{o}C is the absolute maximum temperature the water can reach. Also, by comparing the <Boiler surface> and <HT compressor discharge> temperatures, the observation could be made that the closer you get to 100 ^{o}C, the more work had to be put in the system. The reason for this is because during the whole test the temperature difference between the two lines stayed at about 10 ^{o}C, but from a <Boiler surface> temperature of about 95 ^{o}C, the two lines started to diverge. Which meant that from that point onwards a higher <HT compressor discharge> temperature was needed to achieve the same heat transfer.

Superheat control

Since the system consists of two refrigerant cycles, the superheat for each cycle had to be controlled independently. Starting with the HT cycle, the observation could be made that the <HT evaporator outlet> temperature gradually, but steadily, transforms from a wave function to a constant line. This means that the HT superheat controller is able to automatically regulate the superheat for the HT evaporator. Also, by visually checking the controller screen, a value of around 7 ^{o}C was displayed, which meant that the set HT cycle superheat value was reached.

On the contrary, the LT cycle showed some different results. The <LT evaporator outlet> temperature remained an almost constant linear line throughout the test. This meant that the LT superheat controller was not able to correctly regulate the superheat for the LT evaporator. When looking at the controller screen the observation could then also be made that the set LT cycle superheat value of 4 ^{o}C was not reached, instead it remained at an almost constant 9.5 ^{o}C. There are three possible causes for this, either the EEV opening percentage has to increase, the refrigerant charge has to increase, or the fan speed is too high. First of all, the fan speed could quickly be eliminated, since the tests showed that different fan speeds were not causing the rise in superheat. And secondly, after charging the system with more refrigerant, the superheat still did not decrease. Which means that the current expansion valve is not sized correctly and a bigger one should be used for the system to work properly.

Heat exchanger efficiency

In total there are three heat exchangers in the system, with each their own function and efficiency. Starting with the LT cycle evaporator. The <LT evaporator outlet> temperature at the beginning is around 6 ^{o}C and at the end around 9 ^{o}C. Together with a constant superheat of 9.5 ^{o}C, this meant that at the start of the test the temperature difference between the room temperature and LT cycle evaporating temperature was around 21.5 ^{o}C and at the end around 18.5 ^{o}C. This is a big temperature difference. To decrease this temperature difference and to increase the LT cycle evaporator efficiency, the total heat transfer area needs to increase.

The difference between the <LT compressor discharge> and <HT evaporator outlet> temperature says something about the IHE efficiency. The temperature difference at the beginning of the test was on average around 10 ^{o}C (average is used since it is a wave function) and at the end around 5 ^{o}C (constant line). This temperature difference is smaller than expected, which meant that the heat exchanger had a sufficient efficiency and does not need to be redesigned.

As mentioned before, the difference between the <HT compressor discharge> and <Boiler surface> temperatures is around 10 ^{o}C throughout the whole test. What means that the temperature difference for the HT condenser is in line with the expected value, but there is still room for improvement. The first thing that can be changed to increase the efficiency some more, is to allow the boiler tank to build up pressure and to limit the amount heat loss during the test. For the next prototype this can simply be achieved by using a completely closed off and insulated boiler tank (which was already included in the design in Chapter 3.6.1).

Heating capacity

Since the design of some of the components within the system are not yet optimized, the current heating capacity is much lower than the expected final heating capacity. The current heating capacity can be calculated by first calculating the total required amount of energy and divide that number by the total amount of heating time. Because the HT cycle condenser temperature difference start to increase after a <Boiler surface> temperature of 95 ^{o}C, this point has been used as the measurement end time. Taking this into account, the total required amount of energy, to heat up 5 litres of water from 10 to 95 ^{o}C, will be 1.779.050 Joules (using the formula: $Q = m * c_p * dT$ and a specific heat capacity (c_p) for water of 4.186 J/kg*K). Dividing this amount of energy by the total amount of elapsed time of 23.5 minutes (1410 sec.), results in a heating capacity of 1265 Watt.

5.5 Coefficient of Performance

For calculating the COP value, the input power for each component needed to be measured. By running the system a couple more times, the amount of current could be measured for the centrifugal fan, the LT cycle compressor and the HT cycle compressor. The total amount of amps is dependent on the internal component temperatures, which means that the total amount of power is different at the start and at the end of each test run. At the start a total amount of 922 Watt is used and at the end 1373 Watt. For a complete overview of the measurements and the corresponding power factors see **Appendix L**.

The calculated total heating capacity in the previous section is not in line with the real situation. Because the heat loss in an open tank is much higher than in an insulated one. For this reason the heat loss has also been taken into account. Since heat loss is a negative type of Work, it has been added to the previously calculated heating capacity (because the final system would only transfer a very small amount of thermal energy to its environment). At the start of each test run the total heating capacity is 1294 Watt and at the end 1660 Watt. For a complete overview of the heat loss values see **Appendix L**.

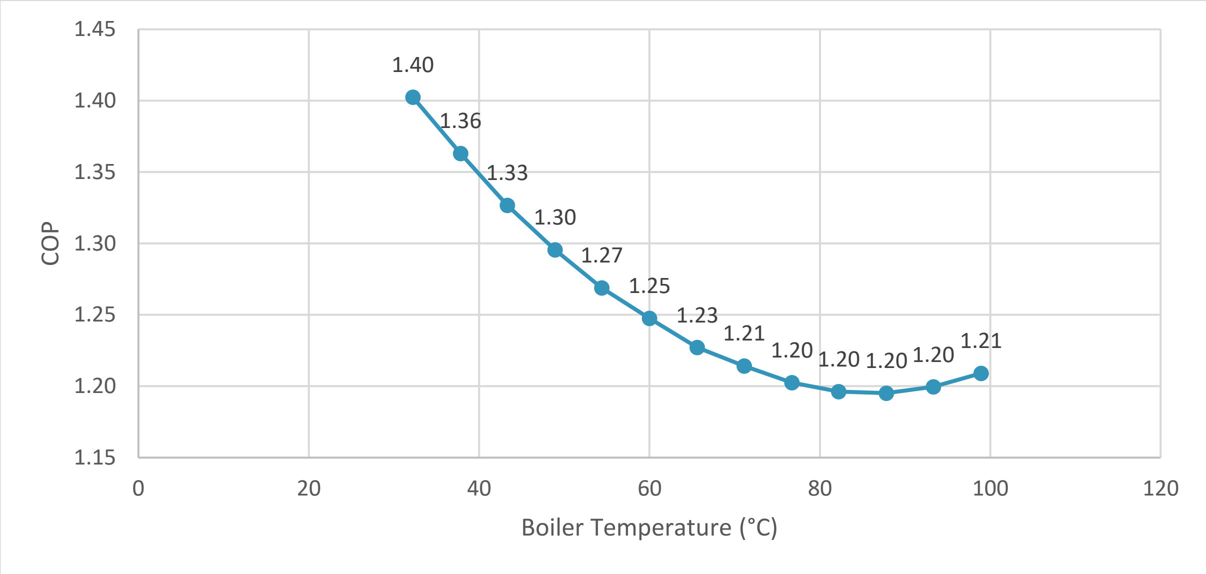

Figure 64 overall system COP at different boiler temperature intervals

With the total amount of power and the total heating capacity known, the COP value could be calculated (using the formula: $COP = \dot{Q}/W_{total}$). And, since both the power and heating capacity are dependent on the internal temperatures of the system, the COP value varies at different time intervals throughout the test. The COP value at the start is 1.40 and at the end 1.21. By taking an average of the COP values at different boiler temperature intervals an overall system COP of 1.26 could be calculated. For a complete overview of the COP values at different temperature intervals see Figure 64 and **Appendix L**.

5.6 Comparison to State-of-the-Art

Chapter 1.3 (State-of-the-art) introduced the HTHP's that are currently being developed. The first analyses was mainly used to showcase which systems are, or will be, available on the market within the next few years. The maximum heat sink temperatures and the refrigerants that are used to reach these temperatures are noted down in Table 1. This section will compare the state-of-the-art again, but also includes the cascade heat pump water boiler system.

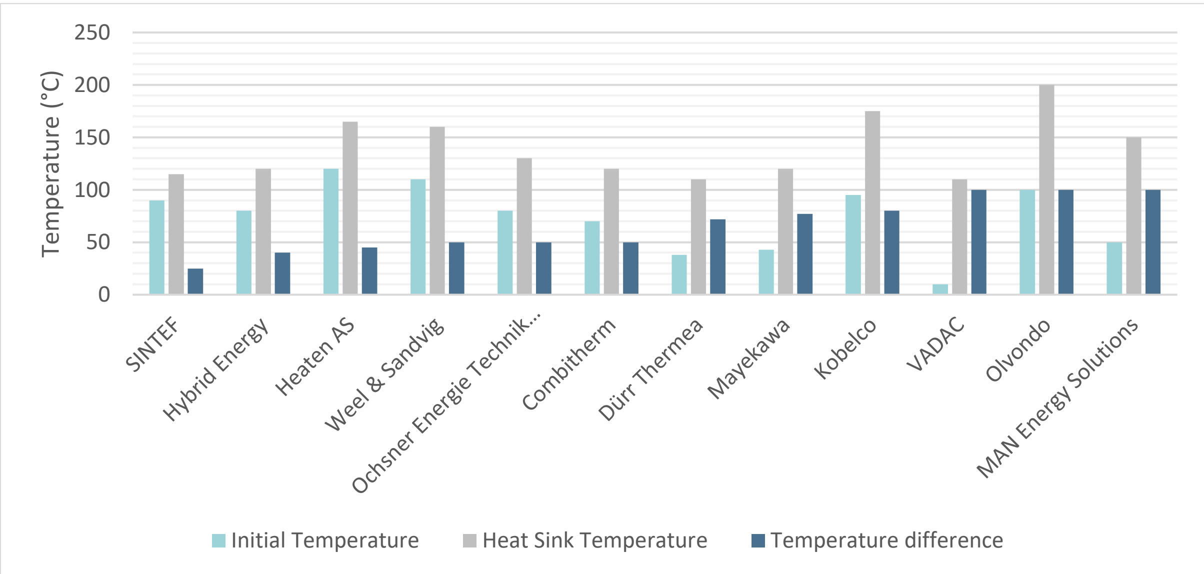

Figure 65 Cascade heat pump water boiler compared to the state-of-the-art

Figure 65 displays the cascade heat pump water boiler (VADAC) among the other heat pump systems. By noting down the initial source temperature and the heat sink outlet temperatures, the temperature difference can be calculated and compared among the systems. Each system is ranked according to their maximum temperature difference (with on the left the lowest and on the right the highest value).

Looking at where VADAC is located among the other systems, the conclusion can be made that the cascade heat pump water boiler is able to bridge a temperature difference much greater than most of the other systems. Actually it is ranked highest, together with the system from Olvondo and MAN Energy Solutions, with a maximum temperature difference of 100 ^{o}C. And, when using a closed boiler tank in the future, this temperature difference could possibly increase even more.

Also, looking at the initial source temperature, the cascade heat pump water boiler starts from a much lower temperature than the other two systems. Meaning that the system from VADAC is able to bridge the same temperature difference, but from an initial point with much less available thermal energy.

6. Conclusions and Recommendations

After evaluating the test results, this section forms a clear conclusion about the aim and objectives of the project. The first part of the conclusion is based on the comparison between the expected results and the actual test results. And the second part will discuss the outcome compared to the predefined list of requirements in **Appendix F**. And finally, for the future development of the system, a list of recommendations and an overview of what could have been done differently is discussed in the last section.

6.1 Conclusions

The overall system performance is lower than the theoretical calculated performance (COP of 1.26 instead of 2.22), but that does not mean that the project has not succeeded. The water in the boiler tank is able to reach its boiling point, which first of all means that the system is able to bridge the big temperature difference of 90 ^{o}C. As for the efficiency, the main causes can be traced back to a couple of components. Starting with the LT cycle evaporator. The total heat transfer area is too small. Instead of extracting a total of 1500 Watts of thermal energy from the surrounding air, it only extracts 331 Watts. Which means that the difference between the total amount of input power and the heating capacity is also only 331 Watts and that causes a big decrease in total system efficiency. And secondly, the LT cycle expansion valve opening is too small, which causes the superheat to not be able to get lower than 9 ^{o}C. This also has a big effect on the overall system efficiency. So, to conclude, the first proof-of-concept succeeded, but the next step is to increase the size of the LT cycle evaporator and to select an expansion valve with a bigger tube diameter and valve opening, to be able to increase the heat exchanger capacity.

Regarding the predetermined list of requirements (**Appendix F**), the following section first discusses the main requirements for the overall system performance and afterwards also separately for each individual component.

Overall system performance

- The system is able to heat up the water in the boiler tank to its boiling point under standard atmospheric pressure.
- All of the components have been subjected to and are able to withstand a minimum pressure of 30 bar.
- The current sound level of 70 dB is higher than the requirement of 68 dB, but this is only a small difference and in the final system this can be limited by using a bigger air vent and by adding sound insulation.
- The total heat loss in the IHE, open tank and copper tubes is currently too high, but this can simply be solved by using a closed of boiler tank and by adding thermal insulation around each component.

Refrigerants

- The GWP value for both the LT and HT cycle refrigerants are less than 150.
- The ODP value for both the LT and HT cycle refrigerants is zero.
- The LT and HT cycle refrigerants are chemically stable, which means they do not break down when operated under the specified pressure and temperature values.
- The first evaluation of the lubrication oils show that they are not effected by either of the refrigerant types or the high temperature. But, to be completely sure that the lubrication oils do not break down over time, they should be chemically tested by experienced laboratory personnel.

Centrifugal fan

- The air flow is sufficient enough for transferring the thermal energy from the air onto the LT cycle evaporator (centrifugal fan is able to draw in 800 m^3/h, but 500 m^3/h is already enough).

Heat exchangers

- The LT cycle evaporator is not as efficient as expected (temperature difference in between 18,5-21,5 ^oC instead of in between 10-15 ^oC). To be able to better transfer the thermal energy from the environment onto the refrigerant, the total heat transfer area needs to increase.
- The intermediate heat exchanger is able to more efficiently transfers the thermal energy from the LT cycle refrigerant onto the HT cycle refrigerant than expected (temperature difference of 5 ^oC instead of 10 ^oC).
- The HT cycle condenser is just as efficient as expected (temperature difference of 10 ^oC), but there is still room for improvement.
- The HT cycle condenser is resistant to a minimum temperature of 110 ^oC.

Compressors

- The LT cycle compressor is resistant to a minimal temperature of 70 ^oC.
- The HT cycle compressor is resistant to a minimal temperature of 120 ^oC (higher than the required 110 ^oC).
- The LT and HT cycle accumulators are sized correctly to prevent liquid refrigerant compression in the compressors.

Electronic expansion valves

- The LT cycle expansion valve/controller is not able to regulate the superheat correctly (superheat of 9 ^oC instead of the set value of 4 ^oC). As previously explained, the cause of this is not the fan speed or the amount of refrigerant charge, but the size of the expansion valve opening. So, to be able to regulate the superheat correctly, an expansion valve with a bigger opening should be used.
- The HT cycle expansion valve/controller is able to automatically regulate the valve opening (around a set superheat value of 7 ^oC).
- The expansion valves are both resistant to a minimum temperature of 110 ^oC.

6.2 Recommendations

After analysing the overall research outcome and test results, there are a couple of things that could have been done differently or which can be implemented in future work. The first section will start with what could have been done differently during the project.

First of all, for determining the right type of compressor for the LT cycle, an inverter type could have been used to precisely control the rotational speed and subsequently the heating capacity of the IHE. An inverter type is maybe more expensive than a constant speed compressor (since it needs a separate controller to operate it), but by knowing the exact required heating capacity at an early stage in the development, this could have saved money later on. Also, instead of starting with two higher heating capacity compressors, the first prototype could have been constructed with lower heating capacity compressors, to decrease the overall prototyping costs and to still be able to provide a first proof-of-concept. Secondly, the boiler tank could have been a closed off type by simply welding on the lid again and the tank could have been covered with cheap insulation material to allow for pressure to build up and to limit the amount of heat loss to the surroundings. Also, the IHE and copper tubes could have been insulated to prevent most of the thermal energy from escaping the system. Thirdly, the coil heat exchanger inside the boiler tank could have been more efficient by adding fins (to increase the heat transfer area) or by some kind of agitation device inside the tank (to move the water around and increase the contact with the heat exchanger). And finally, two extra pressure sensors on the high pressure discharge sides of the LT and HT cycle compressors could have been installed, to provide a more detailed overview of the final pressure-enthalpy diagram of the total system.

The things that can be implemented in future work are a result from the overall research outcomes. To begin with, during the research it was hard to find suitable compressor types, because these refrigerant types are not or minimally being used in current climate control systems. So, in the future, a compressor could maybe be developed specifically for these refrigerant types, to optimise the efficiency and their high temperature compatibility. Secondly, some components can be downsized in the final system. For example the centrifugal fan can be changed from a variable speed to a constant speed type, since the system only needs one predetermined speed to be able to function properly. Also, the control of the system is currently split up in multiple components (for testing purposes), but these can be combined into a single printed circuit board. And the LT cycle expansion valve can maybe change from an electronic type to a thermostatic expansion valve or a capillary tube. And finally, for the next prototype, a closed and insulated boiler tank needs to be designed (to limit the heat loss), the right size of LT expansion valve needs to be used (to lower the LT cycle superheat) and the LT cycle evaporator needs to be bigger (to increase the total amount of heat transfer area). This, to check if, with the right components and parameters, the system is able to reach the theoretically calculated efficiency. And, after the second prototype has been tested and is working properly, a tap and housing also needs to be designed for the final system.

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Appendix

A - Research Plan

Research Plan – Development of a Compressor and Heat Exchanger …

Master Thesis Industrial Design Engineering at Vadac

Objective

Introduction

To find out more about the company who is offering the assignment and the work they do, I asked questions during an interview with Marco van Rooijen (CEO of Vadac B.V.) The questions in the brief background analysis are used to provide information about the organization itself and about the reason or occasion why they offer the assignment. Together with the questions in the brief stakeholder analysis I will try to get an idea about which other people/organizations are involved and who Vadac is designing for. And finally, with all this information, I hope to be able to identify, how I as a master student “Industrial Design Engineering”, can provide added value for the company.

1.1.1 Background analysis:

- *What is the overall ‘change’ or objective your client is aiming at?*

In 2018 Vadac launched a roadmap to sustainable caravanning by rethinking all components. The first step is to replace the traditional gas heater with an energy efficient heat pump. For us this is a logical step in the evolution of the caravan, it removes the risks and inconveniences of the outdated gas heater and takes the caravan fast forward to the pinnacle of climate control.

- *What ‘problems’ or challenges arise with regard to this objective?*

Some of the challenges Vadac is facing currently are the transfer to a sustainable way of camping and to keep up with the innovations within the market.

- *What influence do other stakeholders have?*

Since most of the products Vadac is offering are also sold through a middleman, the list of requirements becomes bigger and the possibility exist that the wrong information is supplied.

- *What is your client’s opinion on causes of the problems or reasons for the identified challenges?*

To reach a bigger customer segment, the products are sold by using a middleman.

- *What possible solutions or changes have been suggested?*

Sell more products directly to the customer (not preferable) or better supply the middleman with the right product information to avoid miscommunication.

1.1.2 Stakeholder analysis:

- *What is the client’s main (business) objective / mission statement?*

At Vadac we share a passion for nature with the caravanning enthusiast and believe this can be combined perfectly with a sustainable, circular and climate friendly future. We believe in making caravans more sustainable and greener by helping people to reduce their carbon footprint while enjoying camping at the same time.

- *What is the client's expertise and interests? (how many employees are involved in product development)*

During more than two decades of experience in designing technical accessories for the caravanning and marine industry, Vadac has accumulated a profound knowledge and understanding of this type of market.

- *What other stakeholders do exist?*

Manufacturers, caravan and camper retailers, and end-users.

- *What expertise do the stakeholders have?*

Manufacturing of the products, buying and selling the product and using the product.

Project aim

The aim of the assignment is first to research the question if it is possible to use compressor and heat exchanger technology to improve an existing household device. Then, when this is possible, I will also start with the development of the system.

This task will be realized by means of applied research. In the pre-phase I will try to understand the assignment problem, how a heat pump system works, which rules and regulations apply, which applications are suitable for optimization and which competitors of these products already exist on the market. The outcome of this preliminary research can be used to develop a diagnosis on how the assignment can be tackled later on. In the next phase, I will go deeper into the chosen application by gathering more information about the existing heat pump system configurations, deployment methods and the working principle behind each individual component within the device. Then, with this information, a list of requirements can be established and the concept phase can start. In the concept phase, I will use the knowledge I gained in the previous phases to come up with ideas, iterations, concepts, etc. for the development of the chosen application.

During the whole project I will have regular progress meetings with the company and other clients, so we can come to the best solution together, while keeping in mind all relevant stakeholders their needs and wishes. After converging towards a final concept, the detailing phase will begin. In this phase the chosen concept (or more concepts) will be modelled in a 3D CAD environment and by using these 3D models a prototype can be constructed. The working prototype, resulting from this phase, will be used in the implementation phase for testing. And finally the results of the testing phase will be evaluated and if the system has proven to work and it solves the corresponding problem, then it can be used for further development. But, when it does not work correctly or does not solve the problem, then I will have to go back to one of the previous phases and reconsider my ideas.

Research questions

Main question:

Is it possible to use heat pump technology to improve an existing household application and make it more sustainable and energy efficient?

Central questions and sub-questions:

1. How does a heat pump system work?
    a. What is a heat pump?
    b. What kind of components does a heat pump consist of?
    c. What kind of functions do each of the components have?
    d. How do the components work together?
    e. Which rules and regulations apply to heat pump systems?
    f. According to the stakeholders, what requirements must the new device meet?
    g. Which types of heat pumps are already available on the market?
    h. What added value are users experiencing when using a heat pump?

2. How can compressor and heat exchanger technology be used to improve one of the existing household devices?
    a. Where are heat pump systems currently already being applied?
    b. Which household devices use a high temperatures?
    c. Which household device consumes the most electrical energy?
    d. Which household device is most suitable for optimization by means of heat pump technology?
    e. Who are the current competitors of the chosen application?
    f. Looking at the devices from the competitors, what are the additional design features that can be used for the improvement of the chosen household device?
    g. What kind of improvements or additional features do users like to have when using the chosen household device?

3. How feasible is the implementation of heat pump technology in the new type of application?
    a. Looking at the preliminary research results, which requirements should be added to the list of components?
    b. According to the list of requirements, which ideas and concepts can be generated?
    c. Keeping the improvements into account, how should all the components work together in the final concept?
    d. How does the final concept work in practice?

Approach

Strategy

Research	
Strategy	Answered questions
Heat Pump Analysis	1a, 1b, 1c, 1d, 1e, 1g
Use case Analysis	1g, 1h, 2a, 2b, 2c, 2d
Competitor Analysis	2e, 2f, 2g
Machine and Workflow Research	1b, 1c, 1d, 1g
Concept development	
Strategy	Answered questions
Ideation and iterations	3a, 3b
Client and UT supervisor meetings	1a, 1b, 1c, 1d, 1f
Concept generation	3c
Prototype construction	3c, 3d
Testing	3d
Evaluation	3c, 3d

Material (sources)

To be able to perform every strategy tool each of them require different kinds of materials. Underneath I made an overview of every strategy tool and matched them to the materials they need.

Strategy	Required materials
Client/Company (Vadac) Analysis	Literature, internet, client knowledge
Heat Pump Analysis	Literature, internet, client and supervisor knowledge
Use Case Analysis	Literature, internet, client and supervisor knowledge
Competitor Analysis	Literature, internet
Machine and Workflow Research	Literature, internet, manufacturer information
Ideation/iteration	Literature, internet, brainstorming, morphological scheme, sketches
Concept generation	System diagrams, 3D CAD software, 3d visualization software, manufacturer information
Prototyping	Prototyping workshop (e.g. 3D printer, metalworking, etc.)
Testing	Prototype, testing site, testing equipment
Evaluation	Test results, user feedback, client feedback, UT supervisor feedback

B - Competitors Technical Data

Quooker

- **PRO3**

Function	Provides 3 litres of instant boiling water (100ºC)
Dimensions (WxDxH) (mm)	152 x 152 x 412 (round)
Volume (Litres)	3
Reheating time (minutes)	10
Material	Stainless-steel and insulation material
Performance (W)	Heating: 1600 Stand-by: 10
Outstanding features	- Retractable hose tap optional - Twin tap option - Several colours available: chrome, stainless steel, black, messing and gold - Can be combined with the CUBE - Safety and feedback ring - Safe touch tap

- **COMBI**

Function	Provides 7 litres of instant boiling water (100ºC) and 15 litres of warm water (60ºC)
Dimensions (WxDxH) (mm)	199 x 199 x 469 (round)
Volume (Litres)	7
Reheating time (minutes)	20
Material	Stainless-steel
Performance (W)	Heating: 2200 Stand-by: 10
Outstanding features	- See PRO3 - Vacuum insulation

- **COMBI+**

Function	Provides 7 litres of instant boiling water (100ºC) and unlimited warm water (60ºC)
Dimensions (WxDxH) (mm)	199 x 199 x 469 (round)
Volume (Litres)	7
Reheating time (minutes)	20
Material	Stainless-steel
Performance (W)	Heating: 2200 Stand-by: 10
Outstanding features	- See PRO3 - Vacuum insulation

- **CUBE**

Function	Provide 60 litres of cooled and sparkling water
Dimensions (WxDxH) (mm)	153 x 270 x 500 (rectangle)
Volume (Litres)	60 litres cooling capacity
Cooling time (minutes)	30
Material	Stainless-steel and insulation material
Performance (W)	Stand-by: 5
Outstanding features	- Active carbon filter optional

Selsiuz

- **Single**

Function	Provide 3,7 litres of instant boiling water (100ºC)
Dimensions (WxDxH) (mm)	225 x 225 x 398 (round)
Volume (Litres)	5
Reheating time (minutes)	18
Material	Stainless steel and insulation material
Performance (W)	Heating: 2200 Stand-by: 16
Outstanding features	- Several colours and designs available: chrome, inox, copper, gold, gun metal, Gessi - Safe touch tap - Two step safety handle

- **Combi Extra**

Function	Provide 3,7 litres of instant boiling water (100ºC) and 7,5 litres of warm water (55ºC)
Dimensions (WxDxH) (mm)	225 x 225 x 398 (round)
Volume (Litres)	5
Reheating time (minutes)	18
Material	Stainless steel and insulation material
Performance (W)	Heating: 2200 Stand-by: 16
Outstanding features	- See Single

- **Titanium**

Function	Provide 3,7 litres of instant boiling water (100ºC) and 7,5 litres of warm water (55ºC)
Dimensions (WxDxH) (mm)	225 x 225 x 398 (square)
Volume (Litres)	5
Reheating time (minutes)	18
Material	Stainless steel and titanium, and insulation material
Performance (W)	Heating: 2200 Stand-by: 16
Outstanding features	- See single - Titanium is more resistant to big temperature differences and corrosion

- **Cooler**

Function	Provide 2 litres of cooled water per minute and/or 18,5 litres of sparkling water
Dimensions (WxDxH) (mm)	185 x 366 x 406 (rectangle)
Volume (Litres)	0
Cooling time (minutes)	Unknown
Material	Stainless steel
Performance (W)	Cooling: 100 Stand-by: 1
Outstanding features	- Calcium filter optional

Franke

- **SOLO S**

Function	Provide 3,5 litres of instant boiling water (100ºC)
Dimensions (WxDxH) (mm)	145 x 200 x 522 (rectangle)
Volume (Litres)	5
Reheating time (minutes)	12
Material	Copper and insulation material
Performance (W)	Heating: 1500 Stand-by: 25
Outstanding features	- Retractable hose tap optional - Two step safety twist handle - Safe touch tap - Many designs available

- **COMBI S**

Function	Provide 3,5 litres of instant boiling water (100ºC) and provide cooled water
Dimensions (WxDxH) (mm)	145 x 200 x 522 (rectangle)
Volume (Litres)	5
Reheating time (minutes)	12
Material	Copper and insulation material
Performance (W)	Heating: 1500 Stand-by: 25
Outstanding features	- See SOLO S

- **COMBI XL**

Function	Provide 7,5 litres of instant boiling water (100ºC) and provide cooled water
Dimensions (WxDxH) (mm)	285 x 300 x 452 (rectangle) Unknown
Volume (Litres)	10
Reheating time (minutes)	35
Material	Copper and insulation material
Performance (W)	Heating: 2200
Outstanding features	- See SOLO S

- **COMBI Xcellent**

Function	Provide 7,5 litres of instant boiling water (100ºC), 32 litres of warm water (40ºC) and cooled water
Dimensions (WxDxH) (mm)	Boiler: 285 x 300 x 452 (rectangle) Cooler: 185 x 386 x 406 (rectangle)
Volume (Litres)	Boiler: 10 Cooler: 0
Reheating time (minutes)	35
Material	Copper and stainless steel, and insulation material
Performance (W)	Heating: 2200 Cooling: 170 Stand-by cooler: 8
Outstanding features	- See SOLO S - Filter optional

Grohe

- Red L

Function	Provide 5,5 litres of boiling water (100ºC) and unlimited warm water
Dimensions (WxDxH) (mm)	210 x 210 x 491 (round)
Volume (Litres)	7
Reheating time (minutes)	unknown
Material	Titanium and stainless steel
Performance (W)	Heating: 2200 Stand-by: 14
Outstanding features	- Two step safety handle - Safe touch tap - Many designs available

- Red Compact

Function	Provide 3 litres of boiling water (100ºC) and 5,5 litres of warm water
Dimensions (WxDxH) (mm)	210 x 210 x 288
Volume (Litres)	4
Reheating time (minutes)	20
Material	Titanium and stainless steel
Performance (W)	Heating: 2200 Stand-by: 14
Outstanding features	- See Red L

- Blue Home

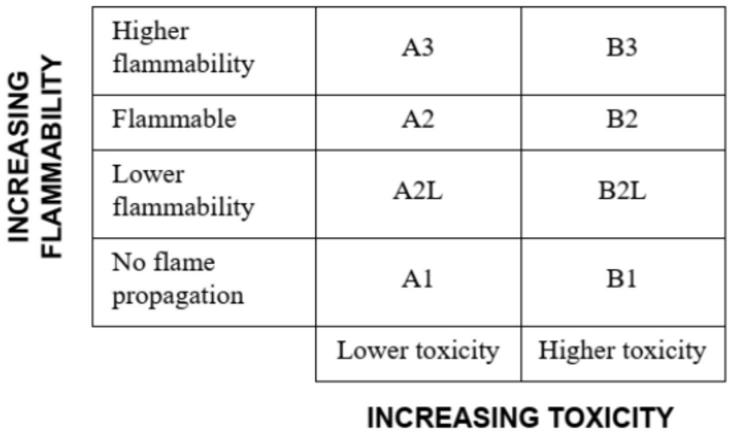
Function	Provide cooled, filtered and sparkling water
Dimensions (WxDxH) (mm)	200 x 500 x 455 (rectangle)
Volume (Litres)	0
Cooling time (minutes)	Unknown
Material	Stainless steel
Performance (W)	Cooling: 180
Outstanding features	- See red L - “GROHE Ondus” app to control the device, the settings and to automatically order new CO2 cartridges and filters

C - Refrigerant Selection List

Number	Name	Type	Zeotropic*	GWP	ODP	Tcrit (C)	Tboil (C)	Toxicity	Flammability	Natural	Category**
R-152a	1,1-Difluoroethane	HFC	no	138	0	113,26	-24,00	low	medium	no	A2
R-161	Fluorethane	HFC	no	4	0	102,22	-37,1	low	high	no	A3
R-170	Ethane	HC	no	6	0	32,17	-88,58	low	high	yes	A3
R-290	Propane	HC	no	3	0	96,74	-42,11	low	high	yes	A3
R-444A	AC5	HFO/HFC	yes	93	0	106,00	-35,70	low	low	no	A2L
R-451A	-	HFO	yes	140	0	95,40	-30,80	low	low	no	A2L
R-468A	-	HFO/HFC	yes	148	0	84,00	-51,20	low	low	no	A2L
R-471A	-	HFO/HFC	yes	148	0	112,00	-16,90	low	low	no	A2L
R-516A	ARM-42	HFO/HFC	yes	131	0	97,00	-29,40	low	low	no	A2L
R-454C	Opteon XL20	HFO	yes	148	0	82,40	-45,90	low	low	no	A2L
R-455A	Solstice L40X	HFO	yes	148	0	85,60	-52,10	low	low	no	A2L
R-600	Butane	HC	no	6,6	0	152,01	0	low	high	yes	A3
R-600a	Isobutane	HC	no	3	0	134,66	-11,75	low	high	yes	A3
R-601	Pentane	HC	no	4	0	196,56	36,10	low	high	yes	A3
R-601a	Isopentane	HC	no	4	0	187,78	27,70	low	high	yes	A3
R-610	Ethyl ether	HC	no	4	0	193,65	34,60	low	high	no	A3
R-611	Methyl formate	HC	no	0	0	213,55	32,00	high	medium	no	B2
R-631	Ethylamine		no	?	0	183	16,60	?	?	yes	?
R-717	Ammonia		no	0	0	132,25	-33,30	high	low	yes	B2L
R-718	Water		no	0,2	0	373,95	100,00	no	no	yes	A1
R-744	Carbon dioxide		no	1	0	31,98	-78,46	low	no	yes	A1
R-1233zd(E)	Trans-1-Chloro-3,3,3-Trifluoropropene	HFO	no	1	0,00034	165,5	18,26	low	no	no	A1
R-1234yf	2,3,3,3-Tetrafluoropropene	HFO	no	4	0	94,70	-29,40	low	low	no	A2L
R-1234ze(E)	Solstice ze	HFO	no	7	0	109,37	-19,00	low	low	no	A2L
R-1270	Propylene	HO	no	1,8	0	92,42	-47,60	low	high	no	A3
R-1336mzz(E)	Trans-1,1,1,4,4,4-Hexafluoro-2-butene	HFO	no	18	0	137,7	7,50	low	no	no	A1
R-1336mzz(Z)	Cis-1,1,1,4,4,4-Hexafluoro-2-butene	HFO	no	2	0	171,3	33,4	low	no	no	A1

*Mixture with liquid components that have different boiling points.

**Classification of refrigerants with regard to safety (see figure below).



Refrigerant safety group classification (ANSI/ASHRAE standard 34-2022)

- Refrigerants in red either have unknown values or a very low ODP value, which makes it uncertain if these can be used.

For the refrigerant selection of the heat pump a total of 8 suitable refrigerant were selected. The following refrigerants were **eliminated**:

- Zeotropic refrigerants (R400 and R500 types) have unfavourable temperature glides.
- R152a, R161, R610 and R611 are not commonly used as refrigerants.
- R290, R717 and R1270 require to high operating pressures.
- R631 and R1336mzz(e) only have a limited amount of available information.
- R170 and R744 require supercritical operating temperatures.
- R718 requires a to high mass flowrate compared to its volumetric heating capacity.

D - Thermodynamic Principles

The process of exchanging heat between materials is part of thermodynamics, which is the science of the relationship between heat, work, temperature and energy (Drake, 2021). The three ways in which heat can be transferred are (Ronquillo, 2021):

- *Conduction* $\dot{Q} = \frac{kA\Delta T}{d}$ *:* the transfer of thermal energy between materials that are in contact with each other (materials with a higher temperature have more molecular motion (kinetic energy) and when in contact with a colder material, transfer thermal energy to come to a steady equilibrium). **Q-dot** represents the transfer rate of heat, **k** the materials conductivity constant, **A** the cross-sectional area, **delta-T** the temperature difference and **d** the thickness of the material.
- *Convection (free/natural)* $\dot{Q} = h_c A \Delta T$ *:* the transfer of thermal energy from a materials surface onto a moving substance like a fluid or gas (increasing temperature makes a substance expand and decreases the density, which makes the particles float (move upwards) on top of the less dense particles and in this way move around and transfer thermal energy). **Q-dot** represents the transfer rate of heat, $\mathbf{h_c}$ the convection heat transfer constant, **A** the exposed surface area and **delta-T** the temperature difference.
- *Thermal radiation* $\dot{Q} = \varepsilon\sigma A_h\left(T_h^4 - T_c^4\right)$ *:* the transfer of thermal energy by means of emitted electromagnetic waves from a heated surface (all materials with a temperature above absolute zero contain molecular motion (kinetic energy) and some of the movement of charges is converted to thermal radiation, a type of energy transfer process that does not require an intervening medium for exchanging heat). **Q-dot** represents the transfer rate of heat, **epsilon** the emissivity constant, **sigma** the Stefan-Boltzmann constant (5,6703 x 10^{-8} W/m^2K^4), $\mathbf{A_h}$ the exposed surface area and **delta-T** the temperature difference.

All of the previously mentioned heat transfer processes operate under the same underlying principles. These principles are the basics for understanding how heat exchangers work and why materials and substances have the tendency to exchange thermal energy. The three basic fundamental principles are (Ronquillo, 2021):

- *Zeroth's Law of Thermodynamics:* if two thermodynamic systems are each in thermal equilibrium with a third system, then they are also in thermal equilibrium with each other (if A=C and B=C, then A=B).
- *First Law of Thermodynamics* $\Delta U_{system} = -\Delta U_{environment}$ *:* energy cannot be created or destroyed (Law of Conservation of Energy), it can only be transferred to another thermodynamic system or converted to another type of energy. **U** is the initial potential energy.
- *Second Law of Thermodynamics* $\Delta S = \frac{\Delta Q}{T}$ *:* an isolated system has the natural tendency to degenerate into a more disordered state (increased entropy) and since entropy can only increase and moves towards the highest possible value, the system eventually reaches a state of equilibrium. **Delta-S** is the change in entropy, **delta-Q** the change in heat and **T** the absolute temperature.

To sum up, Zeroth's Law of Thermodynamics shows that thermal equilibrium is a transitive relation, the First Law of Thermodynamics shows the inversive relationship of the internal energy between systems and the Second Law of Thermodynamics shows that two systems are naturally moving towards thermal equilibrium.

E - Cascade Heat Pump MATLAB Calculation Script

Condensor output power:

```
Qc=2200
```

```
Qc = 2200
```

HT mass flowrate:

```
m2=Qc/(R600.VaporEnthalpy(R600.Temperature==110)- ...
    R600.LiquidEnthalpy(R600.Temperature==110))
```

```
m2 = 0.0093
```

Intermediate heat exchanger transition temperatures:

```
Tihe=40:10:100
```

```
Tihe = 1×7

    40    50    60    70    80    90   100
```

Repetition control structure:

```
for i=1:length(Tihe)
    T=Tihe(i)
```

```
T = 40
T = 50
T = 60
T = 70
T = 80
T = 90
T = 100
```

Intermediate heat exchanger thermal energy:

```
Qihe=m2*(R600.VaporEnthalpy(R600.Temperature==Tihe(i))- ...
    R600.LiquidEnthalpy(R600.Temperature==110))
```

```
Qihe = 1.3699e+03
Qihe = 1.5002e+03
Qihe = 1.6287e+03
Qihe = 1.7545e+03
Qihe = 1.8765e+03
Qihe = 1.9931e+03
Qihe = 2.1020e+03
```

LT mass flowrate:

```
m1=Qihe/(R1234ze.VaporEnthalpy(R1234ze.Temperature==Tihe(i))- ...
    R1234ze.LiquidEnthalpy(R1234ze.Temperature==Tihe(i)))
```

```
m1 = 0.0088

m1 = 0.0103

m1 = 0.0120

m1 = 0.0142

m1 = 0.0170

m1 = 0.0213

m1 = 0.0299
```

Cascade heat pump coefficient of performance:

```
COP=Qc/(m1*(R1234ze.VaporEnthalpy(R1234ze.Temperature==Tihe(i))- ...
    R1234ze.VaporEnthalpy(R1234ze.Temperature==16))+ ...
    m2*(R600.VaporEnthalpy(R600.Temperature==110)- ...
    R600.VaporEnthalpy(R600.Temperature==Tihe(i))))
```

```
COP = 2.2876

COP = 2.4179

COP = 2.5119

COP = 2.5491

COP = 2.5110

COP = 2.3817

COP = 2.1469
```

Compressor power:

```
WcompLT=m1*(R1234ze.VaporEnthalpy(R1234ze.Temperature==Tihe(i))- ...
    R1234ze.VaporEnthalpy(R1234ze.Temperature==16))
```

```
WcompLT = 131.5890

WcompLT = 210.0627

WcompLT = 304.5045

WcompLT = 417.5062

WcompLT = 552.5987

WcompLT = 716.7796

WcompLT = 926.7203
```

```
WcompHT=m2*(R600.VaporEnthalpy(R600.Temperature==110)- ...
    R600.VaporEnthalpy(R600.Temperature==Tihe(i)))
```

```
WcompHT = 830.1293

WcompHT = 699.8021

WcompHT = 571.3275

WcompHT = 445.5391

WcompHT = 323.5485

WcompHT = 206.9302

WcompHT = 98.0001
```

COP-T plot:

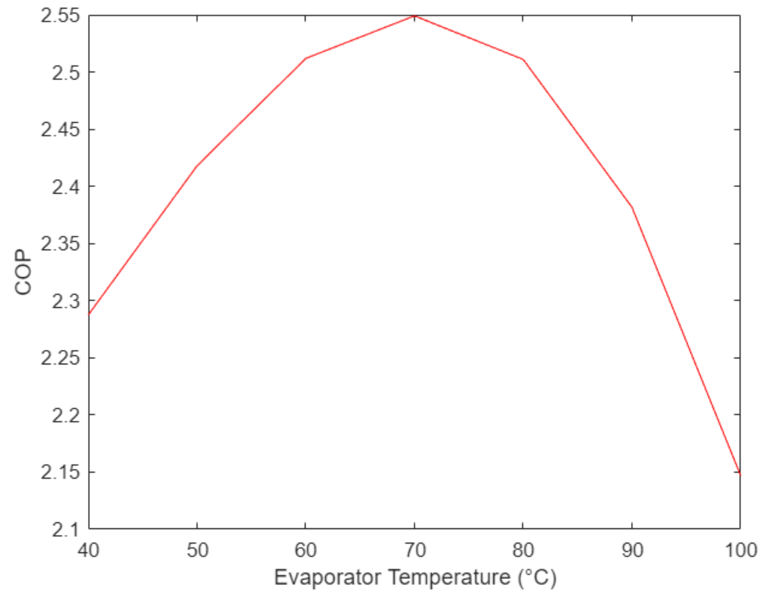
```
COPvalues(i)=COP
```

```
COPvalues = 1×7

    2.2876    2.4179    2.5119    2.5491    2.5110    2.3817    2.1469
COPvalues = 1×7

    2.2876    2.4179    2.5119    2.5491    2.5110    2.3817    2.1469
COPvalues = 1×7

    2.2876    2.4179    2.5119    2.5491    2.5110    2.3817    2.1469
COPvalues = 1×7

    2.2876    2.4179    2.5119    2.5491    2.5110    2.3817    2.1469
COPvalues = 1×7

    2.2876    2.4179    2.5119    2.5491    2.5110    2.3817    2.1469
COPvalues = 1×7

    2.2876    2.4179    2.5119    2.5491    2.5110    2.3817    2.1469
COPvalues = 1×7

    2.2876    2.4179    2.5119    2.5491    2.5110    2.3817    2.1469
```

```
m1values(i)=m1
```

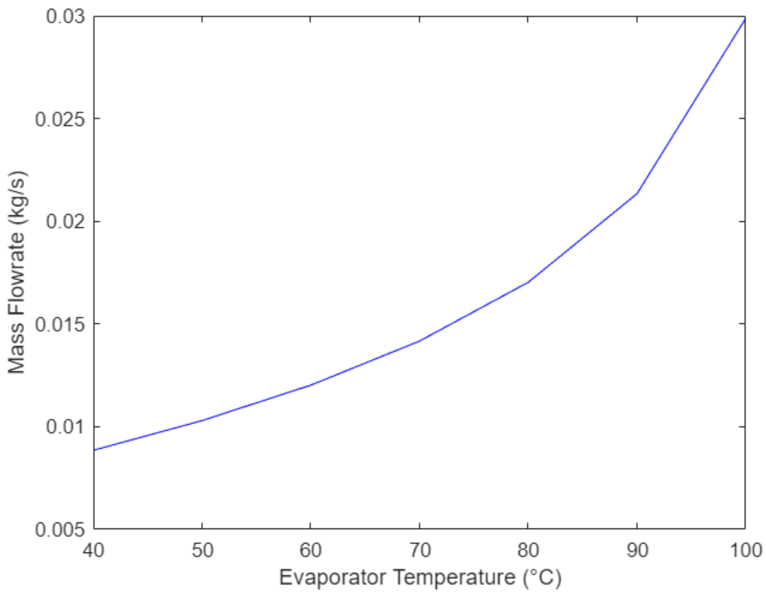
```
m1values = 1×7

    0.0088    0.0103    0.0120    0.0142    0.0170    0.0213    0.0299
m1values = 1×7

    0.0088    0.0103    0.0120    0.0142    0.0170    0.0213    0.0299
m1values = 1×7

    0.0088    0.0103    0.0120    0.0142    0.0170    0.0213    0.0299
m1values = 1×7

    0.0088    0.0103    0.0120    0.0142    0.0170    0.0213    0.0299
m1values = 1×7

    0.0088    0.0103    0.0120    0.0142    0.0170    0.0213    0.0299
m1values = 1×7

    0.0088    0.0103    0.0120    0.0142    0.0170    0.0213    0.0299
m1values = 1×7

    0.0088    0.0103    0.0120    0.0142    0.0170    0.0213    0.0299
```

```
end
plot(Tihe,COPvalues,'Color','r')
xlabel('Evaporator Temperature (°C)')
ylabel('COP')
```



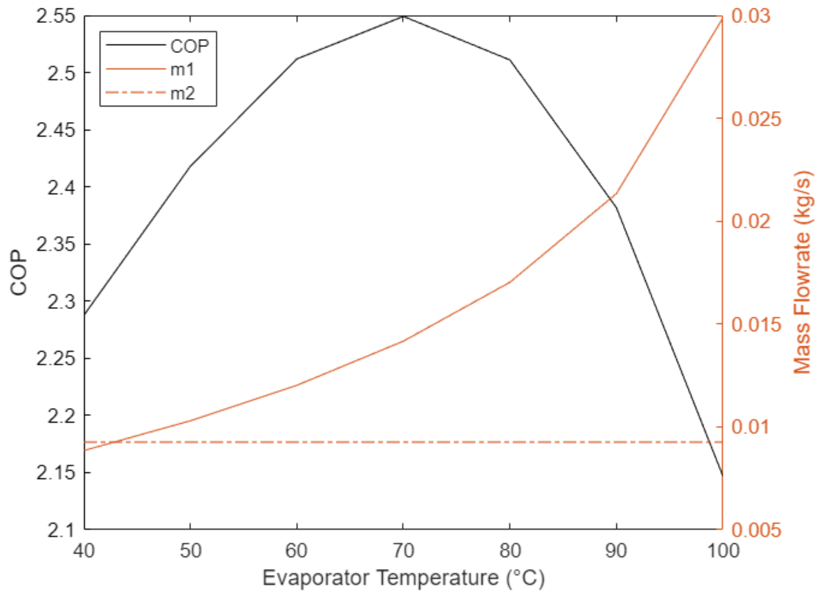
mdot-T plot:

```
plot(Tihe,m1values,'Color','b')
xlabel('Evaporator Temperature (°C)')
ylabel('Mass Flowrate (kg/s)')
```



Combined plot:

```
xlabel('Evaporator Temperature (°C)')
ylabel('COP')

yyaxis right
plot(Tihe,m1values)
xlabel('Evaporator Temperature (°C)')
ylabel('Mass Flowrate (kg/s)')

yline(m2,'color','[0.8500 0.3250 0.0980]','LineStyle','-.','LineWidth',1)

legend('location','northwest')

legend(["COP","m1","m2"])
```



F - List of Requirements

The executed preliminary research and the interviews with potential stakeholders, like clients and manufacturers, resulted in a variety of requirements. This list of requirements, consisting of wishes and demands, is divided into several smaller lists. Most of the lists relate to different components of the machine, these parts are the refrigerant, evaporator, compressor, condenser, expansion valve and housing. The other lists relate to the rules and regulations, user requirements and general requirements. Underneath the lists are shown in tables and for each of the requirements an indication is given from which analysis it resulted from and whether it is a wish or demand.

Refrigerants

#	Demands	Sources
1.1	The refrigerant (at the lower temperature input) should be a vapour at a temperature of 16 ^{o}C and a pressure value off 1,013 bar.	2.1.2 Components and Functions
1.2	The refrigerant (at the higher temperature output) should have a minimum critical temperature of 110 ^{o}C.	2.2.4 Chosen Heat Pump Application
1.3	The refrigerant should have a characteristic odour or tracer element when it is flammable or contains a toxic substance.	2.1.2 Components and Functions 2.1.3 Rules and Regulations
1.4	The refrigerant should be commercially available.	Client meetings
1.5	The refrigerant should not exceed the price of €40,- per kilogram.	Client meetings
1.6	The refrigerant should have a GWP value less than 150.	2.1.3 Rules and Regulations
1.7	The refrigerant should have a ODP value of zero.	2.1.3 Rules and Regulations
1.8	The refrigerant should be chemically stable at the required pressure and temperatures.	2.1.2 Components and Functions 2.1.3 Rules and Regulations
1.9	The refrigerant should not be corrosive or aggressive against the system construction materials or protective coatings.	2.1.2 Components and Functions 2.1.3 Rules and Regulations
1.10	The refrigerant should not react to the lubricating oils.	2.1.2 Components and Functions
1.11	The refrigerant amount may not exceed the corresponding allowable boundary value.	EN 378
	Wishes	
1.12	The refrigerant (at the higher temperature output) should have a critical temperature higher than 204,4 ^{o}C .	2.2.3 Appliances Suitable for Optimization
1.13	The refrigerant should not be poisonous to humans and animals.	2.1.2 Components and Functions 2.1.3 Rules and Regulations
1.14	The refrigerant should not be flammable or explosive.	2.1.2 Components and Functions 2.1.3 Rules and Regulations
1.15	The refrigerant should not contain fluorinated greenhouse gases.	2.1.3 Rules and Regulations

Evaporator

#	Demands	Sources
2.1	The evaporator should be able to efficiently transfer the thermal energy from the environment onto the refrigerant fluid.	2.1.2 Components and Functions
2.2	The evaporator should be able to effectively separate the refrigerant vapour from the liquid.	2.1.2 Components and Functions
2.3	The evaporator should consist of corrosion resistant materials.	2.1.3 Rules and Regulations 3.3.3.3 Construction Type
2.4	The evaporator must function at a minimum temperature of 16 ^{o}C .	2.2 Use Case Analysis
2.5	The evaporator should be resistant to a minimum temperature of minus 10 ^{o}C .	3.3.3.3 Construction Type
2.6	The evaporator should function at and be resistant to a maximum temperature of 50 ^{o}C .	3.3.3.3 Construction Type
2.7	The evaporator must fit in the cabinet underneath the kitchen sink.	2.2.3 Appliances Suitable for Optimization
	Wishes	
2.8	The evaporator should be able to transfer thermal energy onto the refrigerant liquid at a high rate.	2.1.2 Components and Functions
2.9	The evaporator should use as little surface area as possible.	3.3.3.3 Construction Type
2.10	The evaporator should not be constructed with toxic materials.	2.1.3 Rules and Regulations
2.11	The evaporator should function at and be resistant to a maximum pressure of 25 bar.	2.1.2 Components and Functions

Compressor

#	Demands	Sources
3.1	The compressors should be able to efficiently compress and transport the refrigerants	2.1.2 Components and Functions
3.2	The compressors should contain an accumulator with a volume equal to the maximum system volume.	2.1.2 Components and Functions
3.3	The compressors should consist of corrosion resistant materials.	2.1.3 Rules and Regulations 3.3.2.3 Overall Features
3.4	The compressors must function at a minimum temperature of 16 ^{o}C .	2.2 Use Case Analysis
3.5	The compressors should be resistant to a minimum temperature of minus 10 ^{o}C .	3.3.2.3 Overall Features
3.6	The compressor and lubrication oil (in the lower temperature cycle) should be resistant to a minimum temperature of 70 ^{o}C .	2.2 Use Case Analysis
3.7	The compressor and lubrication oil (in the higher temperature cycle) should be resistant to a minimum temperature of 110 ^{o}C .	3.3.2.3 Overall Features
	Wishes	
3.8	The compressors should be as small as possible.	2.2 Use Case Analysis
3.9	The compressors should function and be resistant to a maximum pressure of 25 bar.	2.2 Use Case Analysis

Condenser

#	Demands	Sources
4.1	The condenser should be able to efficiently transfer the thermal energy from the refrigerant fluid to the water reservoir.	2.1.2 Components and Functions
4.2	The condenser should be able to effectively separate the refrigerant liquid from the vapor.	2.1.2 Components and Functions
4.3	The condenser should consist of corrosion resistant materials.	2.1.3 Rules and Regulations 3.3.3.3 Construction Type
4.4	The condenser should function at and be resistant to a minimum temperature of 110 ^{o}C .	2.2 Use Case Analysis
4.5	The condenser should be resistant to a temperature of minus 10 ^{o}C .	2.2 Use Case Analysis
	Wishes	
4.6	The condenser should be able to transfer the thermal energy from the refrigerant liquid at a high rate.	2.1.2 Components and Functions
4.7	The condenser should use as little surface area as possible.	3.3.3.3 Construction Type
4.8	The condenser should not be constructed with toxic materials.	2.1.3 Rules and Regulations
4.9	The condenser should function at and be resistant to a maximum pressure of 25 bar.	2.1.2 Components and Functions

Expansion Valves

#	Demands	Sources
5.1	The expansion valve should be suitable for stepwise adjustments.	2.1.2 Components and Functions
5.2	The expansion valve should be suitable for automatic control.	2.1.2 Components and Functions
5.3	The expansion valve should consist of corrosion resistant materials.	2.1.3 Rules and Regulations
5.4	The expansion valve should be resistant to a minimum temperature of minus 10 ^{o}C.	2.2 Use Case Analysis
5.5	The expansion valve should function at a minimum temperature of 16 ^{o}C.	2.2 Use Case Analysis
5.6	The expansion valve (in the lower temperature cycle) should be resistant to a minimum temperature of 80 ^{o}C.	2.2 Use Case Analysis
5.7	The expansion valve (in the higher temperature cycle) should be resistant to a minimum temperature of 110 ^{o}C.	2.2 Use Case Analysis
	Wishes	
5.8	The expansion valve should not be constructed with toxic materials.	2.1.3 Rules and Regulations
5.9	The expansion valve should function at and be resistant to a maximum pressure of 25 bar.	2.1.2 Components and Functions

Rules and Regulations

#	Demands	Sources
6.1	The refrigerant should be in line with the European regulations (EU) nr. 517/2014 regarding F-gasses.	2.1.3 Rules and Regulations
6.2	The refrigerant should be in line with the European regulations (EU) nr. 1005/2009 regarding ozone depletion.	2.1.3 Rules and Regulations
6.3	The system and refrigerant should be in line with the European general product safety directive (EU) 2001/95/EG.	2.1.3 Rules and Regulations
6.4	The system should be in line with the European pressure equipment directive (PED) (EU) 2014/68/EU.	2.1.3 Rules and Regulations
6.5	The system should be in line with the European guidelines (EU) 2009/125/EC regarding eco-design and energy labelling.	2.1.3 Rules and Regulations
6.6	The system should be in line with the European restriction of hazardous substances directive (RoHS) (EU) 2011/65/EU.	2.1.3 Rules and Regulations
6.7	The system should be in line with the European machinery directive (EU) 2006/42/EC.	2.1.3 Rules and Regulations
6.8	The refrigerant should be in line with the European registration, evaluation, authorization and restriction of chemicals directive (REACH) (EU) EC 1907/2006	2.1.3 Rules and Regulations

User Requirements

#	Demands	Sources
7.1	The boiler should be able to heat up to a temperature of 110 ^{o}C.	2.2.4 Chosen Heat Pump Application 2.3 Competitor Analysis
7.2	The boiler should be easy to clean.	Client meetings
7.3	The boiler should not exceed the acceptable noise level for constant exposure of 68 decibels.	2.1.3 Rules and Regulations
	Wishes	
7.4	The boiler system should be able to switch between temperatures of 55 to 110 ^{o}C.	2.3 Competitor Analysis
7.5	The boiler should provide comfort and feel luxurious.	2.3 Competitor Analysis Client meetings
7.6	The boiler should not exceed a noise level of 40 decibels.	Client meetings

General Requirements

#	Demands	Sources
8.1	The boiler should only work in one direction, namely increasing the temperature at the output.	2.1.1 Heat Pump Principles
8.2	The boiler should not use a reversing valve.	2.1.1 Heat Pump Principles 2.1.2 Components and Functions
8.3	The boiler should avoid the use of geothermal (ground source) heat exchanger technology.	2.1.1 Heat Pump Principles
8.4	The boiler should avoid the use of water source heat exchanger technology.	2.1.1 Heat Pump Principles
8.5	The boiler and heat pump system should be able to withstand the required pressures and temperatures.	2.1.2 Components and Functions
8.6	The boiler should be able to switch between different temperatures.	Client meetings
	Wishes	
8.7	The boiler should avoid the use of solar-assisted heat exchanger technology.	2.1.1 Heat Pump Principles
8.8	The boiler should avoid the hybrid heat pump principle as much as possible.	2.1.1 Heat Pump Principles
8.9	The boiler should have a performance of 2200 Watt.	2.3 Competitor Analysis Client meetings

G - Brazed Plate HE Heat Transfer Area Calculations

SWEP
A DOVER COMPANY

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SE-261 22 Landskrona, Sweden

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CASCADE - DESIGN

SWEP SSP G8 2022.927.1.0

HEAT EXCHANGER: BX8THx16/1P

Date: 04/10/2022

SSP Alias: BX8T

DUTY REQUIREMENTS		**Side 1**		**Side 2**
Fluid		**n-Butane**		**R1234ze(E)**
Flow type				
Circuit		Inner		Outer
Heat load	W		**2240**	
Subcooled liq. temp.	°C			
Inlet vapor quality		**0.332**		**1.000**
Outlet vapor quality		**1.000**		**0.000**
Inlet temperature	°C	65.01		**85.00**
Evaporation temperature (dew)	°C	**70.00**		
Superheating	K	**5.00**		
Condensation temperature (dew)	°C			**80.00**
Subcooling	K			**5.00**
Outlet temperature	°C	75.00		74.95
Flow rate	kg/s	0.01035		0.01777
• Inlet vapor	kg/s	3.437e-3		
Fluid vaporized	kg/s	6.915e-3		
Fluid condensed	kg/s			0.01777
Pressure drop (Design PD)	kPa	1.80 **(50.00)**		2.12 **(50.00)**

PLATE HEAT EXCHANGER		**Side 1**		**Side 2**
Total heat transfer area	m²		0.322	
Heat flux	W/m²		6960	
O.H.T.C. (available/required)	W/m²,°C		617/614	
Pressure drop - total*	kPa	1.80		2.12
- in ports (Inlet/Outlet)	kPa	-0.0138/0.0826		-0.0201/4.91e-3
Pressure drop in fluid distribution	kPa	0.000 - 0.000		
Operating pressure (outlet)	kPa	809		2010
Number of channels per pass		7		8
Number of plates			16	
Oversurfacing	%		0	
Port diameter (up/down)	mm	16.0/16.0		16.0/16.0
Recommended inlet connection diameter	mm	3.07 - 4.85		2.74 - 6.14
Recommended outlet connection diameter	mm	5.14 - 11.5		3.48 - 6.97
Outlet Port velocity	m/s	2.64		
Port velocity	m/s			0.778
Channel velocity	m/s	0.520		0.133
Largest wall temperature difference	K		0.16	
Min./Max. wall temperature	°C	66.85/79.14		66.93/79.18

**Excluding pressure drop in connections.*

PHYSICAL PROPERTIES		**Side 1**	**Side 2**
Reference temperature	°C	67.52	79.98
Liquid • Dynamic viscosity	cP	0.112	0.0988
• Density	kg/m³	526.2	932.1
• Heat capacity	kJ/kg,°C	2.689	1.803
• Thermal conductivity	W/m,°C	0.09055	0.05712
Vapor • Dynamic viscosity	cP	8.71e-3	0.0158
• Density	kg/m³	19.98	120.2
• Heat capacity	kJ/kg,°C	2.175	1.803
• Thermal conductivity	W/m,°C	0.02203	0.02059

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Date: 04/10/2022

Page: 1/2

H - Genetron Properties Suite v1.4.2 Simulation Input Data

Genetron Properties-Cascade Cycle-BUTANE-R1234ZE			
	Parameter	Option	Unit
Description	[--]	[--]	Cascade Cy
INPUT TO SIMULATION			
Evaporator Outlet Superheat	Outlet SuperHeat	[°C]	5
Evaporator Intermediate Heat Ex Evap	Pressure Drop	[bar]	0
Suction Line Temperature Rise	Temperature Rise	[°C]	0
Suction Line Pressure Change	Drop Of Saturation Tempera	[°C]	0
Compressor Isentropic Efficiency	[--]	[--]	0.7
Compressor Volumetric Efficiency	[--]	[--]	0.95
Discharge Line Temperature Change	Temperature Change	[°C]	0
Discharge Line Pressure Change	Drop Of Saturation Tempera	[°C]	0
Condenser Condensing Parameter	Condensing Temperature	[°C]	110
Condenser Temperature Setting	Outlet Subcooling	[°C]	5
Condenser Pressure Setting	Pressure Drop	[bar]	0
Liquid Line Temperature Change	Temperature Change	[°C]	0
Liquid Line Pressure Change	Drop Of Saturation Tempera	[bar]	0
Setting Intermediate Temperatures	Evaporating Temperature	[°C]	70
OVERALL			
GWP	[--]	[--]	4
Heating Capacity	[--]	[W]	2728.96
Cooling Capacity	[--]	[W]	1500
Total Power	[--]	[W]	1229
Cooling COP	[--]	[--]	1.221
Heating COP	[--]	[--]	2.221
EER	[--]	[Btu/W.h]	4.164
Evaporation Temperature for Low Tem	[--]	[°C]	16
Condensation Temperature for High Te	[--]	[°C]	110
HIGH TEMPERATURE (R600)			
PERFORMANCE PARAMETERS			
Refrigerant	[--]	[--]	BUTANE
GWP	[--]	[--]	4
Mass Flow Rate	[--]	[kg/s]	0.01036
Volumetric Cooling Capacity	[--]	[kJ/m³]	3992.971
Volumetric Heating Capacity	[--]	[kJ/m³]	4858.798
Cooling Capacity	[--]	[W]	2242.66
Heating Capacity	[--]	[W]	2728.96
Power	[--]	[W]	486.3
Compressor Isentropic Efficiency	[--]	[--]	0.7
Compressor Volumetric Efficiency	[--]	[--]	0.95
Compressor Displacement	[--]	[m³/s]	0.00056
Cooling COP	[--]	[--]	4.612
Heating COP	[--]	[--]	5.612
EER	[--]	[Btu/W.h]	15.735
HSPF	[--]	[Btu/W.h]	19.147
Subcooling At Expansion Device Inlet	[--]	[°C]	5

Superheat At Evaporator Outlet	[--]	[°C]	5	
Superheat At Compressor Inlet	[--]	[°C]	5	
Cooling Effect	[--]	[kJ/kg]	216.39	
Heating Effect	[--]	[kJ/kg]	263.31	
Condensation Temperature	[--]	[°C]	110	
Evaporation Temperature	[--]	[°C]	70	

EVAPORATOR

			Inlet	Outlet
Temperature	[--]	[°C]	70	75
Pressure	[--]	[bar]	8.09	8.09
Enthalpy	[--]	[kJ/kg]	478.24	694.63
Entropy	[--]	[kJ/kg-K]	1.8656	2.496
Density	[--]	[kg/m³]	55.74	19.42
Quality	[--]	[--]	0.332	1
Saturation Temperature	[--]	[°C]	70	70
Mass Flow Rate	[--]	[kg/s]	0.01036	
Pressure Drop	[--]	[bar]	0	
Capacity	[--]	[W]	2242.66	
Outlet Superheat	[--]	[°C]	5	
Drop Of Saturation Temperature	[--]	[°C]	0	
Evaporator Glide	[--]	[°C]	0	

SUCTION LINE

			Inlet	Outlet
Temperature	[--]	[°C]	75	75
Pressure	[--]	[bar]	8.09	8.09
Enthalpy	[--]	[kJ/kg]	694.63	694.63
Entropy	[--]	[kJ/kg-K]	2.496	2.496
Density	[--]	[kg/m³]	19.42	19.42
Quality	[--]	[--]	1	1
Saturation Temperature	[--]	[°C]	70	70
Mass Flow Rate	[--]	[kg/s]	0.01036	
Pressure Drop In Line	[--]	[bar]	0	
Heat Transfer	[--]	[W]	0	
Drop Of Saturation Temperature	[--]	[°C]	0	
Temperature Change In Line	[--]	[°C]	0	

DISCHARGE LINE

			Inlet	Outlet
Temperature	[--]	[°C]	113.45	113.45
Pressure	[--]	[bar]	18.46	18.46
Enthalpy	[--]	[kJ/kg]	741.55	741.55
Entropy	[--]	[kJ/kg-K]	2.5326	2.5326
Density	[--]	[kg/m³]	47.69	47.69
Quality	[--]	[--]	1	1
Saturation Temperature	[--]	[°C]	110	110
Mass Flow Rate	[--]	[kg/s]	0.01036	
Pressure Drop In Line	[--]	[bar]	0	
Heat Transfer	[--]	[W]	0	

Drop Of Saturation Temperature	[--]	[°C]	0	
Temperature Change In Line	[--]	[°C]	0	

LIQUID LINE

			Inlet	Outlet
Temperature	[--]	[°C]	105	105
Pressure	[--]	[bar]	18.46	18.46
Enthalpy	[--]	[kJ/kg]	478.24	478.24
Entropy	[--]	[kJ/kg-K]	1.8452	1.8452
Density	[--]	[kg/m³]	458.98	458.98
Quality	[--]	[--]	0	0
Saturation Temperature	[--]	[°C]	110	110
Mass Flow Rate	[--]	[kg/s]	0.01036	
Pressure Drop In Line	[--]	[bar]	0	
Heat Transfer	[--]	[W]	0	
Drop Of Saturation Temperature	[--]	[°C]	0	
Temperature Change In Line	[--]	[°C]	0	

COMPRESSOR

			Inlet	Outlet
Temperature	[--]	[°C]	75	113.45
Pressure	[--]	[bar]	8.09	18.46
Enthalpy	[--]	[kJ/kg]	694.63	741.55
Entropy	[--]	[kJ/kg-K]	2.496	2.5326
Density	[--]	[kg/m³]	19.42	47.69
Quality	[--]	[--]	1	1
Saturation Temperature	[--]	[°C]	70	110
Mass Flow Rate	[--]	[kg/s]	0.01036	
Displacement	[--]	[m³/s]	0.00056	
Power Consumption	[--]	[W]	486.3	
Volumetric Efficiency	[--]	[--]	0.95	
Isentropic Efficiency	[--]	[--]	0.7	
Compression Ratio	[--]	[--]	2.2811	

CONDENSER

			Inlet	Outlet
Temperature	[--]	[°C]	113.45	105
Pressure	[--]	[bar]	18.46	18.46
Enthalpy	[--]	[kJ/kg]	741.55	478.24
Entropy	[--]	[kJ/kg-K]	2.5326	1.8452
Density	[--]	[kg/m³]	47.69	458.98
Quality	[--]	[--]	1	0
Saturation Temperature	[--]	[°C]	110	110
Mass Flow Rate	[--]	[kg/s]	0.01036	
Pressure Drop	[--]	[bar]	0	
Capacity	[--]	[W]	2728.96	
Outlet Subcooling	[--]	[°C]	5	
Inlet Superheat	[--]	[°C]	3.45	
Drop Of Saturation Temperature	[--]	[°C]	0	
Condenser Glide	[--]	[°C]	0	

EXPANSION DEVICE

			Inlet	Outlet
Temperature	[--]	[°C]	105	70
Pressure	[--]	[bar]	18.46	8.09
Enthalpy	[--]	[kJ/kg]	478.24	478.24
Entropy	[--]	[kJ/kg-K]	1.8452	1.8656
Density	[--]	[kg/m³]	458.98	55.74
Quality	[--]	[--]	0	0.332
Saturation Temperature	[--]	[°C]	110	70
Mass Flow Rate	[--]	[kg/s]	0.01036	
Pressure Drop	[--]	[bar]	10.36	
Heat Transfer	[--]	[W]	0	

LOW TEMPERATURE (R1234ze(E))

PERFORMANCE PARAMETERS

Refrigerant	[--]	[--]	R1234ZE
GWP	[--]	[--]	1
Mass Flow Rate	[--]	[kg/s]	0.01646
Volumetric Cooling Capacity	[--]	[kJ/m³]	1685.268
Volumetric Heating Capacity	[--]	[kJ/m³]	2519.66
Cooling Capacity	[--]	[W]	1500
Heating Capacity	[--]	[W]	2242.66
Power	[--]	[W]	742.7
Compressor Isentropic Efficiency	[--]	[--]	0.7
Compressor Volumetric Efficiency	[--]	[--]	0.95
Compressor Displacement	[--]	[m³/s]	0.00089
Cooling COP	[--]	[--]	2.02
Heating COP	[--]	[--]	3.02
EER	[--]	[Btu/W.h]	6.891
HSPF	[--]	[Btu/W.h]	10.303
Subcooling At Expansion Device Inlet	[--]	[°C]	5
Superheat At Evaporator Outlet	[--]	[°C]	5
Superheat At Compressor Inlet	[--]	[°C]	5
Cooling Effect	[--]	[kJ/kg]	91.14
Heating Effect	[--]	[kJ/kg]	136.26
Condensation Temperature	[--]	[°C]	80
Evaporation Temperature	[--]	[°C]	16

EVAPORATOR

			Inlet	Outlet
Temperature	[--]	[°C]	16	21
Pressure	[--]	[bar]	3.76	3.76
Enthalpy	[--]	[kJ/kg]	308.49	399.63
Entropy	[--]	[kJ/kg-K]	1.3769	1.6919
Density	[--]	[kg/m³]	39.12	19.47
Quality	[--]	[--]	0.502	1
Saturation Temperature	[--]	[°C]	16	16
Mass Flow Rate	[--]	[kg/s]	0.01646	

Pressure Drop	[--]	[bar]	0	
Capacity	[--]	[W]	1500	
Outlet Superheat	[--]	[°C]	5	
Drop Of Saturation Temperature	[--]	[°C]	0	
Evaporator Glide	[--]	[°C]	0	

SUCTION LINE

			Inlet	Outlet
Temperature	[--]	[°C]	21	21
Pressure	[--]	[bar]	3.76	3.76
Enthalpy	[--]	[kJ/kg]	399.63	399.63
Entropy	[--]	[kJ/kg-K]	1.6919	1.6919
Density	[--]	[kg/m³]	19.47	19.47
Quality	[--]	[--]	1	1
Saturation Temperature	[--]	[°C]	16	16
Mass Flow Rate	[--]	[kg/s]	0.01646	
Pressure Drop In Line	[--]	[bar]	0	
Heat Transfer	[--]	[W]	0	
Drop Of Saturation Temperature	[--]	[°C]	0	
Temperature Change In Line	[--]	[°C]	0	

DISCHARGE LINE

			Inlet	Outlet
Temperature	[--]	[°C]	92.29	92.29
Pressure	[--]	[bar]	20.08	20.08
Enthalpy	[--]	[kJ/kg]	444.75	444.75
Entropy	[--]	[kJ/kg-K]	1.7295	1.7295
Density	[--]	[kg/m³]	105.57	105.57
Quality	[--]	[--]	1	1
Saturation Temperature	[--]	[°C]	80	80
Mass Flow Rate	[--]	[kg/s]	0.01646	
Pressure Drop In Line	[--]	[bar]	0	
Heat Transfer	[--]	[W]	0	
Drop Of Saturation Temperature	[--]	[°C]	0	
Temperature Change In Line	[--]	[°C]	0	

LIQUID LINE

			Inlet	Outlet
Temperature	[--]	[°C]	75	75
Pressure	[--]	[bar]	20.08	20.08
Enthalpy	[--]	[kJ/kg]	308.49	308.49
Entropy	[--]	[kJ/kg-K]	1.3443	1.3443
Density	[--]	[kg/m³]	964.43	964.43
Quality	[--]	[--]	0	0
Saturation Temperature	[--]	[°C]	80	80
Mass Flow Rate	[--]	[kg/s]	0.01646	
Pressure Drop In Line	[--]	[bar]	0	
Heat Transfer	[--]	[W]	0	
Drop Of Saturation Temperature	[--]	[°C]	0	
Temperature Change In Line	[--]	[°C]	0	

COMPRESSOR

			Inlet	Outlet
Temperature	[--]	[°C]	21	92.29
Pressure	[--]	[bar]	3.76	20.08
Enthalpy	[--]	[kJ/kg]	399.63	444.75
Entropy	[--]	[kJ/kg-K]	1.6919	1.7295
Density	[--]	[kg/m³]	19.47	105.57
Quality	[--]	[--]	1	1
Saturation Temperature	[--]	[°C]	16	80
Mass Flow Rate	[--]	[kg/s]	0.01646	
Displacement	[--]	[m³/s]	0.00089	
Power Consumption	[--]	[W]	742.7	
Volumetric Efficiency	[--]	[--]	0.95	
Isentropic Efficiency	[--]	[--]	0.7	
Compression Ratio	[--]	[--]	5.337	

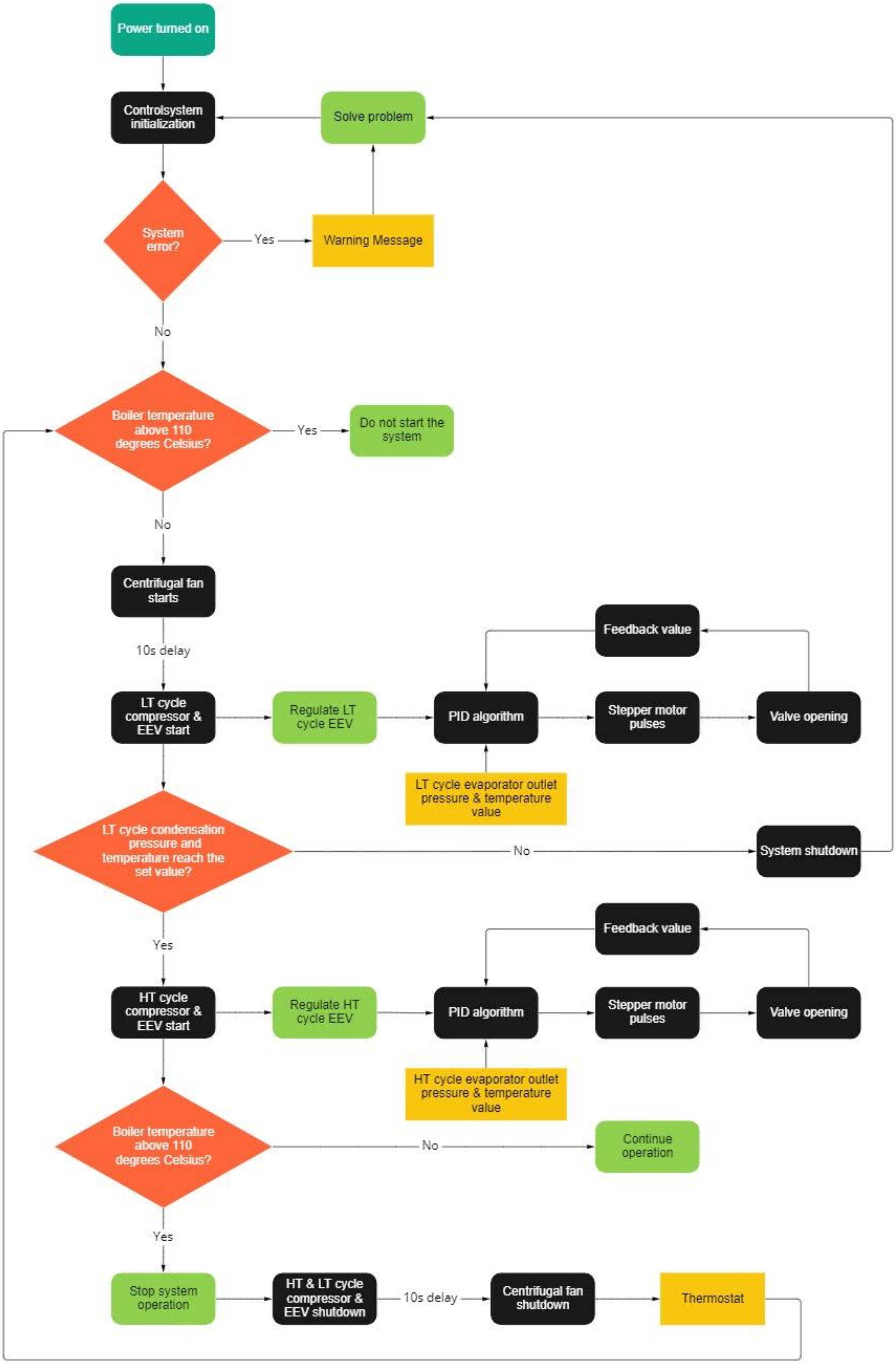
CONDENSER

			Inlet	Outlet
Temperature	[--]	[°C]	92.29	75
Pressure	[--]	[bar]	20.08	20.08
Enthalpy	[--]	[kJ/kg]	444.75	308.49
Entropy	[--]	[kJ/kg-K]	1.7295	1.3443
Density	[--]	[kg/m³]	105.57	964.43
Quality	[--]	[--]	1	0
Saturation Temperature	[--]	[°C]	80	80
Mass Flow Rate	[--]	[kg/s]	0.01646	
Pressure Drop	[--]	[bar]	0	
Capacity	[--]	[W]	2242.66	
Outlet Subcooling	[--]	[°C]	5	
Inlet Superheat	[--]	[°C]	12.29	
Drop Of Saturation Temperature	[--]	[°C]	0	
Condenser Glide	[--]	[°C]	0	

EXPANSION DEVICE

			Inlet	Outlet
Temperature	[--]	[°C]	75	16
Pressure	[--]	[bar]	20.08	3.76
Enthalpy	[--]	[kJ/kg]	308.49	308.49
Entropy	[--]	[kJ/kg-K]	1.3443	1.3769
Density	[--]	[kg/m³]	964.43	39.12
Quality	[--]	[--]	0	0.502
Saturation Temperature	[--]	[°C]	80	16
Mass Flow Rate	[--]	[kg/s]	0.01646	
Pressure Drop	[--]	[bar]	16.32	
Heat Transfer	[--]	[W]	0	

I - Cascade Heat Pump Control Structure



J - Risk Inventory and Evaluation

University of Twente
Laboratory of Thermal Engineering,

Risk Inventory & Evaluation:

Cascade Heat Pump System

Correspondence:

Joost J.F. Bessembinder
J.J.F.Bessembinder@student.utwente.nl

July, 2022

Overview of research

Type of document: RI&E of Experimental set-up

Period

Start date of research: February, 2022

End date of research: October, 2022

Involved persons

	Name	**Signature**
Research group/Study	*Industrial Design Engineering*	
Responsible person	*Joost J.F. Bessembinder*	
UT Supervisor	*Davoud Jafari*	
Assistent Supervisor	*Abishek K. Singh*	
Company Supervisor	*Marco van Rooijen*	
VMM	*Henk-Jan Moed*	

Type of research: Graduation Research, Master Thesis

Name of set-up/experiment

Cascade Heat Pump Water Boiler

Research data

Pressure: *max. 20 bar*
Temperature: *110ºC*
Dimensions of the setup: *700 (l) x 400 (d) x 350 (h) mm*
Type of substances: *water, n-butane (R-600), Solstice® ze (R-1234ze(E))*
Type of research: *moderately high temperature experiment*

Location of the set-up

Thermal Engineering Laboratory: Kleinhorst

Contents

1 Research Project Description

Introduction and aims of the research topic

The ever increasing concern of climate change and the decreasing reserve of fossil fuel, together with increasing energy demand around the world, put a high pressure in the energy sectors to provide sustainable and green energy solutions. One of the systems that is currently being implemented is the heat pump. Heat pump systems are mechanical devices that use refrigerants to extract thermal energy from a low temperature heat source and increase it to a higher temperature through vapor compression. These devices are now mainly being used for heating and cooling of buildings and in the industrial sector they are also used to collect the thermal energy from waste heat so it can be put back into processes to increase the temperature in a more energy-efficient way.

Compared to the residential sector, in industry there are already many more processes in which the heat pump principle is applied. This is why research was done to also find possible applications for heat pump technology in household devices. This is the reason for the development of the cascade heat pump water boiler.

To be able to test the water boiler heat pump system and to check if the calculated theoretical values are the same as in the real life situation, a prototype is build. With this prototype the main goal is to check if it is possible to heat up water from a temperature of 16 degrees Celsius to a temperature of 110 degrees Celsius. Secondly, if the system is able to achieve this, the coefficient of performance also needs to be calculated, to see how efficient the device is. And finally, if the system does not cohere with the expected efficiency, the pressure and temperature sensors are used to find out where the system can be optimized and improved.

Experimental Process

The experiment is carried out in the thermal engineering lab at the Kleinhorst. The area the experimental setup will occupy is roughly 700 mm in length and 400 mm in depth. And the height of the tallest component is about 350 mm. The system will be powered by electricity, which turns the electric motors, that power the compressors and electronic expansion valves. To be able to control the systems heating capacity, temperature and pressure sensors are installed at various places inside the system. With this data, the required movement of the components can be determined and the heating capacity can be regulated.

The system is operated in a temperature range of 16 °C to 110 °C and consists of two cycles which are both filled with a substance called a refrigerant. At room temperature and under normal atmospheric pressure the refrigerant is a vapor. In this way, due to isentropic compression, the temperature of the substances can be increased. The lower temperature cycle is filled with a substance called Solstice® ze and the higher temperature cycle is filled with n-butane. And, by installing a heat exchanger between the two cycles, the thermal energy from one cycle can be transferred to the other. By using this kind of cascaded system, the required maximum pressure is reduced, which in turn reduces the total amount of required compressor power and this should increase the overall coefficient of performance (COP) of the system.

Experimental setup

The system configuration of the cascade heat pump can be found in figure 1, with the explanation of the units noted down to the left of it. Figure 2 shows a schematic overview of the experimental setup of the system prototype, together with a list that corresponds to the component types and numbers. And figure 3 and 4 show the system layout, to give an idea of how the components are configured in the lab.

HT = High Temperature cycle
LT = Low Temperature cycle
$\dot{Q}_e$ (Watt) = evaporator input thermal energy
$\dot{Q}_{IHE}$ (Watt) = internal heat exchanger thermal energy
$\dot{Q}_c$ (Watt) = condenser output power
T_{IHE} (Celsius) = internal heat exchanger temperature
W_1 (Watt) = LT compressor work
W_2 (Watt) = HT compressor work
P_1 (bar) = LT compressor pressure
P_2 (bar) = HT compressor pressure
$\dot{m}_1$ (kg/s) = LT mass flowrate
$\dot{m}_2$ (kg/s) = HT mass flowrate
$\dot{V}_1$ (m^3/s) = LT volumetric flowrate
$\dot{V}_2$ (m^3/s) = HT volumetric flowrate
H (J/kg) = enthalpy
COP = coefficient of performance

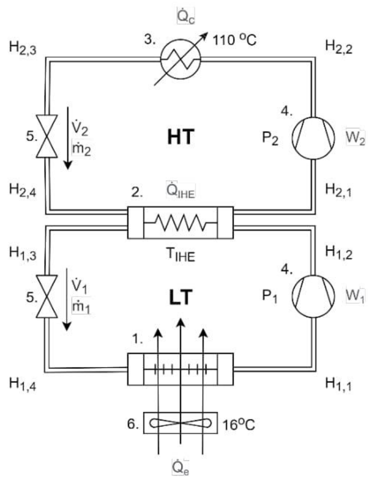


Figure 1 Multi-stage (cascade) heat pump system

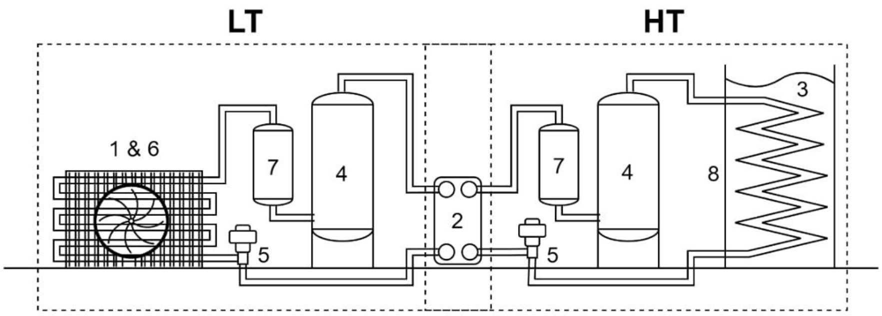


Figure 2 Schematic overview of the prototype set-up

1. *Fin and tube heat exchanger*
2. *Plate heat exchanger*
3. *Coil heat exchanger*
4. *Rotary compressor*
5. *Electronic expansion valve*
6. *Centrifugal fan*
7. *Liquid suction accumulator*
8. *Water tank*

Figure 3 Prototype system layout, side view

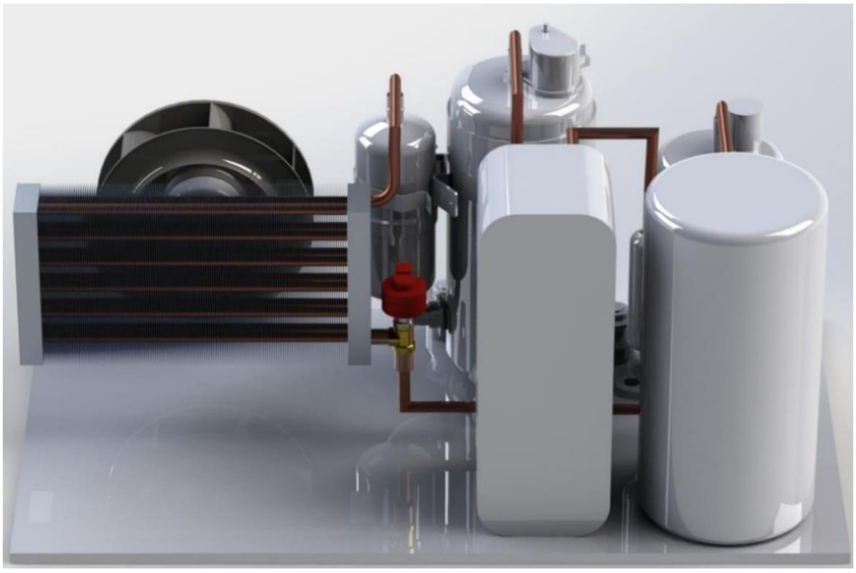


Figure 4 Prototype system layout, front view

2 Manual

Following are the procedures to be followed for the preparation of the experiment, performance of experiment and for the shut down at the completion of experiment. These manuals are available at the experimental setup and must be checked.

Preparation Procedure

After the prototype has been assembled and before it can be tested, the system first needs to be prepared. When the preparation phase is finished, the system can be tested and finally it can be optimized where needed.

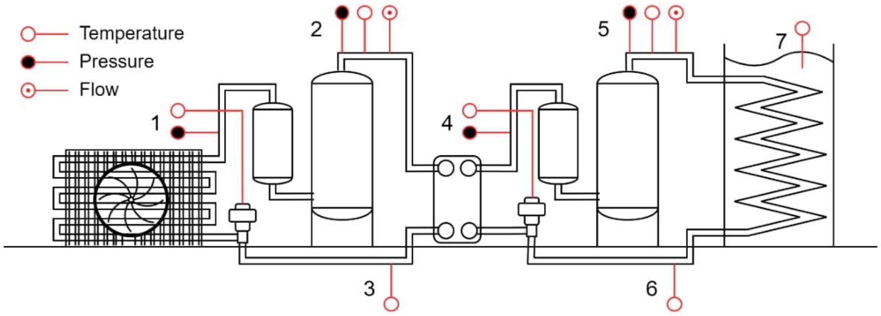


Figure 5 Sensor Placement overview

Action	***Procedure***
1.1	*If the set-up is not clean, cleaning should be done before performing the preparation.*
1.2	*Connect a vacuum pump and pull the system vacuum to get rid of air and other unwanted fluids in the system (repeat for each individual cycle).*
1.3	*Connect a nitrogen tank and open the main supply line to fill the system with nitrogen gas to check if the system does not contain any leaking parts (repeat for each individual cycle).*
1.4	*Connect the vacuum pump again and pull the system vacuum to get rid of the unwanted nitrogen and to prepare the system for the refrigerant filling (repeat for each individual cycle).*
1.5	*Connect the* Solstice® *ze tank to the lower temperature cycle and connect the n-butane tank to the higher temperature cycle and open the main supply line to load the refrigerants into the system.*
1.6	*Place the sensors at the indicated locations (see figure 5) and connect them to the datalogger to be able to retrieve temperature and pressure data within the system.*
1.7	*Connect the control equipment to the sensors and the electric motors to manage the movements of the components (compressors, electronic expansion valves and centrifugal fan) within the system.*
1.8	*Weigh the refrigerants amount before conducting the experiment.*
1.9	*Switch on the laboratory ventilation system before conducting the experiment*
1.10	*Fill the tank with water and completely submerge the helical coil heat exchanger.*

Procedure to Perform Experiment

If the preparation procedures are followed, the setup is ready for the experiment.

Action	*Procedure*
2.1	*If the set-up is not clean, cleaning should be done before performing the experiment.*
2.2	*First check if all the components are connected the right way.*
2.3	*Measure the temperature of the water in the tank and note it down.*
2.4	*Switch on the centrifugal fan.*
2.5	*Switch on the control system to simultaneously start the compressors and electronic expansion valves.*
2.6	*While the system is running, start the stop-watch for analysis of the experimental results afterwards.*
2.7	*Use the data logger to start retrieving the temperature and pressure data during the experiment.*
2.8	*Start the shutdown procedure when water is boiling.*

Shut Down Procedure

Operator should always be present at the setup during the experimental run. To take appropriate action in case of emergency see: 'Emergency Shutdown Procedure'.

Action	*Procedure*
3.1	*Switch off the compressors, stop the time and write down the time of the experiment.*
3.2	*Switch off the centrifugal fan.*
3.3	*Stop the data logger and make a copy of the retrieved data.*
3.4	*Switch off the laboratory ventilation system.*
3.5	*Clean the setup and surroundings before leaving the lab, cleaning should be done after performing an experiment.*

Emergency Shutdown Procedure

In case of an emergency an immediate shutdown of the experiment may be required. The cause of the emergency could be the leakage of refrigerant gas due to a loose connection or a broken part. In this case the following steps should be performed:

- *Press the emergency shut down button. The emergency shut down button will stop the electricity to the setup and will switch off the electricity to the following equipment:*
    - *Control system*
    - *Compressors (2x)*
    - *Electronic expansion valves (2x)*
    - *Centrifugal fan*
- *Items that are still running after emergency shut down are,*
    - *Data logger*
    - *Power to the computer will be on for problem analysis.*

- *If there are other people around you in the lab, inform them about the accident so that they are ready to take appropriate action if needed.*
- *Once the system has shut off and cooled down to room temperature, try to figure out the problem and take necessary steps to eliminate the error.*

To start the setup after the emergency shutdown, press the reset button to turn on electrical power to the set up again and then normal procedures should be followed to prepare and continue with conducting the experiment.

Hardware Safety

High Temperature Shutdown*: The highest temperature point is located at the discharge port of the compressor, where the high pressure refrigerant leaves the compression chamber.*

- *The highest temperature point in the lower temperature cycle is located at the discharge port of the lower temperature cycle compressor, where the high pressure Solstice® ze leaves the compression chamber. The temperature measured there should be between 70-80 ºC. A temperature sensor is attached to the tube located at the discharge port and the temperature output is fed to a safety switch that turns off the power to the setup in case the temperature exceeds the limit. The temperature limit is set to 80 ºC, that is the allowable max. temperature.*
- *The highest temperature point in the higher temperature cycle is located at the discharge port of the higher temperature cycle compressor, where the high pressure n-butane leaves the compression chamber. The temperature measured there should be between 100-120 ºC. A temperature sensor is attached to the tube located at the discharge port and the temperature output is fed to a safety switch that turns off the power to the setup in case the temperature exceeds the limit. The temperature limit is set to 120 ºC, that is the allowable max. temperature.*

High Pressure Shutdown: *The highest pressure point is located at the discharge port of the compressor, where the high temperature refrigerant leaves the compression chamber.*

- *The highest pressure point in the lower temperature cycle is located at the discharge port of the lower temperature cycle compressor, where the medium temperature Solstice® ze leaves the compression chamber. The pressure measured there should be around 16.1 bar. A pressure sensor is attached to the tube located at the discharge port and the pressure output is fed to a safety switch that turns off the power to the setup in case the pressure exceeds the limit. The pressure limit is set to 21 bar, that is the allowable max. pressure.*
- *The highest pressure point in the higher temperature cycle is located at the discharge port of the higher temperature cycle compressor, where the high temperature n-butane leaves the compression chamber. The pressure measured there should be around 18.5 bar. A pressure sensor is attached to the tube located at the discharge port and the pressure output is fed to a safety switch that turns off the power to the setup in case the pressure exceeds the limit. The pressure limit is set to 25 bar, that is the allowable max. pressure.*

Emergency Shutdown Button: *An emergency shutdown button has been placed beside the setup to stop the experiment in case of emergency.*

3 Risk Inventory and Evaluation Overview

This chapter presents an overview of different aspects that have an influence on the safety of the experimental work, the researcher and the setup.

a. Substances

The following substances will be used:

- Solstice® ze (R-1234ze(E)): trans-1,3,3,3- tetrafluoroprop-1-ene
- n-Butane (R-600)
- Water
- Nitrogen (used only during the preparation, to check for leaks)
- Lubricating oils (to be determined)

b. Chemical Reaction

No chemical reactions should occur during the process.

c. Mechanical Protection

Hot surfaces are protected with insulation.

d. Detection

Pressure sensors are used to monitor the pressure levels inside the system. And smoke detectors are installed in the lab which give an automatic alarm to BHV and fire department (Brandweer) when the smoke is detected.

Process parameters

During experiments the system temperature ranges between 100 ºC to 120 ºC and the corresponding pressure will roughly be around 20 bar. The process conditions i.e temperature = 110ºC will not exceed the maximum working temperature of the system. The system pipes will be made of copper and the heat exchanger and compressor chambers are made of stainless steel 316, both materials can withstand high temperatures. The experimental program may be adjusted as required by the experimental condition but will remain below the maximum working temperature of the system (that is 120 ºC), because the risk of the lubrication oils degrading above this temperature is too high. And when some components are not properly lubricated, this may result in a collapse of some parts of the setup and the release of refrigerant gas.

e. Potential risks

The potential risks which can occur during experiments are mapped out in this section. At the connection points between the components there are parts that are connected with a screw connection. Even though the system is coupled very carefully, the joints could be potential points for leakage of refrigerant gas. In the next sections, the precautions are listed to avoid the leakage and to handle the leakage once it occurs.

f. Precaution measures, Safety instruments

Here are the preventions and safety measures listed to avoid the leakage and to handle the leakage once it has occurred.

- Operator should always be present at the setup during the operation.

- During the experiments, furnace hand gloves and safety goggles will be available. Also a fire extinguisher will be available in hand range. A fire blanket and an emergency water shower are also available in the laboratory.

- The experimental set up is placed in the laboratory of thermal engineering (Kleinhorst) of the faculty of science technology, University of Twente.

g. Operation

The subjects:

- Preparation
- Performing experiments
- Shut down procedure

h. Maintenance and reparations of the set-up

1. Qualified personnel of the thermal engineering group will do reparations of the setup.
2. After any significant reparation, an adequate testing of the setup will be done.
3. If changes are made on the setup, the change will be documented and presented in this document.

i. Safety regulations

As far as we know all valid safety regulations have been consulted and followed.

j. Documentation Available documentation:

A copy of this report "Risk Inventory & Evaluation: Cascade Heat Pump System", including:

- Instruction on the emergency shutdown procedure
- Flowsheet of the setup
- HAZOP

4 Organization of Work Place

a. Ergonomics

1. Work space dimensions are: 700mm x 400 mm x 350 mm. (L x W x H)
2. General requirements:
    - Daylight is present or adequate lighting is installed at the ceiling
    - eye goggles and furnace hand gloves are made available
    - floors do fulfil the requirements
    - ventilation of the work space is provided
    - gas detectors are installed
    - there are several grounded electrical power connections
    - The source of warm and cold water is provided in the laboratory.
    - Emergency water shower is present in the laboratory
    - Fire blanket and a fire extinguisher are also present in the laboratory
    - first aid supplies are also present in the laboratory

b. Technical requirements

1. The set-up is placed in an adequately ventilated section of the laboratory
2. Operation of the set-up is clear and the set-up is well accessible.
3. Regular inspection of workspace and set-up is done.

c. Personal protection

1. During the experimental work, personal protection is provided by:
    - safety glasses
    - adequate protection gloves
2. Adequate ventilation (from the roof and point ventilation) is provided to prevent accumulation of gases inside the working space.

d. Safety requirements

1. The following safety items are provided in or close to the work place:
    - fire alarm in the laboratory and corridor
    - fire extinguishers
    - fire blanket
    - two escape exits for the case of emergency
    - first aid kit in a room close to the lab
    - emergency shower in the right corner near the second entrance
2. Safety signs
    - Warning lights at all entrances to the laboratory
    - signs: “safety glasses required”, “no fire”
    - indications concerning the escape routes
    - indications about who to inform in the case of an accident
    - no indications on the presence or absence of people
3. Organization of the place of work
    - indications about location of the First Aid Kit and safety showers

e. Safe Operation

1. Operation of apparatus according to protocols and measurement plan.
2. Controlled presence of people and access to laboratory in operation.
3. Clear view of tasks and responsibilities.
4. Emergency Plan available and trained to handle calamities.

f. Skilled personnel

There is skilled person present at the laboratory able to:

1. Perform any reparation on the setup,
2. Refill the system
3. Repair electrical connections,
4. Give technical assistance.

g. Documentation provided at the setup?

Yes

5 HAZOP (Hazard and Operability) Study

The HAZOP study is presented in this section, in table 1. It consists of analyzing potential deviations of the process parameters.

Table 1. Analysis of the process parameter deviations

Keyword	Parameter	Possible causes	Consequences	Safeguard	Action required
More	*Temperature*	- Temperature sensor malfunction - To high compressor motor speed - Wrong expansion valve opening distance	- Lubricating oil degradation - Motor winding overheating - Failure/breakdown of compressor - Increased fire hazard	High temperature shutdown	• Make sure the system has shut down • Let the system cool down • Repair or replace the necessary components
Less	*Temperature*	• Temperature sensor malfunction • To low compressor motor speed • Wrong expansion valve opening distance	• Decreased heating capacity	None	• Stop the experiment • Repair or replace the necessary components
Other than	*Temperature*	Fire	• Damage to setup • Possible skin burn	High temperature shutdown	• Hit emergency button, run away, press fire alarm • Extinguish if possible

Keyword	Parameter	Possible causes	Consequences	Safeguard	Action required
More	*Pressure*	• To high compressor motor speed • Wrong expansion valve opening distance • System blockage	• Damage to setup • Leakage	• High pressure shutdown • Pressure safety valve • Burst plate	• Make sure the system has shut down • Let the system pressure settle down or open the safety valve • Repair or replace the necessary components
Less	*Pressure*	• To low compressor motor speed • Wrong expansion valve opening distance • System leakage	• Decreased heating capacity	None	• Adjust compressor motor speed or valve opening distance • Repair place of leakage
Other than	*Pressure*	Ignition of flammable vapors	• Damage to setup • Damage to lab • Possible skin burn	• High pressure shutdown • High temperature shutdown	• Hit emergency button, run away, press fire alarm • Extinguish if possible
More	*Electricity*	• Short circuit • Power supply malfunction • Wrong wire connection	• Damage to system components • Overheating	Electricity shutdown	• Stop the experiment • Look for the error • Repair or replace component
Less	*Electricity*	• Short circuit • Power supply malfunction • Wrong wire connection • Overload	System components not working properly	Emergency shutdown button	• Stop the experiment • Look for the error • Repair or replace component

Keyword	Parameter	Possible causes	Consequences	Safeguard	Action required
No	*Electricity*	• Short circuit • Power supply malfunction • Wrong wire connection • Overload	System shuts down	None	• Look for the error • Repair or replace component
More	*Refrigerant flow*	• Expansion valve opening to big • To high compressor motor speed	To high heating capacity	High temperature shutdown	• Manually turn off the system • Find out what causes the increased flow
Less	*Refrigerant flow*	• System blockage • Filling, expansion or safety valve malfunction • To low compressor motor speed	Decreased heating capacity	None	• Manually turn off the system • Find out what causes the decreased flow
Other than	*Refrigerant flow*	• System leakage • Filling or safety valve malfunction	Contamination	None	• In case of pressure loss, shutdown the system • Clean the system • Repair or replace the necessary components • Refill the system
No	*Refrigerant flow*	• System blockage • System electronic shutdown • Compressor motor drive not working • Expansion valve closed	• System not working • Pressure build up	High pressure shutdown	• Let the system pressure settle down or open the safety valve • Remove blockage, repair or replace the necessary components

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Keyword	Parameter	Possible causes	Consequences	Safeguard	Action required
More	*Air flow*	Centrifugal fan motor speed to high	Incorrect superheat	None	Reduce centrifugal fan motor speed
Less	*Air flow*	Centrifugal fan motor speed to low	To low superheat	None	Increase centrifugal fan motor speed
No	*Air flow*	• Centrifugal fan motor not working • Heat exchanger fin blockage	• To low superheat • Decreased heating capacity	None	Remove blockage, repair or replace centrifugal fan
No	*Venting*	Ventilation system not turned on or not working	No ventilation around the setup	None	Stop the experiment
Early	*Data collection*	- Data logger starting to early - Data logger ending to early	Missing data	None	- Remove data points from before the start of the experiment - In case of incomplete dataset, restart the experiment
Late	*Data collection*	- Data logger starting to late - Data logger ending to late	Missing data	None	- Remove data points from after the end of the experiment - In case of incomplete dataset, restart the experiment
No	*Data collection*	- Data logger not working - Incorrect wiring or sensor connections	Missing data	None	Make sure datalogger is working and restart the experiment

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6 Appendix A: Material Safety Data Sheets

Datasheets are included for the following liquids in this order:

- Solstice® ze (R-1234ze(E))
- n-Butane (R-600)

Sources:

Solstice® ze (R-1234ze) | European Refrigerants (honeywell-refrigerants.com)

n-Butane 2.5 Chemical | Netherlands Industrial Gas Store (linde-gas.nl)

SECTION 1. IDENTIFICATION

Product name	:	Solstice® ZE Refrigerant (R-1234ze(E))
Number	:	000000016095
Product Use Description	:	Refrigerant
Manufacturer or supplier's details	:	Honeywell International Inc. 115 Tabor Road Morris Plains, NJ 07950-2546
For more information call	:	800-522-8001 +1-973-455-6300 (Monday-Friday, 9:00am-5:00pm)
In case of emergency call	:	**Medical: 1-800-498-5701 or +1-303-389-1414**
	:	**Transportation (CHEMTREC): 1-800-424-9300 or +1-703-527-3887**
	:	
	:	(24 hours/day, 7 days/week)

SECTION 2. HAZARDS IDENTIFICATION

Emergency Overview

Form	:	Liquefied gas
Color	:	colourless
Odor	:	slight ether-like

Classification of the substance or mixture

Classification of the substance or mixture	:	Gases under pressure, Liquefied gas Simple Asphyxiant

GHS Label elements, including precautionary statements

Symbol(s)	:	
Signal word	:	Warning
Hazard statements	:	Contains gas under pressure; may explode if heated. May displace oxygen and cause rapid suffocation.
Precautionary statements	:	**Prevention:** Use personal protective equipment as required. **Storage:** Protect from sunlight. Store in a well-ventilated place.

Carcinogenicity

No component of this product present at levels greater than or equal to 0.1% is identified as a known or anticipated carcinogen by NTP, IARC, or OSHA.

SECTION 3. COMPOSITION/INFORMATION ON INGREDIENTS

Chemical nature : Substance

Chemical name	CAS-No.	Concentration
trans-1,3,3,3-Tetrafluoroprop-1-ene	29118-24-9	100.00 %

SECTION 4. FIRST AID MEASURES

Inhalation	:	Remove to fresh air. If breathing is irregular or stopped, administer artificial respiration. Use oxygen as required, provided a qualified operator is present. Call a physician.
Skin contact	:	Rapid evaporation of the liquid may cause frostbite. If there is evidence of frostbite, bathe (do not rub) with lukewarm (not hot) water. If water is not available, cover with a clean, soft cloth or similar covering. Call a physician if irritation develops or persists.
Eye contact	:	Rinse immediately with plenty of water, also under the eyelids, for at least 15 minutes. In case of frostbite water should be lukewarm, not hot. If symptoms persist, call a physician.
Ingestion	:	Unlikely route of exposure. As this product is a gas, refer to the inhalation section. Do not induce vomiting without medical advice. Call a physician immediately.

Notes to physician

Indication of immediate medical attention and special treatment needed, if necessary	:	Treat frost-bitten areas as needed.

SECTION 5. FIREFIGHTING MEASURES

Suitable extinguishing media	:	Use extinguishing measures that are appropriate to local circumstances and the surrounding environment. Water mist Dry powder Foam Carbon dioxide (CO2)
Specific hazards during firefighting	:	Contents under pressure. Heating will cause pressure rise with risk of bursting Cool closed containers exposed to fire with water spray. Product is not combustible under normal conditions.

However, this material can ignite when mixed with air under pressure and exposed to strong ignition sources.
Do not allow run-off from fire fighting to enter drains or water courses.
Vapours are heavier than air and can cause suffocation by reducing oxygen available for breathing.
Some risk may be expected of corrosive and toxic decomposition products.
Fire may cause evolution of:
Hydrogen fluoride
Carbon oxides
Carbonyl halides
Halogenated compounds

Special protective equipment for firefighters	:	In the event of fire and/or explosion do not breathe fumes. Wear self-contained breathing apparatus and protective suit. No unprotected exposed skin areas. Exposure to decomposition products may be a hazard to health.

SECTION 6. ACCIDENTAL RELEASE MEASURES

Personal precautions, protective equipment and emergency procedures	:	Immediately evacuate personnel to safe areas. Keep people away from and upwind of spill/leak. Wear personal protective equipment. Unprotected persons must be kept away. Remove all sources of ignition. Avoid skin contact with leaking liquid (danger of frostbite). Ventilate the area. After release, disperses into the air. Vapours are heavier than air and can cause suffocation by reducing oxygen available for breathing. Avoid accumulation of vapours in low areas. Unprotected personnel should not return until air has been tested and determined safe.
Environmental precautions	:	Prevent further leakage or spillage if safe to do so. The product evapourates readily. Prevent spreading over a wide area (e.g. by containment or oil barriers).

Methods and materials for containment and cleaning up	:	Do not direct water spray at the point of leakage. Allow to evaporate.

SECTION 7. HANDLING AND STORAGE

Handling

Precautions for safe handling	:	Handle with care. Avoid inhalation of vapour or mist. Do not get in eyes, on skin, or on clothing. Wear personal protective equipment. Pressurized container. Protect from sunlight and do not expose to temperatures exceeding 50 °C. Follow all standard safety precautions for handling and use of compressed gas cylinders. Use authorized cylinders only. Protect cylinders from physical damage. Do not puncture or drop cylinders, expose them to open flame or excessive heat. Do not pierce or burn, even after use. Do not spray on a naked flame or any incandescent material. Do not remove screw cap until immediately ready for use. Always replace cap after use.
Advice on protection against fire and explosion	:	Do not spray on a naked flame or any incandescent material. Keep away from direct sunlight. Fire or intense heat may cause violent rupture of packages. Vapours may form explosive mixtures with air. The product is not easily combustible.

Storage

Conditions for safe storage, including any incompatibilities	:	Keep containers tightly closed in a cool, well-ventilated place. Keep away from direct sunlight. Protect cylinders from physical damage. Store away from incompatible substances.
Further information on storage conditions	:	Keep only in the original container at temperature not exceeding 50°C

Advice on common storage : Do not store together with:
Oxidizing agents

SECTION 8. EXPOSURE CONTROLS/PERSONAL PROTECTION

Protective measures : Do not breathe vapour.
Avoid contact with skin, eyes and clothing.
Ensure that eyewash stations and safety showers are close to the workstation location.

Engineering measures : Local exhaust

Eye protection : Goggles

Hand protection : Protective gloves

Skin and body protection : Impervious clothing
Wear cold insulating gloves/ face shield/ eye protection.

Respiratory protection : In case of insufficient ventilation wear suitable respiratory equipment.
Wear a positive-pressure supplied-air respirator.

Hygiene measures : Avoid breathing vapours, mist or gas.
Keep working clothes separately.

Exposure Guidelines

Components	CAS-No.	Value	Control parameters	Update	Basis
trans-1,3,3,3-Tetrafluoroprop-1-ene	29118-24-9	TWA : Time weighted average	(800 ppm)	2012	WEEL:US. OARS. WEELs Workplace Environmental Exposure Level Guide

trans-1,3,3,3-Tetrafluoroprop-1-ene	29118-24-9	TWA : Time weighted average	(800 ppm)	31.03.11	Honeywell:Limit established by Honeywell International Inc.

SECTION 9. PHYSICAL AND CHEMICAL PROPERTIES

Physical state : Liquefied gas

Color : colourless

Odor : slight ether-like

pH : Note: neutral

Boiling point/boiling range : -19 °C

Flash point : Note: Not applicable

Lower explosion limit : Note: No LEL and UEL was assigned at standard testing conditions, 20°C., Exhibits flame limits at temperatures in excess of 28˚ C.

Upper explosion limit : Note: No LEL and UEL was assigned at standard testing conditions, 20°C., Exhibits flame limits at temperatures in excess of 28˚ C.

Vapor pressure : 4,271 hPa
at 20 °C(68 °F)
11,152 hPa
at 54.4 °C(129.9 °F)

Vapor density : 4 Note: (Air = 1.0)

Density	:	1.17 g/cm3 at 21.1 °C
Water solubility	:	0.373 g/l
Partition coefficient: n-octanol/water	:	log Pow: 1.6
Ignition temperature	:	368 °C Method: Auto-ignition temperature

SECTION 10. STABILITY AND REACTIVITY

Chemical stability	:	Stable under normal conditions.
Possibility of hazardous reactions	:	Hazardous polymerisation does not occur.
Conditions to avoid	:	Pressurized container. Protect from sunlight and do not expose to temperatures exceeding 50 °C. Can form a combustible mixture with air at pressures above atmospheric pressure. Do not mix with oxygen or air above atmospheric pressure.
Incompatible materials	:	Reactions with alkali metals.
Hazardous decomposition products	:	Halogenated compounds Carbon oxides Hydrogen fluoride Carbonyl halides

SECTION 11. TOXICOLOGICAL INFORMATION

Acute oral toxicity	: Note: Not applicable study technically not feasible
Acute inhalation toxicity	: Species: Mouse Note: Acute (4-Hour) Inhalation Toxicity Screening Study (mouse): No lethality at >100,000 ppm.
	: LC50: > 207000 ppm Exposure time: 4 h Species: Rat
Acute dermal toxicity	: Note: no data available study technically not feasible
Skin irritation	: Species: Rabbit Result: No skin irritation Method: OECD Test Guideline 404
Eye irritation	: Note: no data available study technically not feasible
Sensitisation	: Cardiac sensitization Species: dogs Result: Did not cause sensitisation on laboratory animals.
	: Species: human Result: Does not cause skin sensitisation.
Repeated dose toxicity	: Species: Rat Application Route: Inhalation Exposure time: 13 Weeks Note: Causes mild effects on the heart. NOEL 5,000 ppm

Genotoxicity in vitro	:	Test Method: Chromosome aberration test in vitro Cell type: Human lymphocytes Result: negative Method: OECD Test Guideline 473
	:	Test Method: Ames test Result: negative
Genotoxicity in vivo	:	Test Method: Mutagenicity (in vivo mammalian bone-marrow cytogenetic test, chromosomal analysis) Species: Mouse Cell type: Micronucleus Application Route: Inhalation Method: OECD Test Guideline 474 Result: negative
Reproductive toxicity	:	Test Method: Two-generation study Species: Rat Application Route: Inhalation NOEL: > 20,000 ppm NOEL: > 20,000 ppm Method: OECD Test Guideline 416
Teratogenicity	:	Species: Rabbit Method: OECD 416 Note: Did not show teratogenic effects in animal experiments.
	:	Species: Rat Method: OECD 416 Note: Did not show teratogenic effects in animal experiments.
Teratogenicity	:	Species: RatApplication Route: Inhalation NOAEC: 15,000 ppm Method: OECD Test Guideline 414
Further information	:	Note: Excessive exposure may cause central nervous system effects including drowsiness and dizziness. Excessive exposure may also cause cardiac arrhythmia. Rapid

evaporation of the liquid may cause frostbite.

SECTION 12. ECOLOGICAL INFORMATION

Ecotoxicity effects

Toxicity to fish	: static test LC0: > 117 mg/l Exposure time: 96 h Species: Cyprinus carpio (Carp) Method: OECD Test Guideline 203
Toxicity to daphnia and other aquatic invertebrates	: static test EC50: > 160 mg/l Exposure time: 48 h Species: Daphnia magna (Water flea) Method: OECD Test Guideline 202
Toxicity to algae	: Growth rate NOEC: > 170 mg/l Exposure time: 72 h Species: Algae Method: OECD Test Guideline 201
	: Biomass NOEC: > 170 mg/l Exposure time: 72 h Species: Algae Method: OECD Test Guideline 201

Elimination information (persistence and degradability)

Bioaccumulation	: Note: No bioaccumulation is to be expected (log Pow <= 4).
Biodegradability	: aerobic Result: Not readily biodegradable.

Further information on ecology

Additional ecological information : no data available

SECTION 13. DISPOSAL CONSIDERATIONS

Disposal methods : Observe all Federal, State, and Local Environmental regulations.

SECTION 14. TRANSPORT INFORMATION

DOT

UN/ID No. : UN 3163
Proper shipping name : LIQUEFIED GAS, N.O.S. (trans-1,3,3,3-Tetrafluoroprop-1-ene)
Class 2.2
Packing group
Hazard Labels 2.2

IATA

UN/ID No. : UN 3163
Description of the goods : LIQUEFIED GAS, N.O.S. (trans-1,3,3,3-Tetrafluoroprop-1-ene)
Class : 2.2
Hazard Labels : 2.2
Packing instruction (cargo aircraft) : 200
Packing instruction (passenger aircraft) : 200

IMDG

UN/ID No. : UN 3163
Description of the goods : LIQUEFIED GAS, N.O.S. (TRANS-1,3,3,3-TETRAFLUOROPROP-1-ENE)
Class : 2.2
Hazard Labels : 2.2
EmS Number : F-C, S-V
Marine pollutant : no

SECTION 15. REGULATORY INFORMATION

Inventories

US. Toxic Substances Control Act	:	On TSCA Inventory
Australia. Industrial Chemical (Notification and Assessment) Act	:	On the inventory, or in compliance with the inventory
Canada. Canadian Environmental Protection Act (CEPA). Domestic Substances List (DSL)	:	All components of this product are on the Canadian DSL
Japan. Kashin-Hou Law List	:	On the inventory, or in compliance with the inventory
Korea. Existing Chemicals Inventory (KECI)	:	On the inventory, or in compliance with the inventory
Philippines. The Toxic Substances and Hazardous and Nuclear Waste Control Act	:	Not in compliance with the inventory
China. Inventory of Existing Chemical Substances	:	On the inventory, or in compliance with the inventory
New Zealand. Inventory of Chemicals (NZIoC), as published by ERMA New Zealand	:	On the inventory, or in compliance with the inventory

National regulatory information

SARA 302 Components	:	No chemicals in this material are subject to the reporting requirements of SARA Title III, Section 302.

SARA 313 Components : This material does not contain any chemical components with known CAS numbers that exceed the threshold (De Minimis) reporting levels established by SARA Title III, Section 313.

SARA 311/312 Hazards : Acute Health Hazard
Sudden Release of Pressure Hazard

California Prop. 65 : This product does not contain any chemicals known to State of California to cause cancer, birth defects, or any other reproductive harm.

SECTION 16. OTHER INFORMATION

		HMIS III	NFPA
Health hazard	:	1	2
Flammability	:	1	1
Physical Hazard	:	0	
Instability	:		0

Hazard rating and rating systems (e.g. HMIS® III, NFPA): This information is intended solely for the use of individuals trained in the particular system.

Further information

The information provided in this Safety Data Sheet is correct to the best of our knowledge, information and belief at the date of its publication. The information given is designed only as a guidance for safe handling, use, processing, storage, transportation, disposal and release and is not to be considered a warranty or quality specification. The information relates only to the specific material designated and may not be valid for such material used in combination with any other materials or in any process, unless specified in the text. Final determination of suitability of any material is the sole responsibility of the user. This information should not constitute a guarantee for any specific product properties.

Changes since the last version are highlighted in the margin. This version replaces all previous versions.
Previous Issue Date: 05/12/2016
Prepared by Honeywell Performance Materials and Technologies Product Stewardship Group

SAFETY DATA SHEET

N-Butane

Airgas
an Air Liquide company

Section 1. Identification

GHS product identifier	: N-Butane
Chemical name	: butane
Other means of identification	: n-BUTANE; Methylethylmethane; Diethyl; Butyl hydride; normal-Butane; butane, pure
Product type	: Gas.
Product use	: Synthetic/Analytical chemistry.
Synonym	: n-BUTANE; Methylethylmethane; Diethyl; Butyl hydride; normal-Butane; butane, pure
SDS #	: 001007
Supplier's details	: Airgas USA, LLC and its affiliates 259 North Radnor-Chester Road Suite 100 Radnor, PA 19087-5283 1-610-687-5253
24-hour telephone	: 1-866-734-3438

Section 2. Hazards identification

OSHA/HCS status	: This material is considered hazardous by the OSHA Hazard Communication Standard (29 CFR 1910.1200).
Classification of the substance or mixture	: FLAMMABLE GASES - Category 1 GASES UNDER PRESSURE - Liquefied gas

GHS label elements

Hazard pictograms :

Signal word	: Danger
Hazard statements	: Extremely flammable gas. May form explosive mixtures with air. Contains gas under pressure; may explode if heated. May displace oxygen and cause rapid suffocation.

Precautionary statements

General	: Read and follow all Safety Data Sheets (SDS'S) before use. Read label before use. Keep out of reach of children. If medical advice is needed, have product container or label at hand. Close valve after each use and when empty. Use equipment rated for cylinder pressure. Do not open valve until connected to equipment prepared for use. Use a back flow preventative device in the piping. Use only equipment of compatible materials of construction. Always keep container in upright position. Approach suspected leak area with caution.
Prevention	: Never Put cylinders into unventilated areas of passenger vehicles. Keep away from heat, sparks, open flames and hot surfaces. - No smoking. Use and store only outdoors or in a well ventilated place.
Response	: Leaking gas fire: Do not extinguish, unless leak can be stopped safely. Eliminate all ignition sources if safe to do so.
Storage	: Protect from sunlight. Store in a well-ventilated place.
Disposal	: Not applicable.
Hazards not otherwise classified	: In addition to any other important health or physical hazards, this product may displace oxygen and cause rapid suffocation.

Section 3. Composition/information on ingredients

Substance/mixture : Substance

Chemical name : butane

Other means of identification : n-BUTANE; Methylethylmethane; Diethyl; Butyl hydride; normal-Butane; butane, pure

Product code : 001007

CAS number/other identifiers

CAS number : 106-97-8

Ingredient name	%	CAS number
N-Butane	100	106-97-8

Any concentration shown as a range is to protect confidentiality or is due to batch variation.

There are no additional ingredients present which, within the current knowledge of the supplier and in the concentrations applicable, are classified as hazardous to health or the environment and hence require reporting in this section.

Occupational exposure limits, if available, are listed in Section 8.

Section 4. First aid measures

Description of necessary first aid measures

Eye contact : Immediately flush eyes with plenty of water, occasionally lifting the upper and lower eyelids. Check for and remove any contact lenses. Continue to rinse for at least 10 minutes. Get medical attention if irritation occurs.

Inhalation : Remove victim to fresh air and keep at rest in a position comfortable for breathing. If not breathing, if breathing is irregular or if respiratory arrest occurs, provide artificial respiration or oxygen by trained personnel. It may be dangerous to the person providing aid to give mouth-to-mouth resuscitation. Get medical attention if adverse health effects persist or are severe. If unconscious, place in recovery position and get medical attention immediately. Maintain an open airway. Loosen tight clothing such as a collar, tie, belt or waistband.

Skin contact : Flush contaminated skin with plenty of water. Remove contaminated clothing and shoes. To avoid the risk of static discharges and gas ignition, soak contaminated clothing thoroughly with water before removing it. Get medical attention if symptoms occur. Wash clothing before reuse. Clean shoes thoroughly before reuse.

Ingestion : As this product is a gas, refer to the inhalation section.

Most important symptoms/effects, acute and delayed

Potential acute health effects

Eye contact : No known significant effects or critical hazards.

Inhalation : No known significant effects or critical hazards.

Skin contact : No known significant effects or critical hazards.

Frostbite : Try to warm up the frozen tissues and seek medical attention.

Ingestion : As this product is a gas, refer to the inhalation section.

Over-exposure signs/symptoms

Eye contact : No specific data.

Inhalation : No specific data.

Skin contact : No specific data.

Ingestion : No specific data.

Indication of immediate medical attention and special treatment needed, if necessary

Notes to physician : Treat symptomatically. Contact poison treatment specialist immediately if large quantities have been ingested or inhaled.

Specific treatments : No specific treatment.

Section 4. First aid measures

Protection of first-aiders : No action shall be taken involving any personal risk or without suitable training. It may be dangerous to the person providing aid to give mouth-to-mouth resuscitation.

See toxicological information (Section 11)

Section 5. Fire-fighting measures

Extinguishing media

Suitable extinguishing media : Use an extinguishing agent suitable for the surrounding fire.

Unsuitable extinguishing media : None known.

Specific hazards arising from the chemical : Contains gas under pressure. Extremely flammable gas. In a fire or if heated, a pressure increase will occur and the container may burst, with the risk of a subsequent explosion.

Hazardous thermal decomposition products : Decomposition products may include the following materials:
carbon dioxide
carbon monoxide

Special protective actions for fire-fighters : Promptly isolate the scene by removing all persons from the vicinity of the incident if there is a fire. No action shall be taken involving any personal risk or without suitable training. Contact supplier immediately for specialist advice. Move containers from fire area if this can be done without risk. Use water spray to keep fire-exposed containers cool. If involved in fire, shut off flow immediately if it can be done without risk. If this is impossible, withdraw from area and allow fire to burn. Fight fire from protected location or maximum possible distance. Eliminate all ignition sources if safe to do so.

Special protective equipment for fire-fighters : Fire-fighters should wear appropriate protective equipment and self-contained breathing apparatus (SCBA) with a full face-piece operated in positive pressure mode.

Section 6. Accidental release measures

Personal precautions, protective equipment and emergency procedures

For non-emergency personnel : Accidental releases pose a serious fire or explosion hazard. No action shall be taken involving any personal risk or without suitable training. Evacuate surrounding areas. Keep unnecessary and unprotected personnel from entering. Shut off all ignition sources. No flares, smoking or flames in hazard area. Avoid breathing gas. Provide adequate ventilation. Wear appropriate respirator when ventilation is inadequate. Put on appropriate personal protective equipment.

For emergency responders : If specialized clothing is required to deal with the spillage, take note of any information in Section 8 on suitable and unsuitable materials. See also the information in "For non-emergency personnel".

Environmental precautions : Ensure emergency procedures to deal with accidental gas releases are in place to avoid contamination of the environment. Inform the relevant authorities if the product has caused environmental pollution (sewers, waterways, soil or air).

Methods and materials for containment and cleaning up

Small spill : Immediately contact emergency personnel. Stop leak if without risk. Use spark-proof tools and explosion-proof equipment.

Large spill : Immediately contact emergency personnel. Stop leak if without risk. Use spark-proof tools and explosion-proof equipment. Note: see Section 1 for emergency contact information and Section 13 for waste disposal.

Section 7. Handling and storage

Precautions for safe handling

Protective measures : Put on appropriate personal protective equipment (see Section 8). Contains gas under pressure. Avoid breathing gas. Use only with adequate ventilation. Wear appropriate respirator when ventilation is inadequate. Do not enter storage areas and confined spaces unless adequately ventilated. Do not puncture or incinerate container. Use equipment rated for cylinder pressure. Close valve after each use and when empty. Protect cylinders from physical damage; do not drag, roll, slide, or drop. Use a suitable hand truck for cylinder movement.
Use only non-sparking tools. Avoid contact with eyes, skin and clothing. Empty containers retain product residue and can be hazardous. Store and use away from heat, sparks, open flame or any other ignition source. Use explosion-proof electrical (ventilating, lighting and material handling) equipment.

Advice on general occupational hygiene : Eating, drinking and smoking should be prohibited in areas where this material is handled, stored and processed. Workers should wash hands and face before eating, drinking and smoking. Remove contaminated clothing and protective equipment before entering eating areas. See also Section 8 for additional information on hygiene measures.

Conditions for safe storage, including any incompatibilities : Store in accordance with local regulations. Store in a segregated and approved area. Store away from direct sunlight in a dry, cool and well-ventilated area, away from incompatible materials (see Section 10). Eliminate all ignition sources. Cylinders should be stored upright, with valve protection cap in place, and firmly secured to prevent falling or being knocked over. Cylinder temperatures should not exceed 52 °C (125 °F). Keep container tightly closed and sealed until ready for use. See Section 10 for incompatible materials before handling or use.

Section 8. Exposure controls/personal protection

Control parameters

Occupational exposure limits

Ingredient name	Exposure limits
N-Butane	**NIOSH REL (United States, 10/2016).** TWA: 1900 mg/m³ 10 hours. TWA: 800 ppm 10 hours. **OSHA PEL 1989 (United States, 3/1989).** TWA: 1900 mg/m³ 8 hours. TWA: 800 ppm 8 hours. **ACGIH TLV (United States, 3/2017).** STEL: 1000 ppm 15 minutes.

Appropriate engineering controls : Use only with adequate ventilation. Use process enclosures, local exhaust ventilation or other engineering controls to keep worker exposure to airborne contaminants below any recommended or statutory limits. The engineering controls also need to keep gas, vapor or dust concentrations below any lower explosive limits. Use explosion-proof ventilation equipment.

Environmental exposure controls : Emissions from ventilation or work process equipment should be checked to ensure they comply with the requirements of environmental protection legislation. In some cases, fume scrubbers, filters or engineering modifications to the process equipment will be necessary to reduce emissions to acceptable levels.

Individual protection measures

Hygiene measures : Wash hands, forearms and face thoroughly after handling chemical products, before eating, smoking and using the lavatory and at the end of the working period. Appropriate techniques should be used to remove potentially contaminated clothing. Wash contaminated clothing before reusing. Ensure that eyewash stations and safety showers are close to the workstation location.

Section 8. Exposure controls/personal protection

Eye/face protection : Safety eyewear complying with an approved standard should be used when a risk assessment indicates this is necessary to avoid exposure to liquid splashes, mists, gases or dusts. If contact is possible, the following protection should be worn, unless the assessment indicates a higher degree of protection: safety glasses with side-shields.

Skin protection

Hand protection : Chemical-resistant, impervious gloves complying with an approved standard should be worn at all times when handling chemical products if a risk assessment indicates this is necessary. Considering the parameters specified by the glove manufacturer, check during use that the gloves are still retaining their protective properties. It should be noted that the time to breakthrough for any glove material may be different for different glove manufacturers. In the case of mixtures, consisting of several substances, the protection time of the gloves cannot be accurately estimated.

Body protection : Personal protective equipment for the body should be selected based on the task being performed and the risks involved and should be approved by a specialist before handling this product. When there is a risk of ignition from static electricity, wear anti-static protective clothing. For the greatest protection from static discharges, clothing should include anti-static overalls, boots and gloves.

Other skin protection : Appropriate footwear and any additional skin protection measures should be selected based on the task being performed and the risks involved and should be approved by a specialist before handling this product.

Respiratory protection : Based on the hazard and potential for exposure, select a respirator that meets the appropriate standard or certification. Respirators must be used according to a respiratory protection program to ensure proper fitting, training, and other important aspects of use. Respirator selection must be based on known or anticipated exposure levels, the hazards of the product and the safe working limits of the selected respirator.

Section 9. Physical and chemical properties

Appearance

Physical state	: Gas. [Compressed gas.]
Color	: Colorless.
Odor	: Odorless.
Odor threshold	: Not available.
pH	: Not available.
Melting point	: -138°C (-216.4°F)
Boiling point	: -0.5°C (31.1°F)
Critical temperature	: 151.85°C (305.3°F)
Flash point	: Closed cup: -60°C (-76°F)
Evaporation rate	: Not available.
Flammability (solid, gas)	: Extremely flammable in the presence of the following materials or conditions: open flames, sparks and static discharge and oxidizing materials.
Lower and upper explosive (flammable) limits	: Lower: 1.8% Upper: 8.4%
Vapor pressure	: 16.3 (psig)
Vapor density	: 2.1 (Air = 1)
Specific Volume (ft^3/lb)	: 6.435
Gas Density (lb/ft^3)	: 0.1554
Relative density	: Not applicable.
Solubility	: Not available.
Solubility in water	: 0.06 g/l
Partition coefficient: n-octanol/water	: 2.89
Auto-ignition temperature	: 365°C (689°F)
Decomposition temperature	: Not available.

Section 9. Physical and chemical properties

Viscosity : Not applicable.

Flow time (ISO 2431) : Not available.

Molecular weight : 58.14 g/mole

Aerosol product

Heat of combustion : -45384912 J/kg

Section 10. Stability and reactivity

Reactivity : No specific test data related to reactivity available for this product or its ingredients.

Chemical stability : The product is stable.

Possibility of hazardous reactions : Under normal conditions of storage and use, hazardous reactions will not occur.

Conditions to avoid : Avoid all possible sources of ignition (spark or flame). Do not pressurize, cut, weld, braze, solder, drill, grind or expose containers to heat or sources of ignition.

Incompatible materials : Oxidizers

Hazardous decomposition products : Under normal conditions of storage and use, hazardous decomposition products should not be produced.

Hazardous polymerization : Under normal conditions of storage and use, hazardous polymerization will not occur.

Section 11. Toxicological information

Information on toxicological effects

Acute toxicity

Product/ingredient name	Result	Species	Dose	Exposure
N-Butane	LC50 Inhalation Vapor	Rat	658000 mg/m³	4 hours

Irritation/Corrosion

Not available.

Sensitization

Not available.

Mutagenicity

Not available.

Carcinogenicity

Not available.

Reproductive toxicity

Not available.

Teratogenicity

Not available.

Specific target organ toxicity (single exposure)

Not available.

Specific target organ toxicity (repeated exposure)

Not available.

Section 11. Toxicological information

Aspiration hazard

Not available.

Information on the likely routes of exposure	: Not available.

Potential acute health effects

Eye contact	: No known significant effects or critical hazards.
Inhalation	: No known significant effects or critical hazards.
Skin contact	: No known significant effects or critical hazards.
Ingestion	: As this product is a gas, refer to the inhalation section.

Symptoms related to the physical, chemical and toxicological characteristics

Eye contact	: No specific data.
Inhalation	: No specific data.
Skin contact	: No specific data.
Ingestion	: No specific data.

Delayed and immediate effects and also chronic effects from short and long term exposure

Short term exposure

Potential immediate effects	: Not available.
Potential delayed effects	: Not available.

Long term exposure

Potential immediate effects	: Not available.
Potential delayed effects	: Not available.

Potential chronic health effects

Not available.

General	: No known significant effects or critical hazards.
Carcinogenicity	: No known significant effects or critical hazards.
Mutagenicity	: No known significant effects or critical hazards.
Teratogenicity	: No known significant effects or critical hazards.
Developmental effects	: No known significant effects or critical hazards.
Fertility effects	: No known significant effects or critical hazards.

Numerical measures of toxicity

Acute toxicity estimates

Not available.

Section 12. Ecological information

Toxicity

Not available.

Persistence and degradability

Not available.

Section 12. Ecological information

Bioaccumulative potential

Product/ingredient name	$LogP_{ow}$	BCF	Potential
N-Butane	2.89	-	low

Mobility in soil

Soil/water partition coefficient (K_{OC}) : Not available.

Other adverse effects : No known significant effects or critical hazards.

Section 13. Disposal considerations

Disposal methods : The generation of waste should be avoided or minimized wherever possible. Disposal of this product, solutions and any by-products should at all times comply with the requirements of environmental protection and waste disposal legislation and any regional local authority requirements. Dispose of surplus and non-recyclable products via a licensed waste disposal contractor. Waste should not be disposed of untreated to the sewer unless fully compliant with the requirements of all authorities with jurisdiction. Empty Airgas-owned pressure vessels should be returned to Airgas. Waste packaging should be recycled. Incineration or landfill should only be considered when recycling is not feasible. This material and its container must be disposed of in a safe way. Empty containers or liners may retain some product residues. Do not puncture or incinerate container.

Section 14. Transport information

	DOT	TDG	Mexico	IMDG	IATA
UN number	UN1011	UN1011	UN1011	UN1011	UN1011
UN proper shipping name	BUTANE	BUTANE	BUTANE	BUTANE	BUTANE
Transport hazard class(es)	2.1 	2.1 	2.1 	2.1 	2.1 
Packing group	-	-	-	-	-
Environmental hazards	No.	No.	No.	No.	No.

"Refer to CFR 49 (or authority having jurisdiction) to determine the information required for shipment of the product."

Additional information

DOT Classification : **Limited quantity** Yes.
Quantity limitation Passenger aircraft/rail: Forbidden. Cargo aircraft: 150 kg.
Special provisions 19, T50

TDG Classification : Product classified as per the following sections of the Transportation of Dangerous Goods Regulations: 2.13-2.17 (Class 2).
Explosive Limit and Limited Quantity Index 0.125
ERAP Index 3000
Passenger Carrying Ship Index Forbidden
Passenger Carrying Road or Rail Index Forbidden
Special provisions 29

IATA : **Quantity limitation** Passenger and Cargo Aircraft: Forbidden. Cargo Aircraft Only: 150 kg.

Section 14. Transport information

Special precautions for user : **Transport within user's premises:** always transport in closed containers that are upright and secure. Ensure that persons transporting the product know what to do in the event of an accident or spillage.

Transport in bulk according to Annex II of MARPOL and the IBC Code : Not available.

Section 15. Regulatory information

U.S. Federal regulations : **TSCA 8(a) CDR Exempt/Partial exemption**: Not determined

Clean Air Act (CAA) 112 regulated flammable substances: butane

Clean Air Act Section 112 (b) Hazardous Air Pollutants (HAPs) : Not listed

Clean Air Act Section 602 Class I Substances : Not listed

Clean Air Act Section 602 Class II Substances : Not listed

DEA List I Chemicals (Precursor Chemicals) : Not listed

DEA List II Chemicals (Essential Chemicals) : Not listed

SARA 302/304

Composition/information on ingredients

No products were found.

SARA 304 RQ : Not applicable.

SARA 311/312

Classification : Refer to Section 2: Hazards Identification of this SDS for classification of substance.

State regulations

Massachusetts : This material is listed.

New York : This material is not listed.

New Jersey : This material is listed.

Pennsylvania : This material is listed.

International regulations

Chemical Weapon Convention List Schedules I, II & III Chemicals

Not listed.

Montreal Protocol (Annexes A, B, C, E)

Not listed.

Stockholm Convention on Persistent Organic Pollutants

Not listed.

Rotterdam Convention on Prior Informed Consent (PIC)

Not listed.

UNECE Aarhus Protocol on POPs and Heavy Metals

Not listed.

Inventory list

Australia : This material is listed or exempted.

Canada : This material is listed or exempted.

Section 15. Regulatory information

China	: This material is listed or exempted.
Europe	: This material is listed or exempted.
Japan	: **Japan inventory (ENCS)**: This material is listed or exempted. **Japan inventory (ISHL)**: This material is listed or exempted.
Malaysia	: This material is listed or exempted.
New Zealand	: This material is listed or exempted.
Philippines	: This material is listed or exempted.
Republic of Korea	: This material is listed or exempted.
Taiwan	: This material is listed or exempted.
Thailand	: Not determined.
Turkey	: This material is listed or exempted.
United States	: This material is listed or exempted.
Viet Nam	: Not determined.

Section 16. Other information

Hazardous Material Information System (U.S.A.)

Health	/	1
Flammability		4
Physical hazards		3

Caution: HMIS® ratings are based on a 0-4 rating scale, with 0 representing minimal hazards or risks, and 4 representing significant hazards or risks. Although HMIS® ratings and the associated label are not required on SDSs or products leaving a facility under 29 CFR 1910.1200, the preparer may choose to provide them. HMIS® ratings are to be used with a fully implemented HMIS® program. HMIS® is a registered trademark and service mark of the American Coatings Association, Inc.

The customer is responsible for determining the PPE code for this material. For more information on HMIS® Personal Protective Equipment (PPE) codes, consult the HMIS® Implementation Manual.

National Fire Protection Association (U.S.A.)

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Copyright ©2001, National Fire Protection Association, Quincy, MA 02269. This warning system is intended to be interpreted and applied only by properly trained individuals to identify fire, health and reactivity hazards of chemicals. The user is referred to certain limited number of chemicals with recommended classifications in NFPA 49 and NFPA 325, which would be used as a guideline only. Whether the chemicals are classified by NFPA or not, anyone using the 704 systems to classify chemicals does so at their own risk.

Procedure used to derive the classification

Classification	Justification
FLAMMABLE GASES - Category 1 GASES UNDER PRESSURE - Liquefied gas	Expert judgment Expert judgment

History

Date of printing	: 1/6/2020
Date of issue/Date of revision	: 1/6/2020
Date of previous issue	: 10/5/2018

Section 16. Other information

Version : 2.01

Key to abbreviations : ATE = Acute Toxicity Estimate
BCF = Bioconcentration Factor
GHS = Globally Harmonized System of Classification and Labelling of Chemicals
IATA = International Air Transport Association
IBC = Intermediate Bulk Container
IMDG = International Maritime Dangerous Goods
LogPow = logarithm of the octanol/water partition coefficient
MARPOL = International Convention for the Prevention of Pollution From Ships, 1973 as modified by the Protocol of 1978. ("Marpol" = marine pollution)
UN = United Nations

References : Not available.

Notice to reader

To the best of our knowledge, the information contained herein is accurate. However, neither the above-named supplier, nor any of its subsidiaries, assumes any liability whatsoever for the accuracy or completeness of the information contained herein.
Final determination of suitability of any material is the sole responsibility of the user. All materials may present unknown hazards and should be used with caution. Although certain hazards are described herein, we cannot guarantee that these are the only hazards that exist.

K – Experimental Study Test Results

The table down below shows the end results of each test.

	Test 1	Test 2	Test 3	Test 4	Test 5.1	Test 6	Test 7	Test 8	Test 9	Test 10	Test 11	Test 5.2	Test 5.3
Parameters:													
LT refr. charge (kg)	1.95	1.95	1.95	1.95	1.95	1.95	1.95	1.95	1.95	1.95	1.95	1.95	1.95
HT refr. charge (kg)	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Tank volume (L)	5	5	5	5	5	5	5	5	5	5	5	5	5
Fan speed (m3/h)	600	600	600	600	500	400	300	200	500	500	500	500	500
LT superheat (K)	4 (~9)	4 (~9)	4 (~9)	4 (~9)	4	4	4	4	4	4	4	4	4
LT LSH (K)	3	3	3	3	3	3	3	3	3	3	3	3	3
LT LSd (sec.)	15	15	15	15	15	15	15	15	15	15	15	15	15
LT LSF (K)	4	4	4	4	4	4	4	4	4	4	4	4	4
HT superheat (K)	10	9	8	7	7	7	7	7	7	7	7	7	7
HT LSH (K)	5	5	5	5	5	5	5	5	5	5	5	5	5
HT LSd (sec.)	15	15	15	15	15	15	15	15	15	15	15	15	15
HT LSF (K)	6	6	6	6	6	6	6	6	6	6	6	6	6
HT start T (Celsius)	-	-	-	-	-	-	-	-	62	43	38	-	-
HT start time (min.)	0	0	0	0	0	0	0	0	9	3	2.5	0	0
Results:													
Heating time (min.)	27	24	23	23	25	25	26	26	22	27.5	27	24.5	23.5
Heating time (sec.)	1620	1440	1380	1380	1500	1500	1560	1560	1320	1650	1620	1470	1410
Room T (Celsius)	~18	~18	~18	~18	~18	~18	~18	~18	~18	~18	~18	~18	~18
Water initial T (Celsius)	~10	~10	~10	~10	~10	~10	~10	~10	~10	~10	~10	~10	~10
Actual LT superheat (K)	~9	~9	~9	~9	~9	~9	~9	~9	~9	~9	~9	~9	~9
Actual HT superheat (K)	~10	~9	~8	~7	~7	~7	~7	~7	~7	~7	~7	~7	~7
Final T (Celsius):													
Boiler middle	90.11	92.38	89.49	90.39	93.91	90.34	92.18	95.16	-	92.32	90.17	-	-
Boiler surface	98.62	98.37	98.06	97.27	97.06	95.38	97.49	98.02	72.88	98	97.1	95.1	95.23
LT evap. outlet	10.56	10.81	10.87	10.45	10.24	8.11	7.21	5.85	7.65	9.39	9.56	9.18	9.39
LT comp. discharge	48.42	47.95	47.55	47.15	47.37	44.68	43.2	41.47	43.3	45.93	45.61	45.05	45.38
LT cond. outlet	34.51	35.05	35.97	34.72	35.02	31.16	30.93	28.78	28.39	33.66	33.15	31.61	31.78
HT evap. outlet	44.75	45.8	40.86	43.16	44.25	39.55	40.24	39.51	31.07	42.71	41.84	40.76	41.03
HT comp. discharge	117.56	118.7	111.36	112.74	118.12	104.12	109.89	108.47	80.5	112.67	110.61	105.56	105.75
HT cond. outlet	69.94	72.21	73.94	71.54	74.04	69.73	70.77	71.53	56.22	71.42	70.06	69.01	69.91
Heating capacity (W)	1145	1284	1336	1324	1215	1191	1174	1181	997	1116	1125	1212	1265
dT LT evap.	16.44	16.19	16.13	16.55	16.76	18.89	19.79	21.15	19.35	17.61	17.44	17.82	17.61
dT IHE	3.67	2.15	6.69	3.99	3.12	5.13	2.96	1.96	12.23	3.22	3.77	4.29	4.35
dT HT cond.	18.94	20.33	13.3	15.47	21.06	8.74	12.4	10.45	7.62	20.35	13.51	10.46	10.52

L – Heat Capacity, Heat Loss and Overall COP Calculations

Electric current and power factor:

Start:					
	Voltage (V)	Current (A)	Power Factor	Working P (W)	Apparent P (VA)
Fan	230	0.34	0.53	41.446	78.2
LT Comp.	230	2.4	0.94	518.88	552
HT Comp.	230	1.43	0.72	236.808	328.9
			Total:	797.134	959.1
End:					
	Voltage (V)	Current (A)	Power Factor	Working P (W)	Apparent P (VA)
Fan	230	0.34	0.53	41.446	78.2
LT Comp.	230	2.84	0.97	633.604	653.2
HT Comp.	230	3.3	0.96	728.64	759
			Total:	1403.69	1490.4

Heat loss values:

	Heat loss from liquid surface (W/m²)				Heat loss through tank wall (W/m²)	
T (°C)	Evaporation	Radiation	Total Loss		Steel (1 mm)	Insulation (1 inch)
32.2	252	158	410		158	37.8
37.8	504	221	725		221	47.3
43.3	757	284	1041		284	59.9
48.9	1135	347	1482		347	72.5
54.4	1513	426	1939		426	85.1
60	2081	504	2585		504	97.7
65.6	2711	567	3278		567	107
71.1	3468	662	4130		662	120
76.7	4350	741	5091		741	132
82.2	5485	820	6305		820	145
87.8	6809	914	7723		914	158
93.3	8449	1009	9458		1009	167
98.9	10214	1135	11349		1135	180

Total heat loss:

Top (0.0227 m²)		Wall (0.117 m²)		Bottom (0.0227 m²)		
T (°C)	Heat loss (W)	T (°C)	Heat loss (W)	T (°C)	Heat loss (W)	Total Loss
32.2	9.307	32.2	18.486	32.2	0.85806	28.65106
37.8	16.4575	37.8	25.857	37.8	1.07371	43.38821
43.3	23.6307	43.3	33.228	43.3	1.35973	58.21843
48.9	33.6414	48.9	40.599	48.9	1.64575	75.88615
54.4	44.0153	54.4	49.842	54.4	1.93177	95.78907
60	58.6795	60	58.968	60	2.21779	119.86529
65.6	74.4106	65.6	66.339	65.6	2.4289	143.1785
71.1	93.751	71.1	77.454	71.1	2.724	173.929
76.7	115.5657	76.7	86.697	76.7	2.9964	205.2591
82.2	143.1235	82.2	95.94	82.2	3.2915	242.355
87.8	175.3121	87.8	106.938	87.8	3.5866	285.8367
93.3	214.6966	93.3	118.053	93.3	3.7909	336.5405
98.9	257.6223	98.9	132.795	98.9	4.086	394.5033

COP values at different temperature intervals:

	Total capacity (W)			
T (°C)	Heating	Exclu. loss	Input power (w)	COP
32.2	1265	1293.6511	922.346	1.40
37.8	1265	1308.3882	959.871	1.36
43.3	1265	1323.2184	997.396	1.33
48.9	1265	1340.8862	1034.921	1.30
54.4	1265	1360.7891	1072.446	1.27
60	1265	1384.8653	1109.971	1.25
65.6	1265	1408.1785	1147.496	1.23
71.1	1265	1438.929	1185.021	1.21
76.7	1265	1470.2591	1222.546	1.20
82.2	1265	1507.355	1260.071	1.20
87.8	1265	1550.8367	1297.596	1.20
93.3	1265	1601.5405	1335.121	1.20
98.9	1265	1659.5033	1372.646	1.21
			Average:	1.26