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Heat recovery from vacuum brazing furnaces

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Abstract

By partly replacing the use of primary energy sources with waste heat recovery, climate and environmental goals for the future will be closer at hand. This thesis investigates the waste heat potential of Alfa Laval's vacuum brazing furnaces in Ronneby and alternative ways of integrating the furnace's waste heat into the building's HVAC system.

The main challenge was the low-temperature qualities associated with the cooling water, which constituted an obstacle to recovering waste heat without any additional equipment, such as a heat pump. Tests and analyses performed in this thesis are, therefore, mainly aimed at raising the temperature quality of the cooling water. A test was conducted on the cooling system to calculate the energy losses with regards to the cooling water. In one 11-hour cycle, 1546 kWh of electricity was used to heat the furnace. Out of that, 1360 kWh was cooled off to the atmosphere.

Additionally, a test on the furnace's clean-up cycle was performed. The maximum cooling water temperature reached during this test was 44°C. This shows excellent potential in the possibility of recovering the waste heat without any additional equipment.

Further, this thesis aims to broaden the knowledge around areas concerning increased cooling water temperatures, which, during the writing, seemed to have a gap in documented sources. The results of this thesis indicate that a temperature quality increase of the furnaces' cooling water is possible. Cooling system changes have also been suggested, which is necessary for an efficient and safe heat recovery.

Keywords: Waste heat, Vacuum furnace, Heat recovery and HVAC.

Acknowledgements

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This master's thesis has been a collaboration between the universities of Lund and Umeå, where both participants have done everything together. Each step in this thesis builds on the previous step, and therefore it cannot be divided in any particular way. We have worked agilely, continuously making plans for and carrying out mapping, calculations, measurements, and analyses as we gained access to new information. This report is also uploaded at UMU with the DiVA id: **diva2:1763678**

Contents

1 Introduction

A frequently discussed topic of the modern world is the global energy crisis, and finding solutions to the problem of global warming caused by greenhouse gases. During the year 2020 Sweden had a total energy input of 508 TWh, of which 355 TWh accounted for the final usage. The difference is partly explained by losses in conversion and transmission [1]. The Swedish Energy Agency further describes that during 2020, the industry sector in Sweden used 136 TWh, which corresponds to just under 40 % of the total energy usage.

By implementing waste heat as an alternative energy source, the use of primary sources in the industry sectors could be reduced [2]. Reducing the use of primary energy sources and increase the energy efficiency through, for example, recovering waste energies are vital if we are to reach the energy and climate goals of the future. The European Commission has an existing ambition of a reduction in greenhouse gas emission by 40 % and an improvement in energy efficiency of at least 32.5 %, both compared to levels presented in 1990 [3]. Furthermore the International Energy Agency (IEA) describes a pathway for reaching a goal of net zero CO_2 emissions produced by the global energy sector. The goal to be reached in 2050 is consistent with limiting the global temperature rise to 1.5°C [4]. IEA also highlights the importance of innovation and new emerging technologies in order to achieve the net zero goal.

Industrial waste heat recovery can also be a great way to reduce carbon emissions. In Europe, it is estimated that the energy potential of waste heat is about 300 TWh/year[5]. One-third of this is waste heat at a temperature below 200°C, which is considered low-temperature waste heat. One-fourth is in the range 200°C to 500°C, and the rest is above 500°C. Low-temperature waste can often be used for heat recovery applications, such as heating buildings or offices, and higher-temperature waste can be used for heat-to-power conversion.[5].

Alfa Laval uses vacuum brazing furnaces in its manufacturing process. These furnaces demand cooling, and today the cooling energy is not recovered. The cooling temperature is kept relatively low due to the risk of hot surfaces and personal safety. It has emerged that it might be possible to obtain high-tempered excess heat for heating purposes from the furnaces directly, without for example the use of heat pump technology.

What we think today limits the cooling temperatures from the furnaces are not technical limitations instead it is more of a safety issue, that the furnace and pipe surfaces are uninsulated and therefore the cooling temperature is kept low. We need to investigate if it affects the products and investigate alternatives.

We also want to clarify the power and energy potential, the possibilities to insulate/shield the hot surfaces and to raise the temperature in the cooling circuit. We will also investigate how we can integrate and recover the excess heat for heating Alfa Laval's facility or share heat locally and necessary adjustments. Better use of the current energy usage and knowledge about the problems is also in line with reduced climate/carbon footprint. Insulation of uncontrolled heat sources in the production room will also provide a better indoor climate and working environment.

During the literature search, described in Table 1, very few sources that discuss increasing cooling water temperatures for vacuum furnaces were found. The sources that were found concerning heat recovery from cooling water already had water temperatures above 55°C, or in many cases proposed the integration of heat pumps in order to increase the cooling water temperature quality. In this way, this thesis can also partially fill the knowledge gap that exists regarding this particular area of expertise, namely increasing cooling water temperatures of furnaces in order to recover energy more efficiently.

1.1 Aim of the project

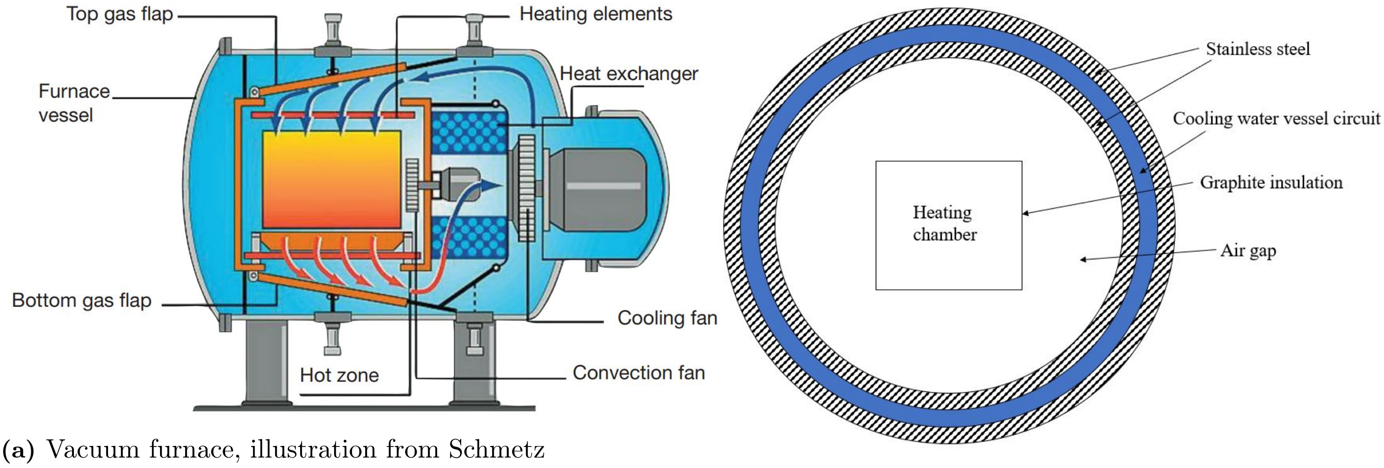
This thesis aims to study how to raise the temperature of the cooling water in and out from the vacuum brazing furnace and by that increase the quality which makes it easier to recover. Find ways of and integrate the recovered heat to the buildings HVAC system on site at Alfa Laval Ronneby.

The master thesis also aims at clarifying the opportunities of recycling heat energy in industries worldwide.

2 Theory

2.1 Vacuum furnace

A principal schematic of a vacuum furnace is presented in Figure 1. During operation, vacuum is used to prevent oxidation of the heated products, limit heat losses through convection, and remove sources of contamination. Vacuum levels and maximum furnace temperatures depend on the heated materials' melting points and vapor pressures [6]. A vacuum furnace is often used in processes such as annealing, sintering, brazing, and heat treatment with low contamination acceptance, in which oxygen, water and hydrocarbons are the most common contaminates. Vacuum furnaces like the ones in this study have two cooling systems, the vessel circuit, and the quick cooler (represented by the heat exchanger in Figure 1). The vessel circuit runs water in the furnace shell to cool during the heating of the products. The quick cooler runs water through a heat exchanger inside the furnace during the furnace's cooling phase. During the cooling phase inert gas is also circulated and controlled by a cooling fan, situated in the back of the furnace. This allows for a convectional cooling which speeds up the process of bringing the material back to non-metallurgical levels. This thesis has studied vacuum brazing furnaces at Alfa Laval in Ronneby from two different companies, namely company A and B.



(a) Vacuum furnace, illustration from Schmetz GmbH Vacuum Furnaces

(b) Vessel circuit, cross-sectional area

Figure 1 – Basic principle schematics of a vacuum furnace

2.1.1 Clean-up cycle

A clean-up cycle is a cycle that runs once a month on every vacuum furnace referred to in this study. The cycle is used to clean the inside of the furnace of debris, and while doing it also check for vacuum leaks. The difference from a regular cycle is that there are no brazing loads in the furnace, no quick cooling during the cooling phase and the furnace is run to a higher temperature of about 100°C above regular production cycles. Regular production cycles operate with temperatures above 1000°C.

2.2 Vacuum brazing process

Brazed and fusion-bonded plate heat exchangers are manufactured at Alfa Laval by using vacuum furnaces. Sheets of stainless steel and a braze alloy, often called filler metal, in this case copper, are stacked together. The base material, in this case stainless steel, is positioned so that a small gap is separating that from the next steel sheet. By applying heat, a metallurgical bond between the two pieces copper and stainless steel appears. The braze alloy is drawn into the gaps by capillary action and forms one unit. After cooling a solid joint is formed. Vacuum brazing is used to avoid reactions between metals and alloys and gases such as oxygen and nitrogen [6]. Brazing cycle times varies depending on materials processed and its quantities, normal cycle times at Alfa Laval lies between 8-18 hours. A general description of a vacuum brazing cycle is presented by (Andersson et al.) [6] and refers to Figure 2.

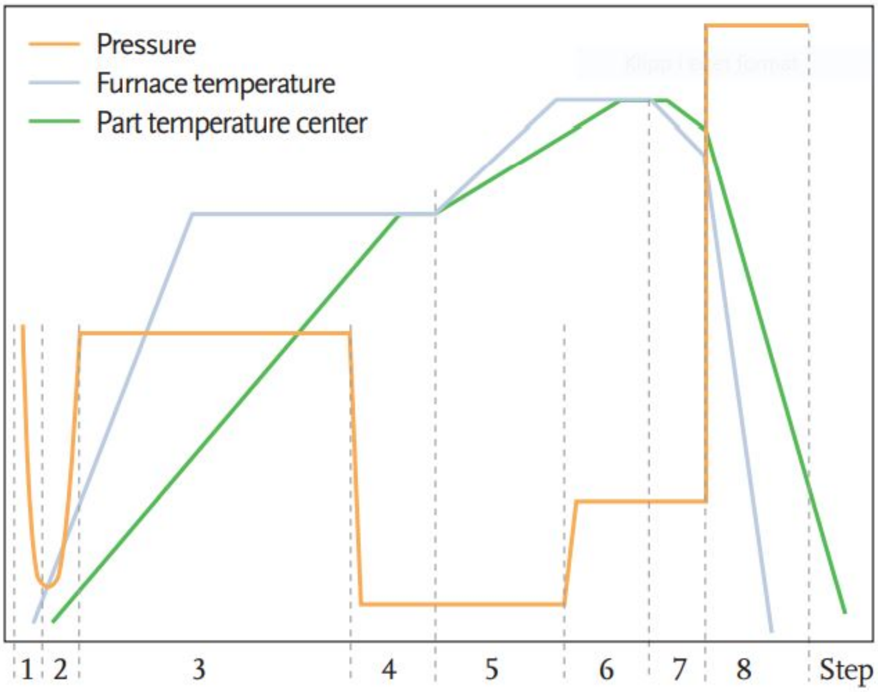


Figure 2 – Pressure and temperature of a vacuum brazed cycle during its phases/steps

Step 1: A brazing cycle starts with the load being charged into the furnace followed by a vacuum pump that reduces the pressure from atmospheric pressure.

Step 2: Nitrogen is let into the furnace to allow for convective heating of the materials, provided that the furnace has a fan, otherwise pressure maintains low and heating will consist of radiation.

Step 3: The parts are heated uniformly to minimize distortion, then held at a temperature below the filler alloy's solidus temperature for a soak period.

Step 4: A low pressure is created through vacuum pumping to remove volatile species and dirt.

Step 5: Temperature is then increased to start the actual brazing process, where the braze alloy melts and is drawn into the joint.

Step 6: The pressure may be increased if necessary, and the soak time at brazing temperature is carefully controlled to assure melting of all braze alloy and prevent embrittlement. The final properties of the braze joint are influenced by the time at temperature. If necessary, an extended time at the brazing temperature is used to allow the lower melting point elements in the filler alloy to diffuse into the base material.

Step 7: The temperature is lowered until all the braze alloy is solidified with the use of vacuum cooling.

Step 8: Finally, to acquire room temperature during this called quenching phase, nitrogen is again let into the furnace to create an over-pressure, the increased pressure allows for a higher cooling capacity through convection. Cooling rates depend on the risk of distortion and requirements of material properties.

2.3 Cooling system

The overall cooling system for the furnaces at Alfa Laval is presented in Figure 3. Company A, providing the furnace solutions, has set recommendations regarding both the temperatures, pressures and volume flows for the furnace cooling water circuits. The recommendations consist of inlet temperatures specified at 30°C and a maximum gauge pressure of 3 bar, and these are further monitored throughout the brazing cycle. The outlet temperature of the vessel circuit is not specified, but the outlet temperature of the quick cooler is specified at a maximum of 90°C. Flow recommendations for the quick cooler and vessel circuit are 35 m^3/h and 15 m^3/h respectively. Today, the flow for the vessel circuit is 35 m^3/h during the heating phase and both circuits at 65 m^3/h during cooling.

Two water tanks of each 10 m^3 are intended to increase the thermal inertia of the cooling system and respond to the fluctuating cooling needs of the furnaces. The cooling needs of the furnace strongly depend on which phase during the brazing cycle that is in progress, where the cooling phase is currently critical for the overall cooling system. Tank number 1, with an average measured temperature of 23°C supplies the secondary cooling circuit, while tank 2 supplies the primary cooling circuit, with an average measured temperature of 12°C. Further, the temperatures of the tanks varies during the different seasons, with regards to the outside air temperature.

The two cooling circuits of the furnace is both cooled through the secondary cooling circuit (left side in Figure). A gasketed plate heat exchanger, HEX 1, transfers heat from the hot outlet of the vessel circuit to the secondary cooling tank. During the heating phase of the brazing cycle most cooling water is run through the vessel circuit. A smaller amount of cooling water goes through the half inch bypasses for both the quick cooler and the roughing pump. The quick cooling circuit uses the bypass with a control valve during this stage only to stop the water that's inside the furnace from boiling. During the quenching phase of the brazing cycle the quick cooling bypass' control valve is shut and cooled water instead enters through the main quick cooling circuit, at a higher rate. The higher rate of water flow through the quick cooler, accompanied with a cooling fan inside the furnace, allows for a faster convective cooling.

The pumps used in the system consists of two centrifugal pumps and one multistage pump. The multistage is placed in the water vessel circuit and the centrifugal pumps are placed in the primary respective secondary water cooling circuits. The centrifugal pump, connected to the quick cooler and heat exchanger is frequency controlled, 35 Hz at the heating phase of the cycle and 50 Hz during the cooling phase. The second centrifugal pump connected to the water vessel circuit and the multistage pump connected to the cooling tower are both constantly operated at 50 Hz during a cycle.

In order to keep the inlet temperature of the cooling water to a maximum of 30°C, both furnace cooling circuit temperatures are maintained using a primary circuit (right side in Figure). The primary circuit is in turn connected to a cooling tower with another loop, located at the building roof. Heat is exchanged through the primary cycle to the secondary via a brazed plate heat exchanger, HEX 2. There's also a bypass installed over HEX 2, which is controlled with a control valve. A set point for the inlet temperature in the secondary circuit, currently set at 20°C, controls how much of the water is run through the bypass and through heat exchanger 2 respectively, in order to keep the desired furnace cooling water inlet temperature. If the cooling capacity of the system wouldn't be sufficient, there's an emergency cooling line containing cold city water, directly connected to the furnace inlet cooling water. The emergency cooling is currently set to start at 30°C and will continue pumping the cold cooling water until the temperature of the furnace cooling water inlets remains below 30°C. Company A recommend temperature and flow for the emergency cooling at 15°C to 25°C and 5 $m^3 \cdot h^{-1}$. During the year 2022, the cooling system studied in more detail used an average city water volume of 353 $m^3 \cdot$ $month^{-1}$ according to Alfa Laval.

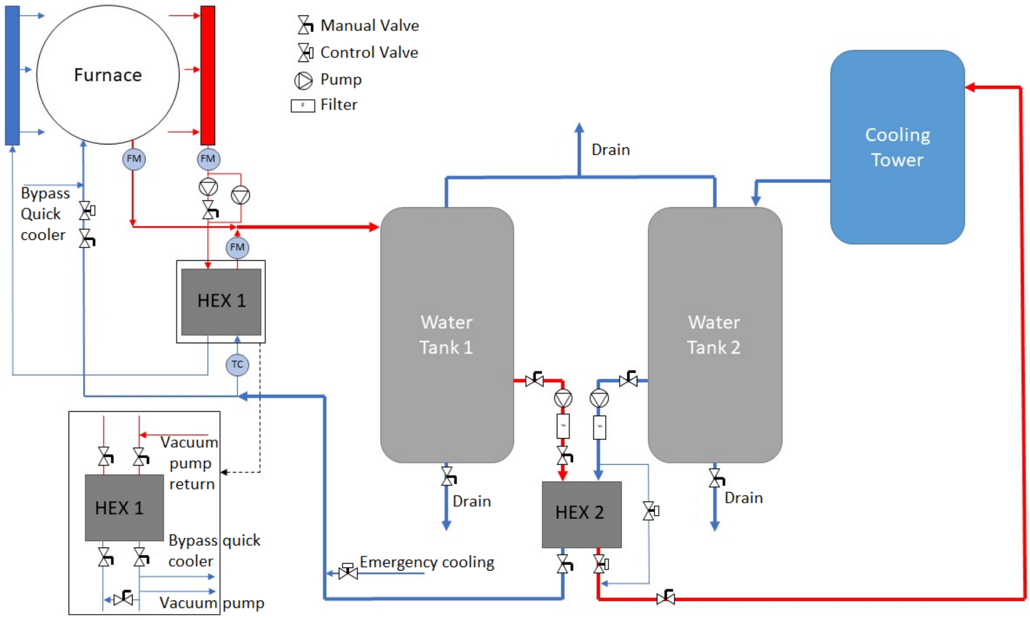


Figure 3 – Overview of existing cooling system.

Some parts of the furnace are more sensitive to higher temperatures and require specific temperature supervision. The vacuum pumping station consists of one roughpump/forepump which requires a cooling water flow of 720 l· h^{-1} at a maximum inlet temperature of 30°C and an air cooled, or in some cases water cooled roots pump, which starts pumping air at an absolute pressure of 8 mbar. Power cords with a maximum current of 400A are led through the top of the furnace into the heating chamber. The power cord temperatures are has a protection of bi-metals, those bi-metals closes at a temperature of 90°C and breaks the electrical circuit that supplies heat to the furnace. A water cooled convective fan with a power capacity of 37/110 kW, located inside the back of the furnace, generate large amounts of heat during the brazing cycle cooling phase and is also of crucial importance regarding the risk of overheating.

For the systems studied in this thesis, water tanks 1 and 2 together with the cooling tower in Figure 3 generally supplies two furnaces with cooling water. The exception is the clean-up cycle, which is discussed in upcoming sections, that cooling system only supplies one furnace with cooling water, but it's still connected the same way as in Figure 3.

2.4 Wet cooling tower

For power plants and industries that generate large quantities of waste heat, nearby lakes or rivers are examples of used heat sinks. However, in some cases, the supply of cooling water from lakes or rivers is limited, or there could be severe concerns about thermal pollution. When this is the problem, the heat can be rejected to the atmosphere through the use of cooling towers. A wet cooling tower, is an evaporative cooler that uses evaporation energy to cool. A schematic of a induced-draft counterflow wet cooling tower is shown in Figure 4. The fan sitting on top of the tower draws air from the bottom of the tower and out through the top. In this air, water is pumped into the tower at the top and sprayed into an airstream. The purpose of spraying the water is to increase the surface area of the water in the air to increase the evaporation rate. There is also a fill between the hot side and the cold side to increase the surface area of the tower allowing for greater evaporation rates.[7]

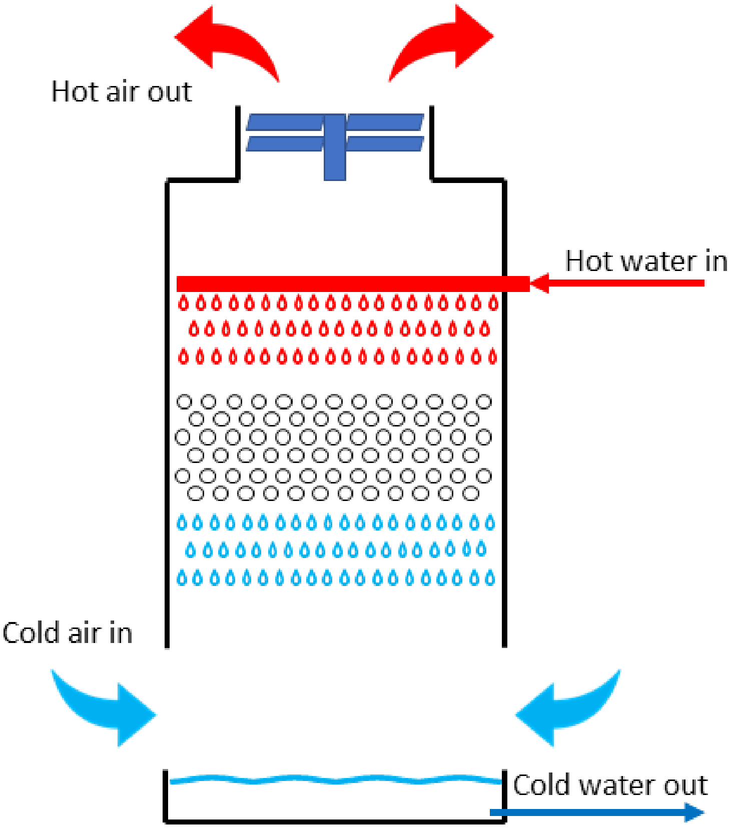


Figure 4 – Cooling system for the vacuum furnace.

When the air in the cooling tower is distributed by a fan it is classified as a forced-draft cooling tower, like the one in Figure 4. Another popular type of cooling towers are natural draft cooling tower that is frequently used in power plants. These look like large chimneys and works like an ordinary chimney. The water in the tower will have high water vapor content and will be lighter then the dry air outside and will therefore rise and escape at the top of the tower. This air will then be replaced with dry air in the bottom. This creates a natural flow in the cooling tower and the rate of air is depending on the density differences between hot and cold air.

2.5 Building heating system

Alfa Lavals' building in Ronneby have a balanced mechanical supply and exhaust ventilation system. The system does not have any heat recovery. The air is heated by district heating from Ronneby Miljö och Teknik, the supply network is presented in Figure 5.

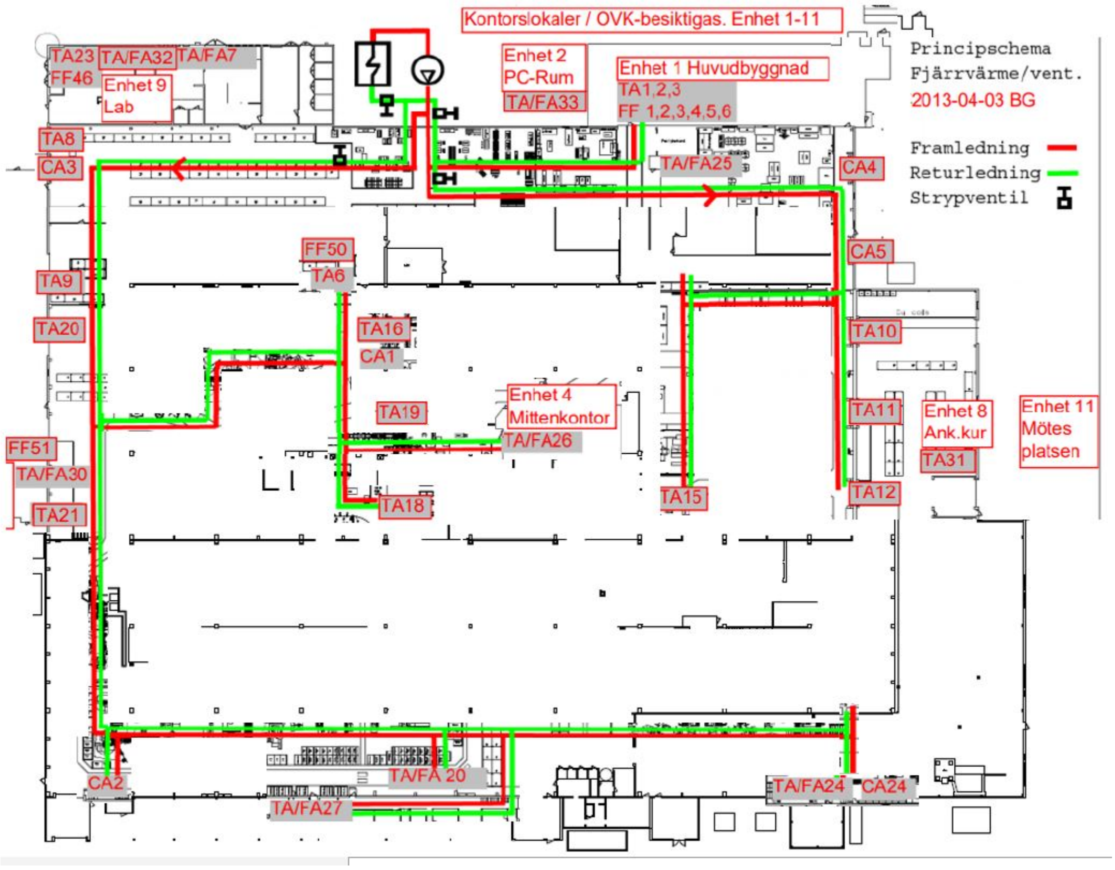


Figure 5 – Schematics for the supply of district heating to the ventilation.

The district heating network is connected to the Ronneby site by a three way connection that can be seen in Figure 6.

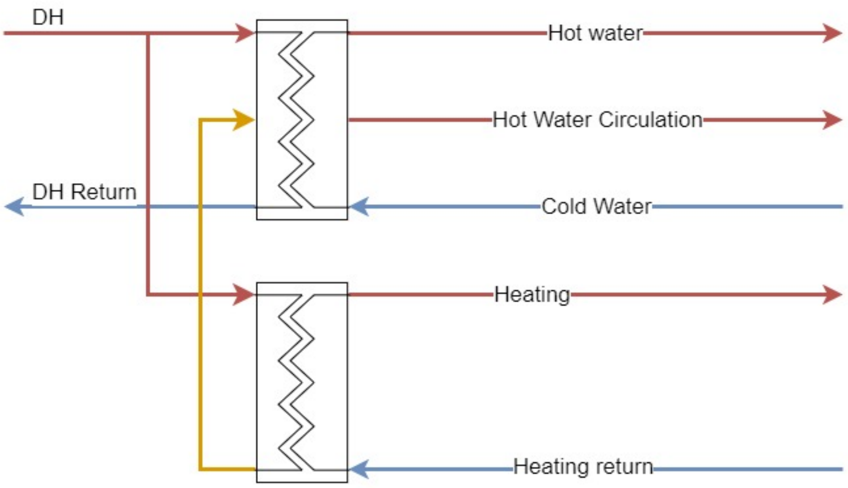


Figure 6 – Diagram of a three way connection for the district heating at Ronneby.

3 Method

The overall approach during this master project was to work flexible where investigations, evaluations and plans were made continuously as new information was collected. A literature study was conducted to determine the current state of knowledge and to potentially highlight alternative ways of conducting and implementing our project. Information and instructions regarding the site and furnaces at Alfa Laval in Ronneby have been studied during different occasions throughout the project. Supplementary help and knowledge were also given from relevant staff at Alfa Laval. Measurements, energy balances and tests were carried out to increase our knowledge of the process but also as a basis to present findings and structure problems, which opened up for new interesting discussions and alternative solutions. Section 3.1 to 3.8 will explain the different methods used in more detail.

3.1 Literature study

At the beginning of the project, a literature study was conducted to better understand the processes. For this literature survey, articles that investigated the same subject that our master thesis would deal with were searched for. The number of found relevant articles were few, so we broadened our approach of finding relevant information that could benefit our work. We used LUB search, the UMU library search engine, and Google Scholar to search for peer reviewed material. Most of the information and articles found were from Lund University's scientific database, which is the combined entry to printed and digital material at Lund University. If search results were too broad and off topic, an advanced search function was used with and, or and not as logical functions. The search was based on keywords presented in Table 1, where the advanced search function was used frequently. Some relevant and used articles from the Table is included in more than one search.

Table 1 – Keywords used for the literature study

Keywords	Number of articles	Relevant & used articles
Vacuum furnace	9132	2
Brazing & vacuum furnace	290	1
Brazing process	105	1
Cold wall furnace	85	1
Rotary retort furnace	7	
furnace & insulation	1550	1
Furnace & insulation	2872	2
Heat recovery furnace	1617	3
Cooling system & furnace	437	1
Cooling water & furnace	308	-
Raised cooling water temperature & furnace	8	-
Heat exchanger & waste heat	4396	4
Waste heat recovery	25001	10
Global waste heat potential	1	1
Low temperature & waste heat	1152	8
Low temperature & energy source	9	2
Excess heat & industry	621	3
HVAC & industry	5458	1
Industry & heating systems	6296	2
Industrial piping systems	33	-
Industrial water systems & heating	4	-
Heat pumps & waste heat	3310	12
Heat integration & industry	985	6
District heating & Europe	823	8
4th generation district heating	318	1
Low grade waste heat & District heating	178	4
Thermal grids	160	1
Burn risks	20	2
Legionella & cooling water	1358	1

3.2 Heat transfer calculations and furnace power balance

Energy balance calculations was performed to map out a rough estimation of the energy potential that can be recovered from the furnaces. All equations used in the energy balance refers to [8]. By using the first law of thermodynamics (1), the energy balance of the furnaces considered at Alfa Laval could be derived to equation (2).

$$\Delta U = Q - W \tag{1}$$

where U is the internal energy in J, Q the heat added to the system in J, and W the work performed by or on the system in J.

$$W_{electricity} - Q_{coolingwater} - Q_{loss} = \Delta U_{load} \tag{2}$$

Energy lost from the cooling water circuit of the furnace to the atmosphere through cooling towers were calculated using equation 3.

$$P = \dot{m} \cdot C_{p,water} \cdot (T_{outletwater} - T_{inletwater}) \tag{3}$$

where the cooling effect P is in W, $\dot{m}$ the mass flow of cooling water in kg$\cdot$ s^{-1}, C$_p$ the specific heat of water in kJ$\cdot$ kg$^{-1}\cdot$ K^{-1} and T the temperatures in K for the furnace cooling water outlet respectively inlet.

Measurements regarding the electricity use during a full brazing cycle was provided by Alfa Laval. In order to analyze the heat losses via convection and radiation, temperatures of the furnaces shells at Alfa Laval production site in Ronneby were measured. Pictures where taken with an IR-camera, E60BX Flir, with an emissivity setting of 0.95, which displayed the surface temperature of different furnaces during various stages of the brazing process. The pictures were vital for identifying the furnaces hot spots, which in the later insulation process would be useful. With the collected information regarding temperatures, equations 4 to 10 were used for the rough hand calculation of heat losses. To simplify the calculations by hand the furnaces surfaces were considered as one horizontal cylinder and two vertical surfaces, vertical being the front respectively back side. The emissivity of the furnace wall paint was considered a value of 0.95. Since the furnaces are situated indoors, convection was solely regarded as natural convection. Heat losses for the cylinder were calculated using

$$Q_{loss} = Q_{conv} + Q_{rad}, \tag{4}$$

where Q_{rad} and Q_{conv} represents the heat losses of the furnace in W. Q_{rad} is the radiation heat loss to the surroundings and can be written as

$$Q_{rad} = \epsilon \cdot A \cdot \sigma \cdot (T^4_{surface} - T^4_{surroundings}), \tag{5}$$

with ϵ as emissivity, A as the area in m^2, the Stefan-Boltzmann constant $\sigma = 5.67 \cdot 10^{-8}$ in W$\cdot$m$^{-2}\cdot$K^{-4} and T as temperature in K. Q_{conv} is the convection heat loss to the surroundings and can be written as

$$Q_{conv} = h \cdot A \cdot (T_{surface} - T_{surroundings}), \tag{6}$$

and h as the convective heat transfer coefficient in W$\cdot$m$^{-2}\cdot$K^{-1}. The convective heat transfer is calculated with

$$Nu_D = \frac{h \cdot D}{k} \Rightarrow h = \frac{Nu_D \cdot k}{D}, \tag{7}$$

where the Nusselt number is Nu, k as thermal conductivity in W·m^{-1}·K^{-1} and D the diameter of the furnace in m. The nusselt number depends on the geometry of the furnace and needs to be calculated for a horizontal cylinder and two vertical walls, for a horizontal cylinder the nusselt number is calculated with

$$Nu_D = \left(0.6 + \frac{0.387 \cdot (Ra_D)^{(\frac{1}{6})}}{(1 + (\frac{0.559}{Pr})^{\frac{9}{16}})^{\frac{8}{27}}}\right)^2. \tag{8}$$

where Pr is the Prandtl number and Ra the Rayleigh number that were calculated with

$$Ra_D = \frac{g \cdot \beta \cdot (T_{Surface} - T_{surroundings}) \cdot D^3}{\nu \cdot \alpha}, \tag{9}$$

where g is the gravitational acceleration in m· s^{-2}, β as the thermal expansion coefficient in K^{-1}, ν as kinematic viscosity in m^2· s^{-1} and α as thermal diffusivity in m^2· s^{-1}. Calculation of the heat losses from front and backside of the furnace were carried out similarly as for the cylinder, with the assumption that it can be calculated as a vertical wall with

$$Nu_L = \frac{h \cdot L}{k} \Rightarrow h = \frac{Nu_L \cdot k}{L}, \tag{10}$$

where $L = A \cdot P^{-1}$ is the characteristic length in m with P as the perimeter of the furnace surface in m. The nusselt number for a vertical wall is similar to a cylinder and is calculated with

$$Nu_L = 0.68 + \frac{0.67 \cdot (Ra_L)^{(\frac{1}{4})}}{(1 + (\frac{0.492}{Pr})^{\frac{9}{16}})^{\frac{4}{9}}}. \tag{11}$$

The Rayleigh number for equation 10 is calculated with characteristics length instead of the diameter with

$$Ra_L = \frac{g \cdot \beta \cdot (T_{surface} - T_{surroundings}) \cdot L^3}{\nu \cdot \alpha}. \tag{12}$$

Equation 13 was used to calculate the difference in energy of the material entering and leaving the furnace during a brazing cycle. The different masses of the materials, stainless steel, copper and graphite were partly weighed but also prescribed in specific production orders. So a total weight of materials were calculated and estimated with a relatively small margin of error. The temperature of the exiting parts graphite, copper and stainless steel were measured with the IR-camera. Two different measured average values for the temperatures were used in the calculations, 80°C for graphite and 30°C for stainless steel and copper. Other estimations regarding measurements were that the materials leaving the furnace had a uniform temperature, and that internal parts of the furnace had the same temperature in the beginning as in the end of the brazing cycle.

$$\begin{aligned}\Delta U_{load} = {} & m_{cu} \cdot C_{p,cu} \cdot (T_2 - T_1) \\ & + m_{steel} \cdot C_{p,steel} \cdot (T_2 - T_1) \\ & + m_{graphite} \cdot C_{p,graphite} \cdot (T_2 - T_1)\end{aligned} \tag{13}$$

where m is the mass of the objects in kg and C_p the specific heats of the materials in kJ$\cdot$ kg$^{-1}\cdot$ K^{-1}.

3.3 Measurements

As a part of the power balance of the furnace, temperature and flow measurements of the cooling water were conducted at two consecutive brazing cycles. Measurement points for the cooling water supply and return of the furnace cooling system were placed according to Figure 7. Both the temperatures and flow were measured outside of the pipes, using thermocouples for the temperatures, and a clamp-on meter for the flow. A wall thickness probe was also used to measure the thickness of the pipe , resulting in a thickness of 2 mm at the measurement point.

Temperatures on the inside and outside of the pipes were assumed to be uniform, due to the relatively thin stainless steel pipes thicknesses. Six "Onset HOBO data loggers" with temperature probes were used to log the average temperatures once every minute during the recorded cycles. According to specifications [9], the Hobo probes has a temperature measurement accuracy of ± 0.35°C from 0°C to 50°C, and a temperature range of -20°C to 70°C.

The flow meter "Portable ultrasonic flowmeter fluxus ADM 6725" was used to measure the flow FM2, closest to the water tank in Figure 7. The two remaining flows, FM1 and the quick cooler flow would later be determined by examining the furnace monitoring system.

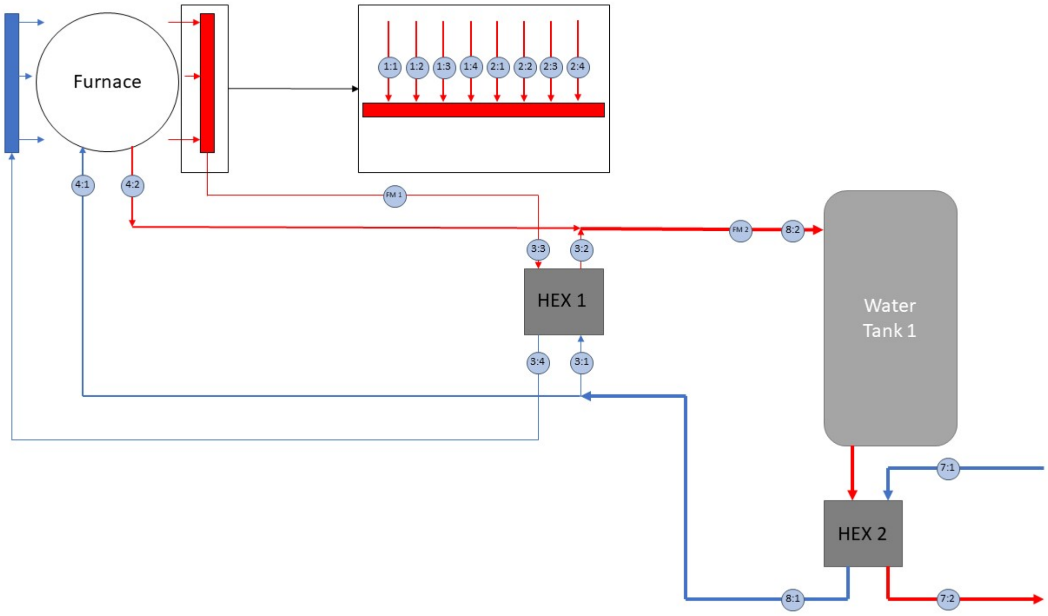


Figure 7 – Measurement points placed on cooling system

3.4 Efficiency of cooling tower

The efficiency of the cooling tower was calculated to see how well it performed, considering supplying the furnace cooling system with cooled water. Its efficiency was calculated with

$$\eta_{Cooling\ tower} = \frac{T_{water\ inlet} - T_{water\ outlet}}{T_{water\ inlet} - T_{wet\ bulb\ temperature}} \tag{14}$$

where $T_{water\ inlet}$ and $T_{water\ outlet}$ are the water temperatures in K that enters and exits the the cooling tower. Both values were measured during a brazing and can be seen in Figure 7, corresponding to placements 7:1 and 7:2. Wet bulb temperatures, associated to the outside dry bulb temperatures were estimated using a mollier diagram[10] together with measured values of the dry bulb temperature and the relative humidity, both supplied by Alfa Laval.

3.5 Interview with furnace manufacturer

An interview was conducted with a sales engineer and a furnace design engineer from company A. The purpose of the interview was to discuss the possibilities of raising the cooling water temperature of the furnace to an inlet temperature of around 50°C, and the limitations and dangers of doing so. The overall focus of the discussion referred to the safety of the furnace parts and its limitations in terms of heat tolerance, as well as personal safety. Following questions were prepared prior to the interview.

- What are the maximum cooling water temperatures of the furnace cooling water inlets and outlets for both the vessel circuit and quick cooler?
  - Are there any differences for the maximum cooling water temperatures for the vessel circuit and quick cooler?
  - What would be the immediate dangers of raising the temperatures of the cooling water?
  - What are the sensitive parts of the furnace regarding cooling circuit temperatures?
  - Could temperature-sensitive parts potentially be cooled separately?
  - Could the maximum outlet and inlet temperatures be kept during a full cycle?
- What are the minimum and maximum requirements for the volume flow of the quick cooler and vessel circuit?
- How would an increased temperature of the cooling water affect the cooling phase regarding time?
- Have you had any part in the development of the cooling systems for the furnaces at Alfa Laval?

3.6 Test of increasing furnace cooling water temperature

Three different test procedures were proposed to and discussed with the management and furnace experts at Alfa Laval in Ronneby. A clean-up cycle test was set to be the first test in the series. By starting to test with that cycle, and analysing results from it, no brazing load inside the furnace would risk being damaged or otherwise have any unwanted changed material properties. The clean-up cycle test consisted of two parts, first an ordinary test, and then the second part would raise cooling water temperatures above recommendations set by furnace company A. Along with the test, an execution plan was conducted in case temperatures of the furnace or associated parts would get too high during the different cycles.

3.6.1 Test on clean-up cycle

A test protocol for a furnace clean-up cycle was made for the maximum temperature of the cooling water according the manufactures specifications.

1. Set up thermocouples according to Figure 7 to log the temperatures of the cooling water of the furnace during the test.
2. Change the setting for the emergency cooling to turn on at 35°C.
3. Change the setting on the by-pass between heat exchanger and cooling tower to 30°C.

4. Start the clean-up cycle.
5. Monitor temperatures over sensitive areas via furnace own monitoring software.
6. Thermograph the furnace continuously during the cycle to identify any hot-spots.

After the test is done the results will be analysed and evaluated to see if it's possible to run the test on a normal cycle.

3.6.2 Test on a normal cycle

If the first test is successful and no problems or too high temperatures are recorded in the clean-up cycle, the same test will be completed on a normal cycle. The difference between the normal and clean-up cycles is the cooling phase, in this test the focus will be on the cooling phase to see if the higher temperature in the cooling system will have an impact on the time it takes to cool the furnace. This test will determine if it's possible to use a higher inlet temperature than 30°C on the cooling water in the system Alfa Laval uses today.

3.6.3 Desired test

If the conclusion for the test on a normal cycle is that there are no problems with 30°C for the cooling water inlet temperature, then an optimal test would be to raise the inlet temperature of the cooling water so the desired outlet temperature is met, at 55°C. This would be done in a clean-up cycle to ensure that there is no interference with the production. The test would be done similar to the first, but raising the inlet temperature in increments of 5°C, and when the system is in equilibrium, evaluate if it is safe to continue to the next temperature step.

3.6.4 Execution at excessively high cooling water temperatures

1. Turn on the emergency cooling and reduce the bypass temperature setting between heat exchanger and cooling tower to 20°C. Lower temperature than 20°C of incoming cooling water risks condensation of the cooling water
2. Safety systems monitor the sensitive parts of the furnace continuously during the heating process. Fuses or "bi-metals" go off at the electrode feedthroughs if the temperature exceeds 90°C and further heating of the furnace is interrupted. The furnace returns to a normal state when the temperature of the bi-metals has cooled sufficiently, which approximately takes 30 minutes according to Alfa Laval.

3.7 Improvements to the cooling system

Upon analysing the results from measurements, mapping out cooling systems for the furnaces and speaking with furnace experts at Alfa Laval, we realized that changes had to be made to the current cooling systems. The systems were at the time working well enough to control the furnaces temperature, though with the occasional use of city water as emergency cooling when temperatures of the furnaces got too high. But the current cooling system would not be able to support the desired increase of temperature quality over the furnaces cooling circuits, which was necessary for recovering as much energy as possible. The improvements would allow for a more controlled cooling, where water from the cooling towers could be stored in a more efficient way and be of better use in the later brazing cycles' cooling phase.

3.8 Recovery of waste heat

There were a lot of concerns from both the furnace company and Alfa Laval employees that recovering waste heat from the furnace would make the cooling of the furnace significantly longer. Therefore the focus has been on recovering waste heat during the heating phase of the cycle to not impact the length of the cycle and limit the production. Depending on the results from the test that are going to be done there are two cases on how to recover the energy from the furnaces. Both aim to minimize the usage of district heating with a goal to not use any additional machinery. 55°C was chosen because toady's system is designed for that temperature and legionella will not be a problem above this temperature.

3.8.1 Case 1 : Less than 55°C

If the temperature quality is lower than 55°C the waste heat will be used to heat the buildings hot water return and lower the need from the district heating network. Seen from the district heating companys' perspective, this alternative is less desirable since the district heatings' return water will be hotter. There is also the alternative to add a heat pump to raise the temperature quality to 55°C or higher to be able to satisfy the heating need, even if extra equipment then would be needed.

3.8.2 Case 2 : Equal to or above 55°C

If the temperature quality is higher than 55°C the waste heat will be used in parallel with the district heating system. If there is no waste heat the district heating system will be used.

4 Results

This chapter presents the general findings of our literature study, measurements, interviews and calculations. Further comments and analyzes regarding the obtained information in this chapter is discussed in chapter 5.

4.1 Literature study

4.1.1 Brazing vacuum furnace

Historically vacuum furnaces has enabled a wide range of applications including annealing, brazing and different forms of hardening operations. Cold wall vacuum furnaces like the ones operated at Alfa Laval consist of a heating source produced by electric elements in the central part of the furnace, directly affecting the brazed parts through heat radiation. Graphite is mostly used to isolate the hot zone and heat source, followed by an air gap. The cold wall consists of two layers of stainless steel, outer and inner shell, which are separated by circulating chilled water to keep a safe surface temperature, close to the ambient air [11].

Brazing in vacuum furnaces is particularly used to join metals and alloys which easily reacts to either nitrogen, oxygen or other gases. The vacuum creates an atmosphere with a minimum amount of gases in order to avoid oxidation, carburizing, decarburizing or nitriding. Complex assemblies, for example heat exchangers made of stainless steel are increasingly vacuum brazed. The system for achieving various vacuum levels generally require three pumps consisting of a roughing, booster and diffusion pump with a pressure range as low as $1.3 \cdot 10^{-5}$ Pa. [6]

A brazing cycle starts with the load being charged into the furnace, vacuum and inert gas are used to reduce the pressure, and heating is done by convection and radiation. The parts are heated uniformly to minimize distortion, then held at a temperature below the filler alloy's solidus temperature for a soak period. Then, a low pressure is created through vacuum pumping to remove volatile species and dirt. The temperature is then increased to the brazing temperature, where the braze alloy melts and is drawn into the joint. The pressure may be increased if necessary, and the soak time at brazing temperature is carefully controlled to assure melting of all braze alloy and prevent embrittlement. The final properties of the braze joint are influenced by the time at temperature, and if necessary, an extended time at the brazing temperature is used to allow the lower melting point elements in the filler alloy to diffuse into the base material. Finally, the temperature is lowered until all the braze alloy is solidified. Cooling rates depends on the risk of distortion and requirements of material properties.[6]

4.1.2 CCSRF

Like the furnaces used at Alfa Laval [12] lisuch et.al implemented CCSRF (Controlled Shell Cooling System for Rotary Furnaces) on a rotary furnace at SMZ Jelsava to decrease the furnace shell losses, releasing heat to the ambient air. By introducing the heated air gap in between the original shell and newly installed water cooled shell of the furnace, shell heat losses dropped from 13.95 % to 5.21 %. Because of the increase in temperature on the original shell, the temperature gradient in the furnace wall was reduced, resulting in a lower heat flow through the original furnace shell. The newly installed CCSRF also reduced the use of fuel (natural gas) by 8 %.

4.1.3 Waste heat recovery

About 40 % of the total fuel consumption in the modern world is used for domestic heating, industrial heating and processes. About one-third of this is wasted to the atmosphere at many stages of processes.[13] There are different ways of recovering this waste heat, directly or indirectly, with the latter being the most common. Direct heat recovery is usually a cheap alternative but has more restrictions on location and contamination concerns. Indirect is when some heat transfer surface separates two fluid streams, this can be done with a passive heat exchanger that requires no external energy input or an equipment such as a heat pump.

When discussing waste heat recovery, the temperature level is often specified in grades. There are three different grades of heat waste, low grade when the temperature is less than 100°C, medium grade when the temperature is between 100°C to 400°C, and high grade when it is over 400°C.[13] Low-grade waste heat can only be effectively recovered when there is a high quantity of waste heat. However, in medium and high grades, there are many examples of recovery projects that were able to make significant cost savings.

The potential sources for high-grade waste heat are mainly limited to iron, steel, glass, ceramics, and bricks industries that often use furnaces that run very hot in their process. Medium-grade waste heat is found in food and drink, chemicals, and other process industries. Low grade can be found in all areas of industry and is generally the hardest to recover cost-effectively. It is often used for heating buildings and hot water production.[13]

Alternative ways of using low waste heat instead of heat pumps is discussed by Ammar[14]. The potential of adsorption refrigeration as an efficient way of using low waste heat. Driven at temperatures below 100°C (hot water source at 45°C to 90°C) it allows the use of a wider range of temperature qualities. A multistage cycle has been simulated, with a reported COP of 0.38 using low grade heat at 80°C, cooling temperature of 30°C, inlet chilled water temperature of 14°C and chilled water production at 6°C.

Although 75 % of the earth's surface consists of water, only 3 % is fresh water of which 0.5 % is available for drinking. An interesting way of using low waste heat could therefore be to produce fresh water on site in areas without or with a small access to fresh water. A small phase change desalination unit developed by Gude and Nirmalakhandan is an alternative when considering reusing waste heat. The technology in the study used saline water and let it evaporate at 45°C to 50°C under vacuum level pressures without mechanical power put in. With a power input of 312 W and evaporation temperatures of40°C 6 litres was produced per day [14].

Pinch analysis is a method for assessing and identifying improvements in process heat recovery, by targeting and designing of heat exchanger networks. Data regarding heating and cooling demands, and the actual process streams are taken into account when the maximum internal heat recovery of the process is determined. Pinch analysis is a relatively simple method for the visualisation of heat recovery potential between different processes and a co generation system used on a site [15]. However it is further described that the conventional pinch analysis isn't suited for process flows with different heat recovery temperatures. An alternative similar method more suited to the varying heat recovery temperatures is the "tangency technology", presented in a study performed by Fang [16]. Tangency technology enables the optimization of collecting waste heat sources with multiple temperature grades. According to the study, a temperature and heat flow compound curve is firstly drawn in a diagram. Secondly a tangency line is drawn which coincides with the available heat sources in the diagram. In the optimal theoretical process, multiple heat exchangers can then be used to recover waste heat from a single source in the drawn sections diagram. However, this can result in a complex piping layout and heat exchanger installation. A practical optimal process is therefore derived from the theoretical one to simplify the design and make it more feasible.

4.1.4 Heat pump

Data centers generates low temperature waste heat via both air and water cooling reaching up to 80°C. Huang[17] states that by connecting the waste heat to the district heating network, especially in Nordic countries is an effective and efficient way to connect data centers to the energy system and recover the excess energy flows. Further, the author suggests upgrading the heat through heat pumps if necessary. Depending on the different ranges of temperatures reused, multi-stage cycles with two or more evaporators can be used to increase the overall efficiency of the system dramatically. An architecture of the overall system connection is also introduced, with the use of an energy sharing heat pump connected between the data centre and district heating. The system is in turn supported by a ground source heat pump and two borehole fields acting as hot respectively cold thermal storage.

4.1.5 Organic rankine cycle

The organic rankine cycle is viable for converting heat to electricity when discussing low-grade heat waste recovery. This cycle is possible by circulating an organic working fluid in a closed thermodynamic cycle. Although usually, the rankine cycle uses steam that requires high temperature, the organic rankine cycle features advantages to this by utilizing favorable working fluid properties of organic fluids in low-temperature applications. The temperature for the evaporator can span from 50°C to 350°C depending on the chosen working fluid.[18] Some advantages of the organic rankine cycle are that it does not require superheating, has a lower turbine inlet temperature, lower evaporating pressure, and no need for a water-treatment system. However, there are some disadvantages too: some working fluid is not very environmentally friendly, could be flammable or toxic, has lower efficiency, and costs more than water.[18]

4.1.6 Fourth and fifth generation of district heating

Energy use and efficiency is currently a discussed topic. According to the Danish Energy Agency [19], energy usage for heating of buildings is progressively decreasing, while the efficiency of consumer sides rises. However the heat demand in buildings decreases, and with it, the relative heat losses in traditional district heating increases. The combination of efficiency and low relative losses enables low temperature district heating, i.e. fourth generation, to grow. Fourth generation is aiming for a 50°C temperature supplied at the consumer, with a peak-load supply line of about 65°C to 75°C in Northern Europe [19].

Persson [20] also points at a distribution temperature of 50°C with a return temperature of 25°C, which is reducing heat losses while making pipe materials more flexible and cheaper. Persson further presents a map produced 2014, consisting of Europe's cities with one or more district heating systems. Former generations technologies for district heating highlights the substantial temperature drop of currently developing generation systems, which drastically increases the opportunities of using recycled energy and low temperature sources [19]. The first generation using high temperature steam, <300°C, second using pressurised water, <100°C, and third, also referred to as "Scandinavian district heating technology", still using pressurised water but mostly below 100°C [21].

According to Lund et al [21] future grids may use systems with annual distribution temperatures of 50°C and 20°C regarding supply respectively return pipes. The fifth generation in turn can be seen as the most advanced district heating system, working with temperature levels of 12°C to 30°C in the hot line and 4-22°C in the colder line of distribution [22]. Instead of high temperatures, Kadir and Özkan states that buildings themselves use heat pumps to acquire the required temperature, whether it is needed for cooling or heating.

4.1.7 Safety

According to Colella [23], contact burn injuries depend on physical parameters such as material properties, duration of exposure, temperature of the hot object as well as physiological properties, such as body tissue composition and hydration. Moritz and Henriques has previously formed a burn threshold curve showing the exposure time required to reach a first, second or third degree burn at different skin temperatures. Two standards regarding burn injuries are ASTM C1055 and ISO 13732-1 where the former directly relies on Moritz and Henriques burn curve and the latter asses the risk of a burn injury depending on the surface temperatures of the hot object. The material of the hot surface i.e the conduction capacity also has a significant impact on the threshold curves, it is seen that metals yield a lower 1st degree burn temperature then for example plastics.

When dealing with water in for example evaporating air coolers, it's of importance to consider the growth of Legionella. It grows in the range of 20°C to 45°C and especially between 35°C to 40°C. Reaching a uniform temperature of at least 50°C is necessary to kill most of the bacteria which in other cases may spread via water fog.[24] Alternative actions towards preventing or reducing Legionella is chemical treatment or the use of UV lighting.

4.1.8 Insulation

A study of four different insulation alternatives on a domestic furnace was conducted by the Istanbul Technical University[25]. The reference furnaces insulation, all sides 30 mm glass wool, all sides 20 mm aerogel and a combination of glass wool (20 mm) and aerogel (20 mm) was examined. With the 30 mm glass wool, the authors found a decrease of 4.5 % in the energy usage, while the other alternatives increased the energy usage, in relation to the reference furnace.

In another study done at the University of Kragujevac[26], they investigated the possibilities to use a recuperator for recovering waste heat from a rotary kiln. To limit the heat losses to the surroundings, adding insulation on the outer layer of the recuperator was investigated. It was determined that only 3 % of the initial heat loss from the kiln should be lost through the insulation and 97 % recovered to preheat the combustion air. With the help of this, the thickness of the insulation could be calculated and depending on the section of the recuperator, the thickness would be 3.2-3.8 cm.

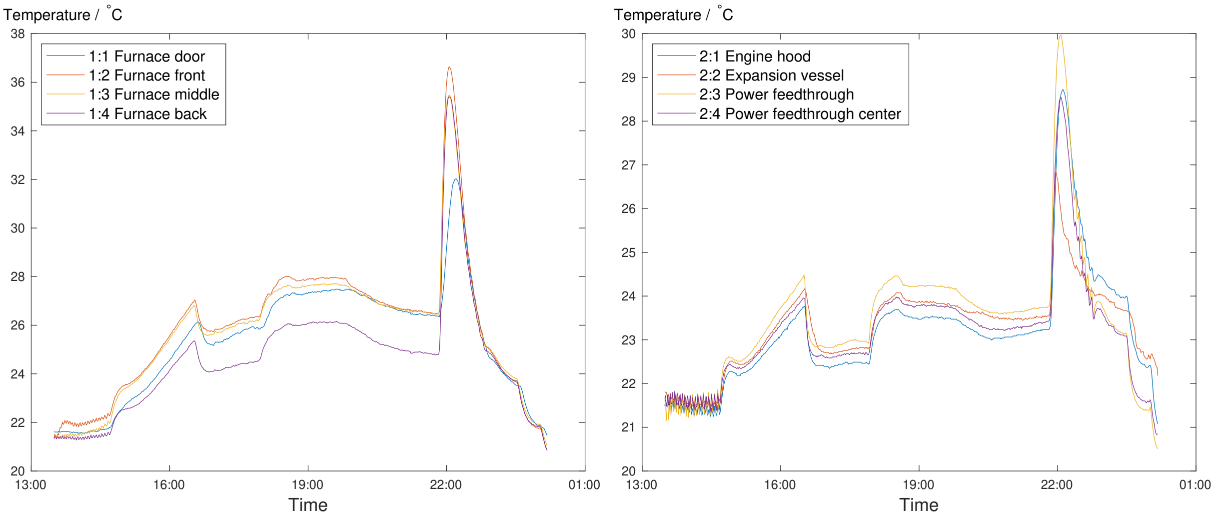
4.2 Answers from the interview with the furnace manufacturer

The maximum inlet temperatures of the furnace cooling water were specified to 30°C, corresponding to the temperatures described in the furnace vessel document that follows when purchasing a furnace. The general cautions that should be kept during a raise of the cooling water temperature were very high temperature gradients in the vacuum pump, power supply cables and the furnace cooling fan. According to company A it wasn't technically possible to guarantee being under specific temperature points throughout the cooling circuits, with risks like the water starting to boil and heat exchangers bursting because of the increased pressure.

Furthermore, the cooling phase of the cycle is already operating at a maximum temperature as it is, and the cooling water inlet temperature can not be raised anymore. All heat that is located in the load is transported to the furnace vessel circuit during the cooling phase and an increase of the temperature would decrease the cooling capacity. This could potentially lead to copper leaving its cavities in the brazed heat exchangers during the vacuum cooling. Company A also mentioned a longer overall cooling time for the cycle with an increased temperature of the cooling water. Apart from longer cycle times, the stainless steel parts of the heat exchanger could risk carbide formation because of the extended quenching phase, leaving the heat exchangers more brittle than desirable.

4.3 Measurements of cooling system with 2 supplied furnaces

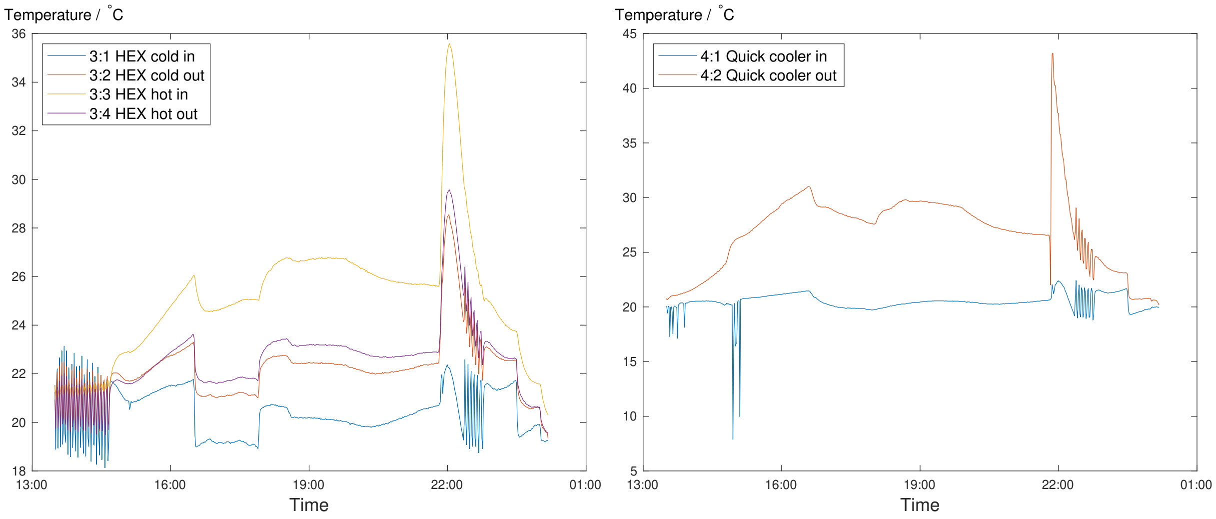
The measured temperature values corresponding to the test setup described in section 3.3 are presented in Figure 8 to 13. A sudden distinct raise of the cooling water temperature from the furnace outlets can be seen in both cycles, measured with logger 1,2 3 and 4. The raise of temperature coincides with the start of the cooling phase of the brazing cycle and lasts for roughly 2 hours before it's back to its average temperature of around 24°C. The maximum cooling water outlet temperatures for the vessel circuit and quick cooler were measured to 37°C and 44°C respectively for both cycles. Some disturbances were picked up by the temperature loggers resulting in fluctuating curves, where logger 7 and 8, measuring the cooling tower and second heat exchanger, accounted for some rapid temperature spikes. Both cycles also showed some cyclic variations between higher and lower over the second heat exchanger, shown most clearly in Figure 13.



(a) Vessel circuit outlet temperatures

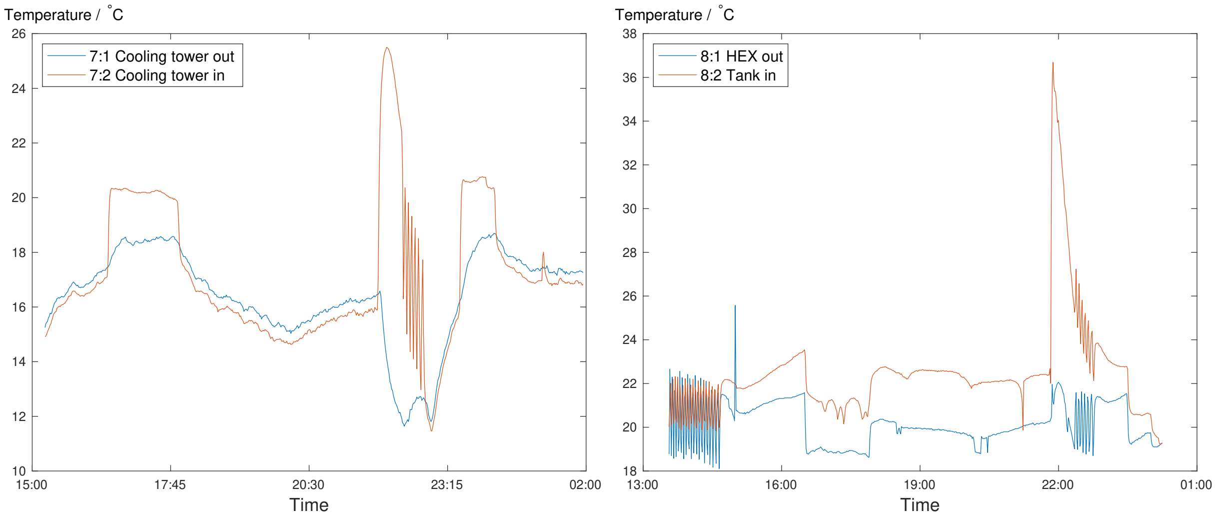
(b) Vessel circuit outlet temperatures

Figure 8 – Furnace vessel circuit temperatures during first cycle



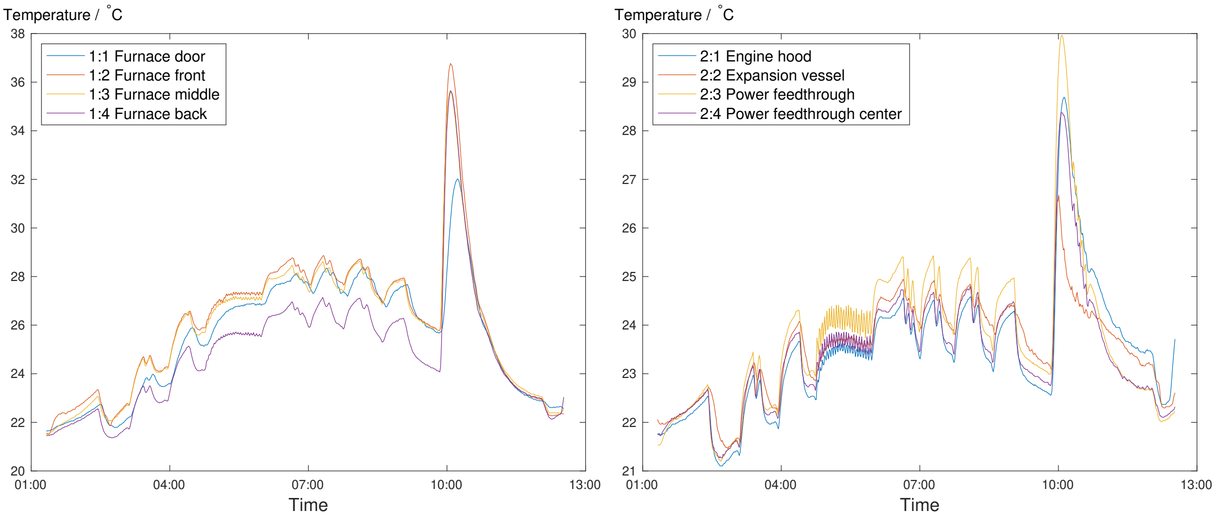
(a) HEX 1 **(b)** Quick cooler

Figure 9 – Heat exchanger 1 and quick cooler temperatures during first cycle



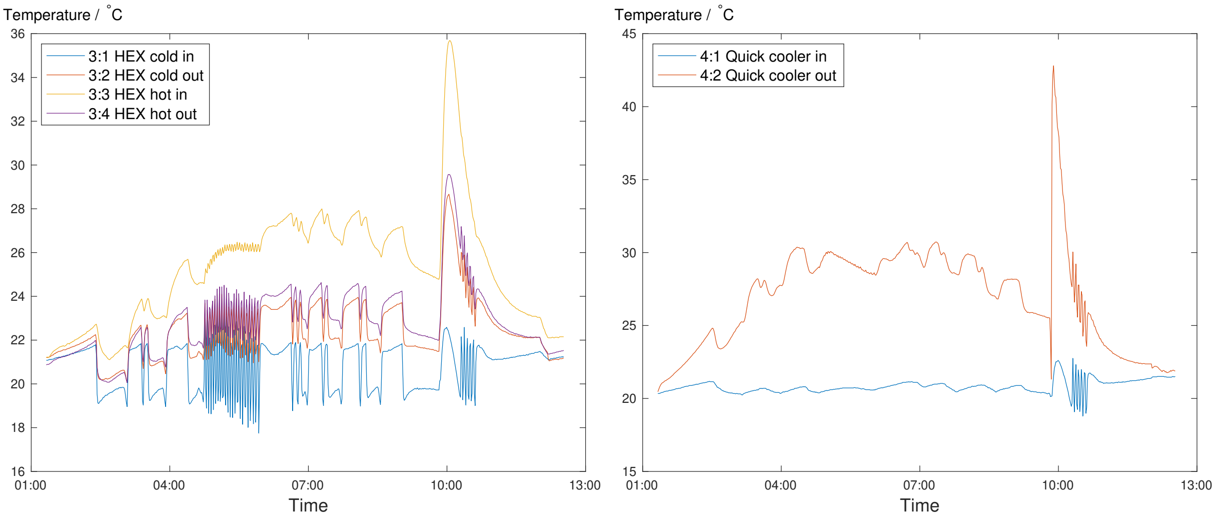
(a) HEX 2 **(b)** HEX 2

Figure 10 – Cooling tower and second heat exchanger during first cycle



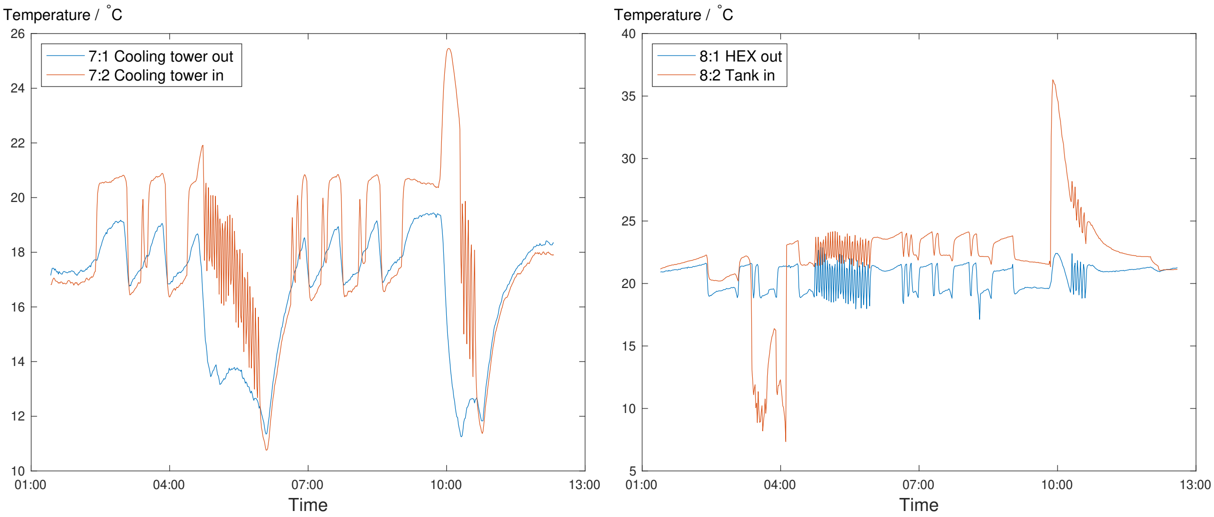
(a) Vessel circuit outlet temperatures **(b)** Vessel circuit outlet temperatures

Figure 11 – Furnace vessel circuit temperatures during second cycle



(a) HEX 1 **(b)** Quick cooler

Figure 12 – Heat exchanger 1 and quick cooler temperatures during second cycle



(a) HEX 2 **(b)** HEX 2

Figure 13 – Cooling tower and second heat exchanger during second cycle

Figure 14 shows the measured flow of cooling water through heat exchanger 1 and the furnace quick cooler. During the heating phase of the brazing cycle, the flow were measured at a rate of 35 $m^3 \cdot h^{-1}$ with an additional 31 $m^3 \cdot h^{-1}$ through the quick cooler during the cooling phase.

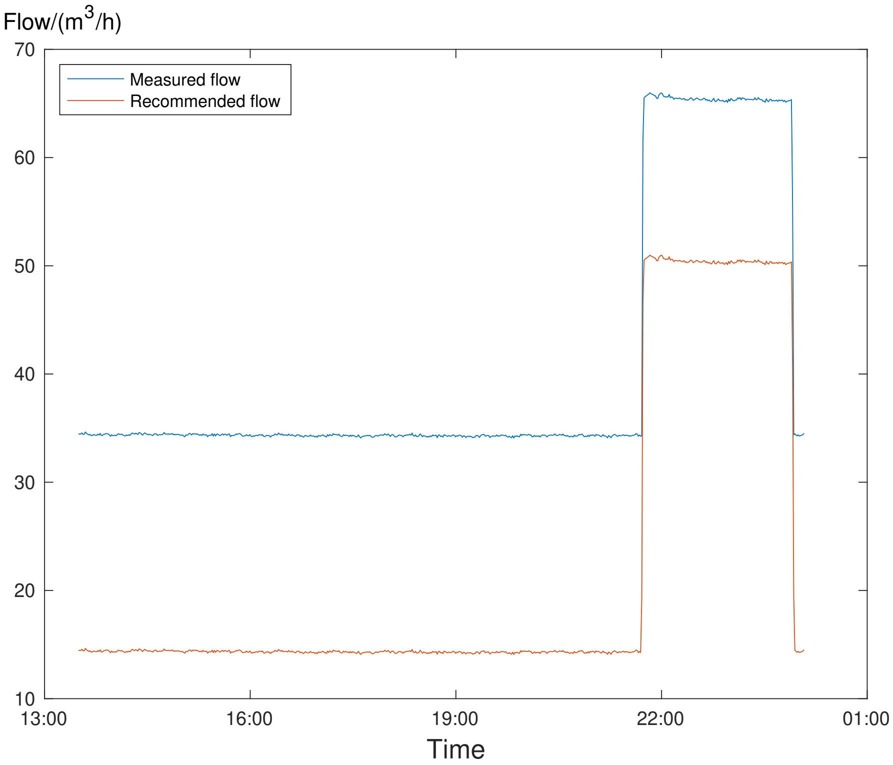
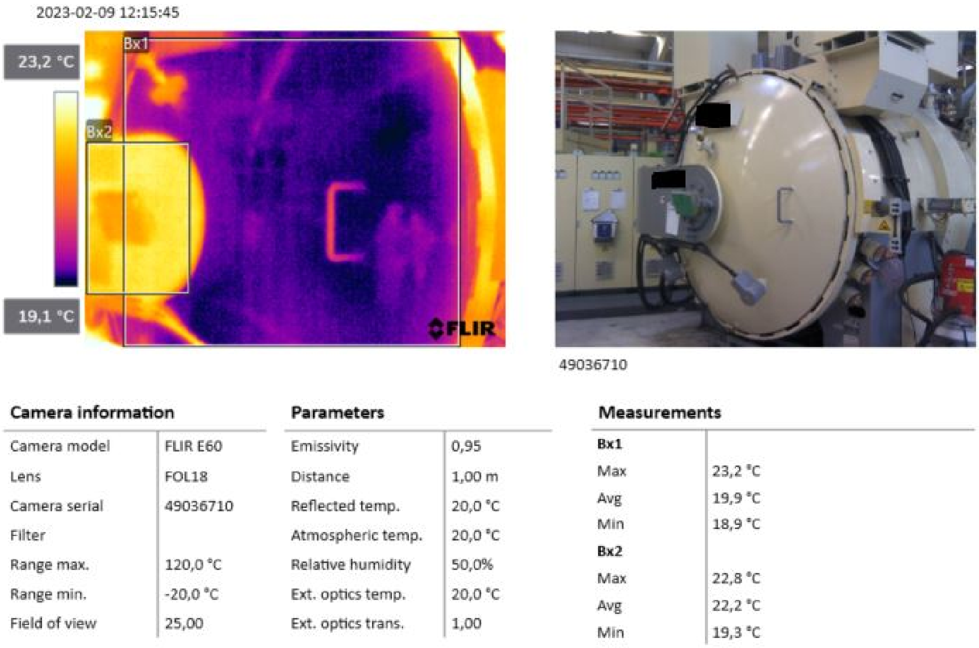


Figure 14 – Measured cooling water flow through HEX 1 and quick cooler

4.4 Power balance

IR pictures of furnace A, B and C during different phases of the cycle are shown in Figure 15 to 18. Remaining Figures which illustrates surface temperatures of furnaces from company B can be seen in appendices, Figure 39 to 41.

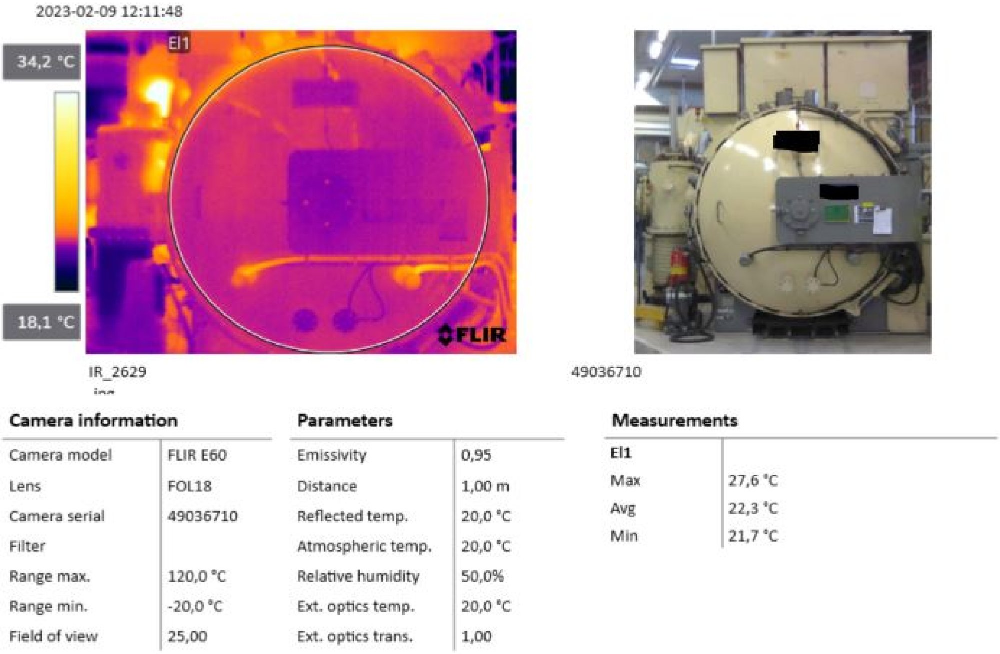


Camera information	
Camera model	FLIR E60
Lens	FOL18
Camera serial	49036710
Filter	
Range max.	120,0 °C
Range min.	-20,0 °C
Field of view	25,00

Parameters	
Emissivity	0,95
Distance	1,00 m
Reflected temp.	20,0 °C
Atmospheric temp.	20,0 °C
Relative humidity	50,0%
Ext. optics temp.	20,0 °C
Ext. optics trans.	1,00

Measurements	
Bx1	
Max	23,2 °C
Avg	19,9 °C
Min	18,9 °C
Bx2	
Max	22,8 °C
Avg	22,2 °C
Min	19,3 °C

Figure 15 – IR pictures on the front of furnace A, end of brazing cycle

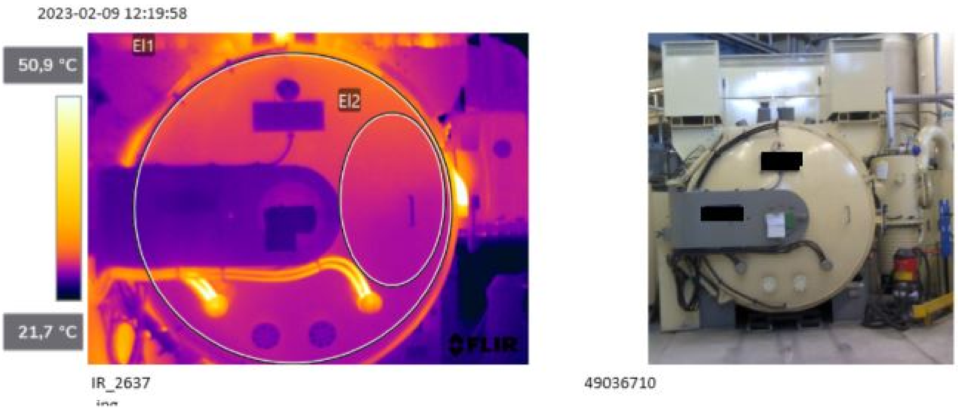


Camera information	
Camera model	FLIR E60
Lens	FOL18
Camera serial	49036710
Filter	
Range max.	120,0 °C
Range min.	-20,0 °C
Field of view	25,00

Parameters	
Emissivity	0,95
Distance	1,00 m
Reflected temp.	20,0 °C
Atmospheric temp.	20,0 °C
Relative humidity	50,0%
Ext. optics temp.	20,0 °C
Ext. optics trans.	1,00

Measurements	
El1	
Max	27,6 °C
Avg	22,3 °C
Min	21,7 °C

Figure 16 – IR picture of furnace B, heating phase at 300°C



Camera information

Camera model	FLIR E60
Lens	FOL18
Camera serial	49036710
Filter	
Range max.	120,0 °C
Range min.	-20,0 °C
Field of view	25,00

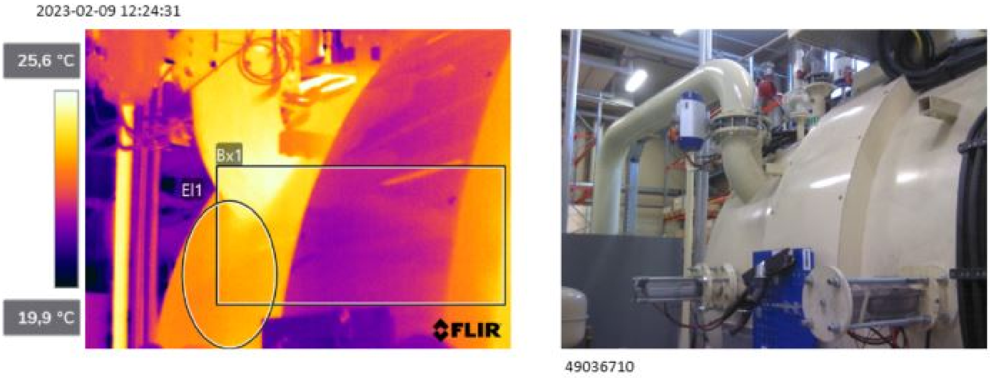
Parameters

Emissivity	0,95
Distance	1,00 m
Reflected temp.	20,0 °C
Atmospheric temp.	20,0 °C
Relative humidity	50,0%
Ext. optics temp.	20,0 °C
Ext. optics trans.	1,00

Measurements

El1	
Max	59,2 °C
Avg	27,2 °C
Min	24,1 °C
El2	
Max	28,9 °C
Avg	27,2 °C
Min	25,0 °C

Figure 17 – IR pictures on the furnace front of furnace C, heating phase above 1000°C



Camera information

Camera model	FLIR E60
Lens	FOL18
Camera serial	49036710
Filter	
Range max.	120,0 °C
Range min.	-20,0 °C
Field of view	25,00

Parameters

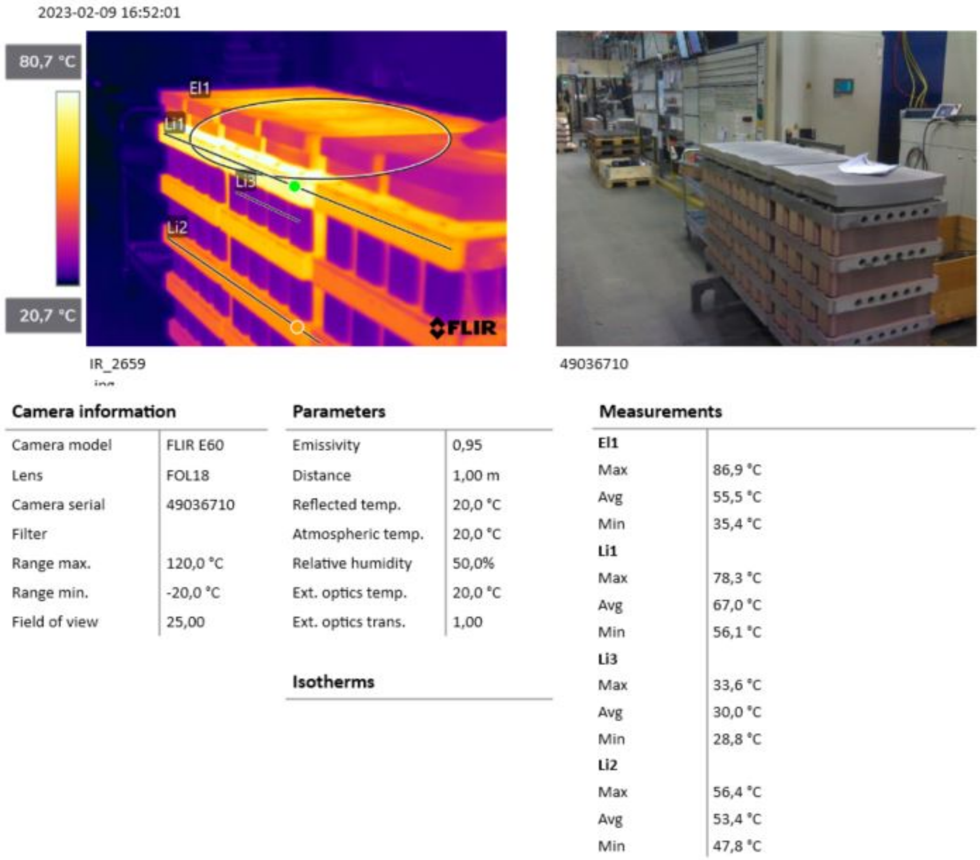
Emissivity	0,95
Distance	1,00 m
Reflected temp.	20,0 °C
Atmospheric temp.	20,0 °C
Relative humidity	50,0%
Ext. optics temp.	20,0 °C
Ext. optics trans.	1,00

Measurements

Bx1	
Max	25,4 °C
Avg	23,0 °C
Min	21,6 °C
El1	
Max	25,0 °C
Avg	23,7 °C
Min	21,3 °C

Figure 18 – IR pictures on the furnace side of furnace C, heating phase above 1000°C

Based on the IR pictures above, the average surface temperature of the furnaces were approximated to 25°C. Temperatures for the loads exiting the furnace, consisting of copper, stainless steel and graphite were respectively 30°C, 30°C and 80°C based on Figure 19 and 20.



Camera information

Camera model	FLIR E60
Lens	FOL18
Camera serial	49036710
Filter	
Range max.	120,0 °C
Range min.	-20,0 °C
Field of view	25,00

Parameters

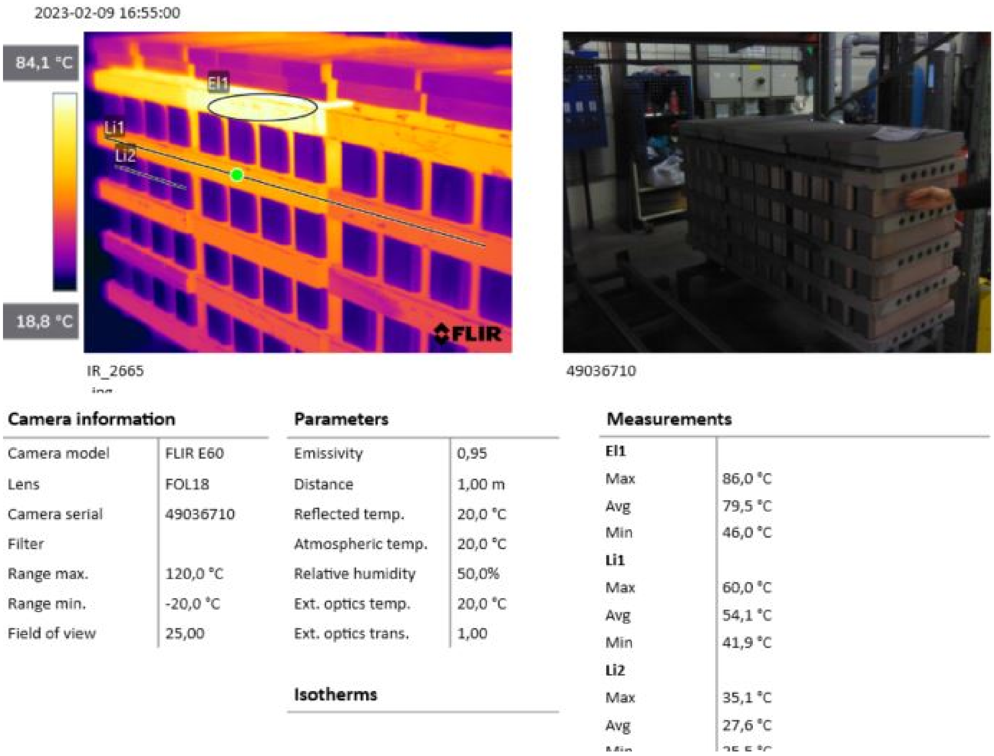
Emissivity	0,95
Distance	1,00 m
Reflected temp.	20,0 °C
Atmospheric temp.	20,0 °C
Relative humidity	50,0%
Ext. optics temp.	20,0 °C
Ext. optics trans.	1,00

Isotherms

Measurements

El1	
Max	86,9 °C
Avg	55,5 °C
Min	35,4 °C
Li1	
Max	78,3 °C
Avg	67,0 °C
Min	56,1 °C
Li3	
Max	33,6 °C
Avg	30,0 °C
Min	28,8 °C
Li2	
Max	56,4 °C
Avg	53,4 °C
Min	47,8 °C

Figure 19 – IR pictures of brazing load



Camera information

Camera model	FLIR E60
Lens	FOL18
Camera serial	49036710
Filter	
Range max.	120,0 °C
Range min.	-20,0 °C
Field of view	25,00

Parameters

Emissivity	0,95
Distance	1,00 m
Reflected temp.	20,0 °C
Atmospheric temp.	20,0 °C
Relative humidity	50,0%
Ext. optics temp.	20,0 °C
Ext. optics trans.	1,00

Isotherms

Measurements

El1	
Max	86,0 °C
Avg	79,5 °C
Min	46,0 °C
Li1	
Max	60,0 °C
Avg	54,1 °C
Min	41,9 °C
Li2	
Max	35,1 °C
Avg	27,6 °C

Figure 20 – IR pictures of brazing load 3 min later

During a cycle the temperatures of the cooling water tanks were also thermographed. Figure 21 and 22 shows the temperatures of both the tanks, and the thermal stratification of the hot water tank at an average temperature of 23°C during the time of the measurement.

Camera information

Camera model	FLIR E60
Lens	FOL18
Camera serial	49036710
Filter	
Range max.	120,0 °C
Range min.	-20,0 °C
Field of view	25,00

Parameters

Emissivity	0,95
Distance	1,00 m
Reflected temp.	20,0 °C
Atmospheric temp.	20,0 °C
Relative humidity	50,0%
Ext. optics temp.	20,0 °C
Ext. optics trans.	1,00

Isotherms

Measurements

Bx1	
Max	14,7 °C
Avg	13,0 °C
Min	12,0 °C
Bx2	
Max	24,2 °C
Avg	22,0 °C
Min	20,7 °C
Bx3	
Max	12,7 °C
Avg	12,1 °C
Min	11,7 °C
Bx4	
Max	24,9 °C
Avg	23,3 °C
Min	22,3 °C

Figure 21 – IR picture of Cold (left) and hot (right) cooling tanks

Camera information

Camera model	FLIR E60
Lens	FOL18
Camera serial	49036710
Filter	
Range max.	120,0 °C
Range min.	-20,0 °C
Field of view	25,00

Parameters

Emissivity	0,95
Distance	1,00 m
Reflected temp.	20,0 °C
Atmospheric temp.	20,0 °C
Relative humidity	50,0%
Ext. optics temp.	20,0 °C
Ext. optics trans.	1,00

Measurements

Bx1	
Max	22,3 °C
Avg	22,0 °C
Min	21,7 °C
Bx3	
Max	24,4 °C
Avg	24,0 °C
Min	23,5 °C

Isotherms

Figure 22 – IR picture of thermal stratification in hot cooling tank

Results of the power balance during a measured brazing cycle can be seen in Table 2.

Table 2 – Energy balance

Supply	Losses			Differences
$W_{electricity}$	$Q_{coolingwater}$	$Q_{radiation+convection}$	ΔU_{load}	Pipe losses or measurement errors
1546 kWh	1360 kWh	153 kWh	25 kWh	8 kWh

4.5 Efficiency cooling tower

Results of the calculated efficiency of the cooling tower can be seen in Figure 23. The calculations are based on the same cycle temperatures that are presented in Figure 11 to 13. The maximum calculated efficiency with respect to our measurements were 41 %.

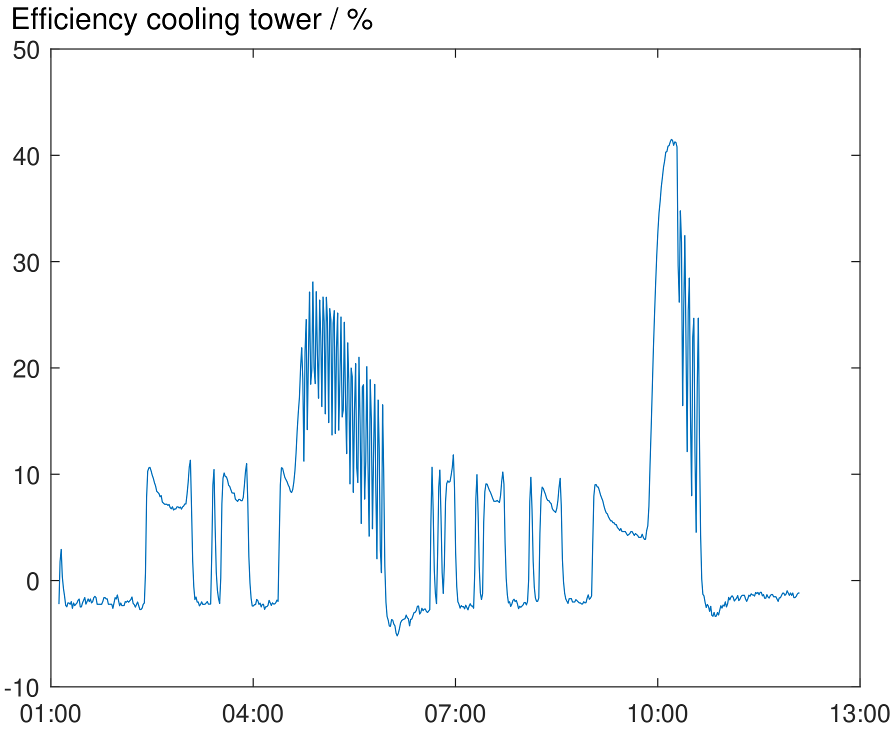


Figure 23 – Efficiency of the cooling tower during second brazing cycle

4.6 Energy potentials

During the year 2022 the Alfa Laval production site in Ronneby used a total of 1.7 GWh in form of district heating. By using equation 3, the total cooled off energy from the cooling towers during the heating phase were calculated to 630 kWh. Assuming that at least 3 furnaces consistently operate during the heating phase, 1.2 GWh of purchased district heating energy could be saved yearly, reducing the total district heating usage by 70 %. The calculation however assumes that 100 % of the cooled off energy from the cooling water could be recovered. Figure 24 shows the potential energy coverage from the furnaces cooling water that could replace current district heating.

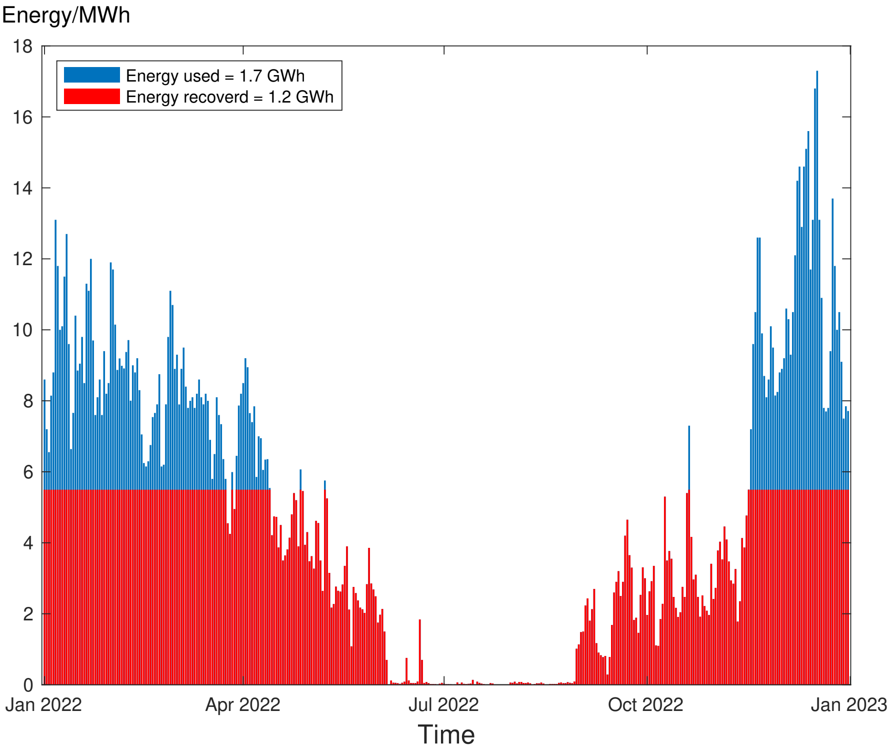
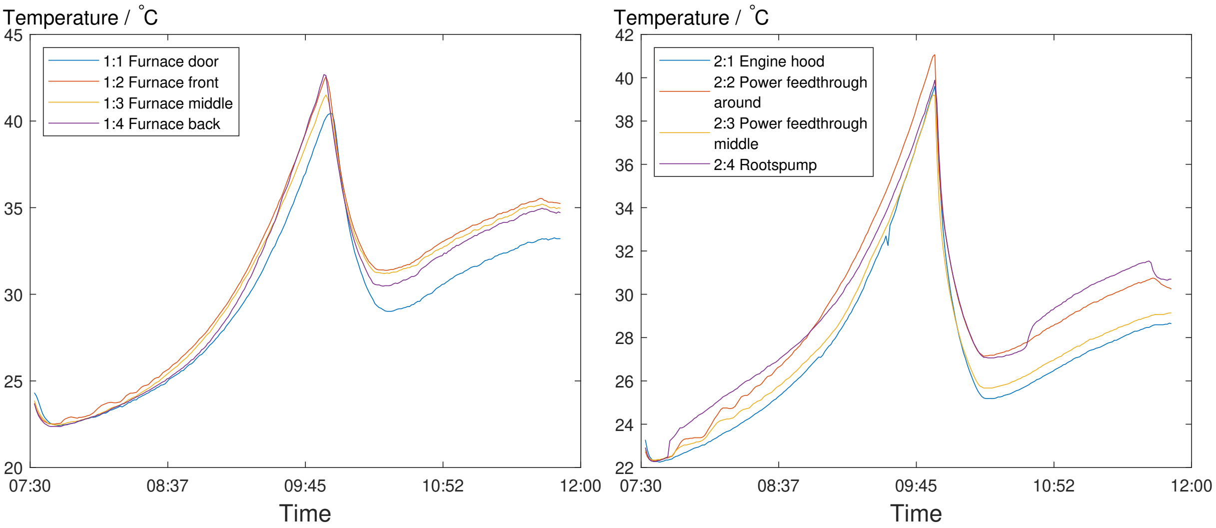


Figure 24 – Potential energy recovery from 3 furnaces, each bar representing one day

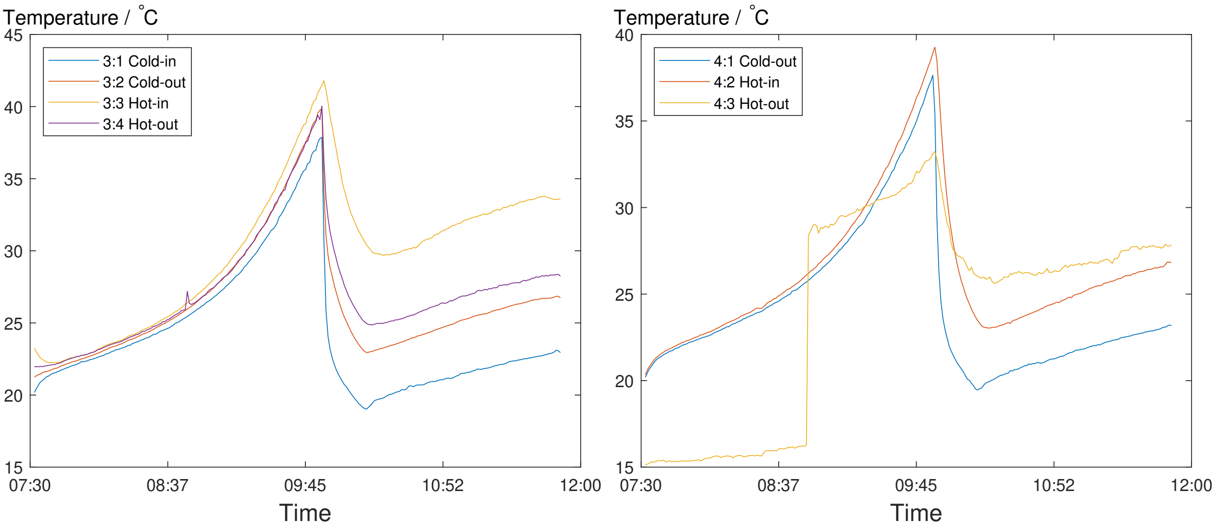
4.7 Measurements of clean-up cycle

Figure 25 to 27 shows the measured cooling water temperatures from the clean-up cycle. Outlet temperatures of the furnace cooling water reached a maximum of 43°C. Measurement points of the cooling water and references such as HEX 1 are the same as in the previously conducted measuring test, described in section 3.3.



(a) Vessel circuit outlet temperatures **(b)** Vessel circuit outlet temperatures

Figure 25 – Furnace vessel circuit temperatures during clean-up cycle



(a) HEX 1 **(b)** HEX 2

Figure 26 – HEX 1 and 2 temperatures during clean-up cycle

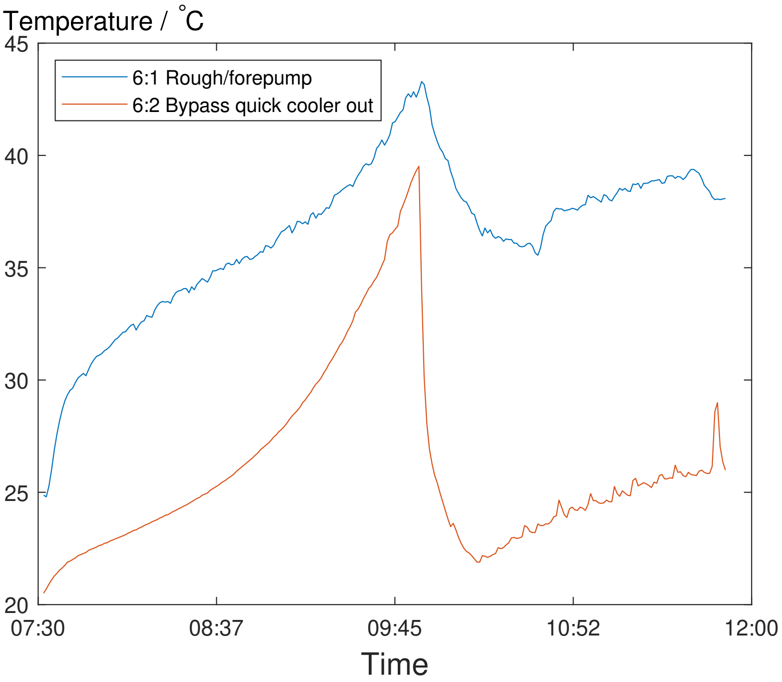
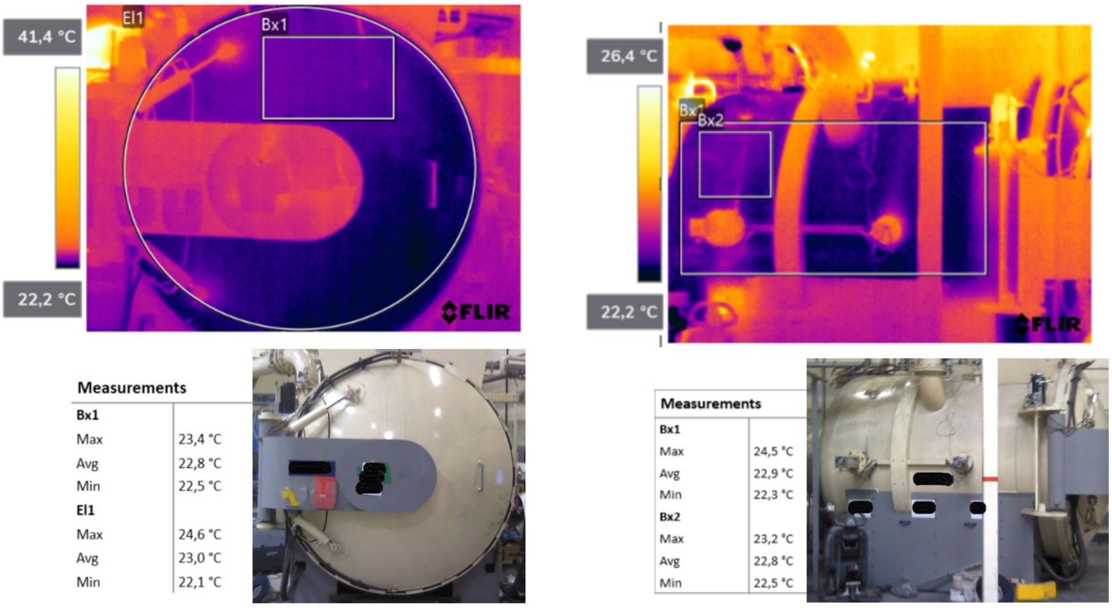


Figure 27 – Forepump and quick cooler outlet temperatures during clean-up cycle

IR pictures that were taken throughout the clean-up cycle are presented in Figure 28 to 34. These IR pictures are directly related to the cooling water temperatures in Figure 25 to 27. At 09:53 the furnace surfaces were at their hottest state, with an average surface temperature of around 36°C. Simultaneously the outside bearing of the roughpump had an average surface temperature of 83°C.



[redacted]

Measurements

Bx1	
Max	23,4 °C
Avg	22,8 °C
Min	22,5 °C
El1	
Max	24,6 °C
Avg	23,0 °C
Min	22,1 °C

[redacted] [redacted] [redacted] [redacted]

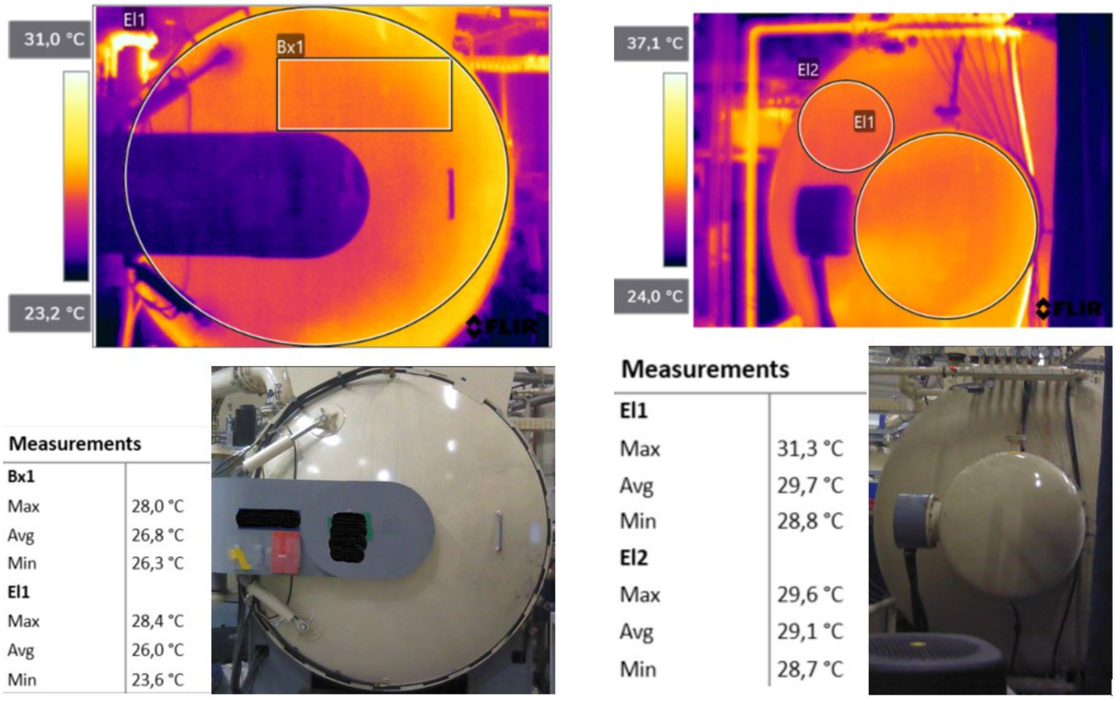
Measurements

Bx1	
Max	24,5 °C
Avg	22,9 °C
Min	22,3 °C
Bx2	
Max	23,2 °C
Avg	22,8 °C
Min	22,5 °C

(a) Furnace front view

(b) Furnace side view

Figure 28 – IR pictures of furnace taken at 08:00

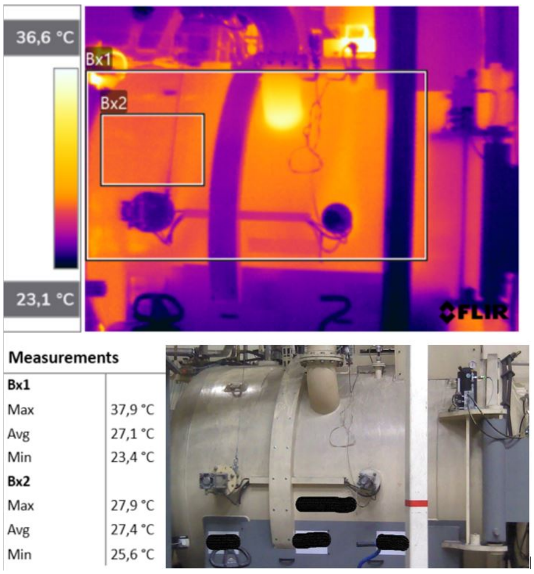


Measurements	
Bx1	
Max	28,0 °C
Avg	26,8 °C
Min	26,3 °C
El1	
Max	28,4 °C
Avg	26,0 °C
Min	23,6 °C

(a) Furnace front view

Measurements	
El1	
Max	31,3 °C
Avg	29,7 °C
Min	28,8 °C
El2	
Max	29,6 °C
Avg	29,1 °C
Min	28,7 °C

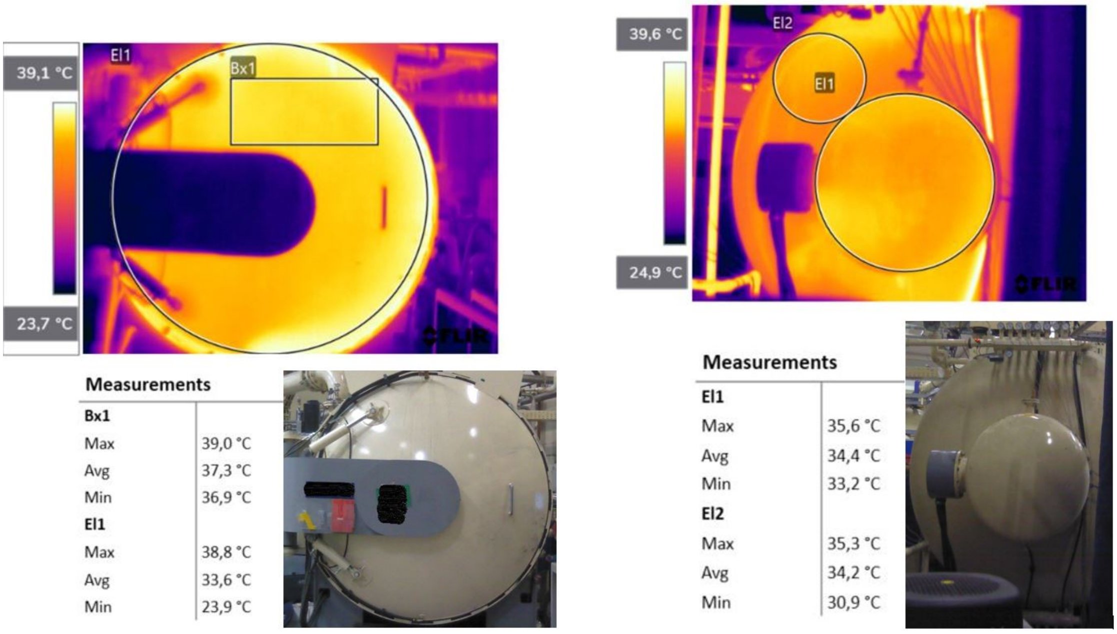
(b) Furnace back view



Measurements	
Bx1	
Max	37,9 °C
Avg	27,1 °C
Min	23,4 °C
Bx2	
Max	27,9 °C
Avg	27,4 °C
Min	25,6 °C

(c) Furnace side view

Figure 29 – IR pictures of furnace taken at 09:15

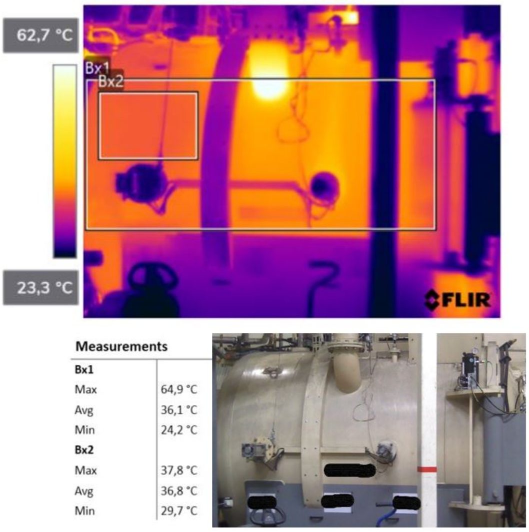


[redacted] [redacted]

Measurements	
Bx1	
Max	39,0 °C
Avg	37,3 °C
Min	36,9 °C
El1	
Max	38,8 °C
Avg	33,6 °C
Min	23,9 °C

Measurements	
El1	
Max	35,6 °C
Avg	34,4 °C
Min	33,2 °C
El2	
Max	35,3 °C
Avg	34,2 °C
Min	30,9 °C

(a) Furnace front view **(b)** Furnace back view

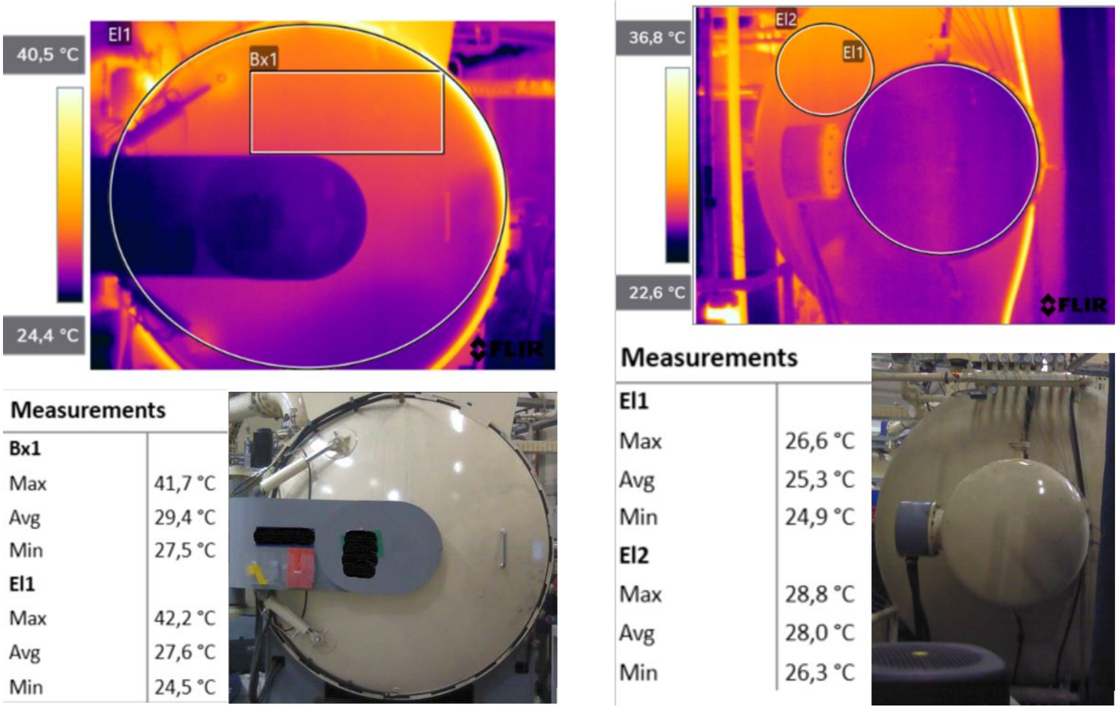


[redacted] [redacted] [redacted] [redacted]

Measurements	
Bx1	
Max	64,9 °C
Avg	36,1 °C
Min	24,2 °C
Bx2	
Max	37,8 °C
Avg	36,8 °C
Min	29,7 °C

(c) Furnace side view

Figure 30 – IR pictures of furnace taken at 09:53



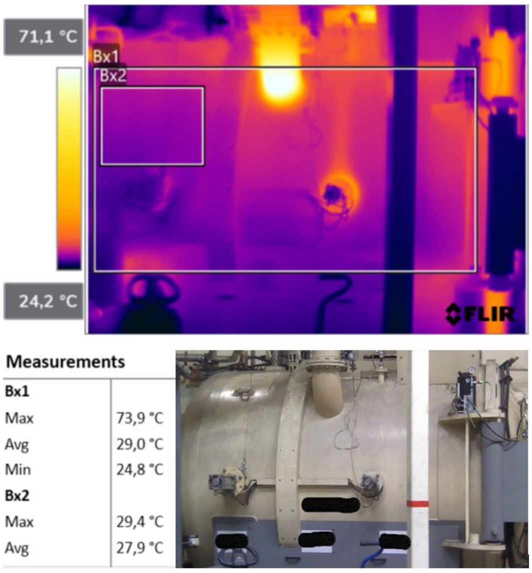
[redacted] [redacted]

Measurements	
Bx1	
Max	41,7 °C
Avg	29,4 °C
Min	27,5 °C
El1	
Max	42,2 °C
Avg	27,6 °C
Min	24,5 °C

Measurements	
El1	
Max	26,6 °C
Avg	25,3 °C
Min	24,9 °C
El2	
Max	28,8 °C
Avg	28,0 °C
Min	26,3 °C

(a) Furnace front view

(b) Furnace back view

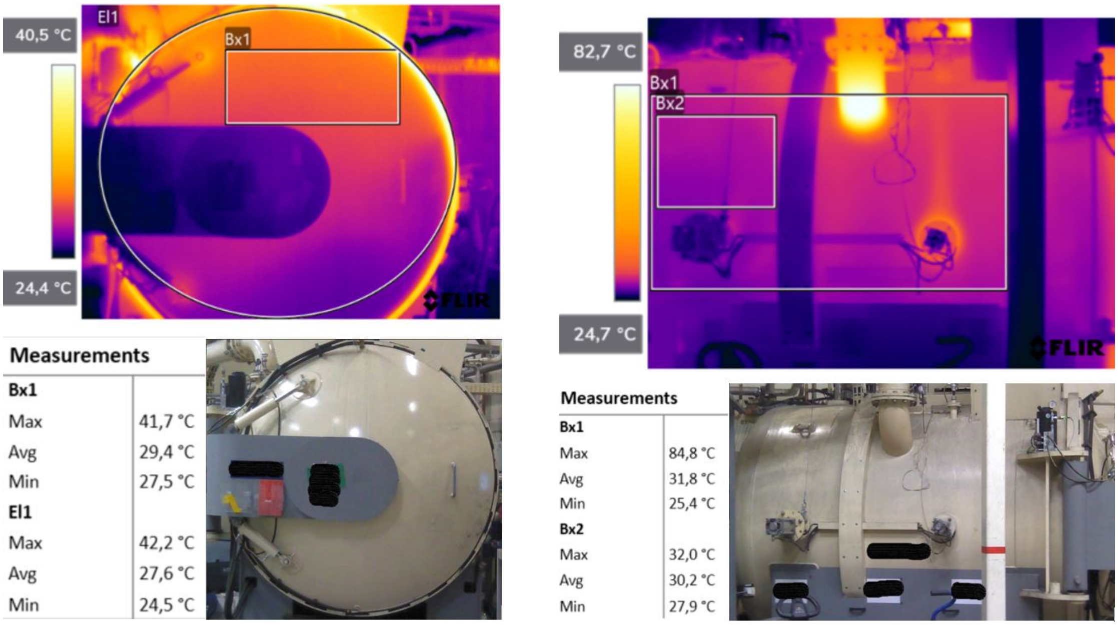


[redacted] [redacted] [redacted] [redacted]

Measurements	
Bx1	
Max	73,9 °C
Avg	29,0 °C
Min	24,8 °C
Bx2	
Max	29,4 °C
Avg	27,9 °C

(c) Furnace side view

Figure 31 – IR pictures of furnace taken at 10:30



[redacted] [redacted]

[redacted] [redacted] [redacted] [redacted]

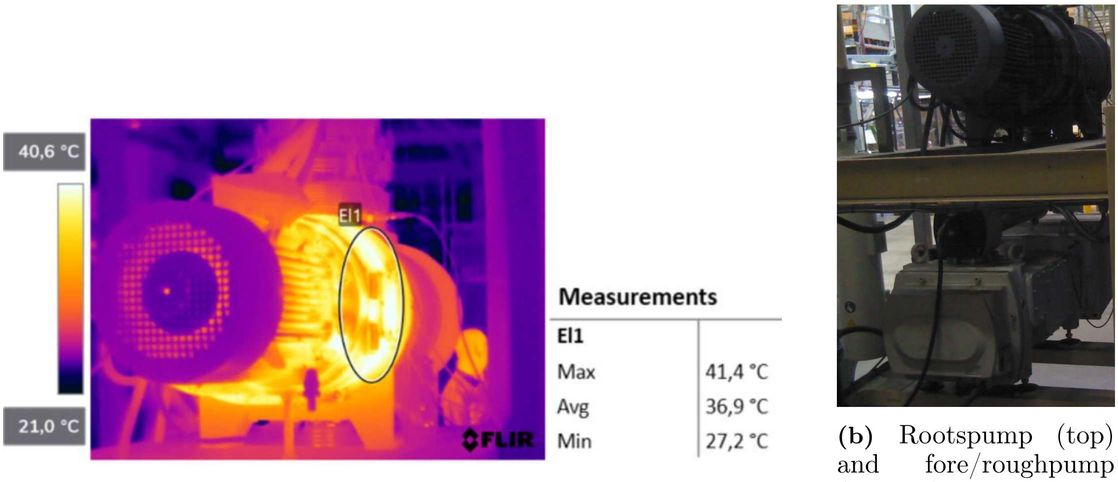
Measurements	
Bx1	
Max	41,7 °C
Avg	29,4 °C
Min	27,5 °C
El1	
Max	42,2 °C
Avg	27,6 °C
Min	24,5 °C

Measurements	
Bx1	
Max	84,8 °C
Avg	31,8 °C
Min	25,4 °C
Bx2	
Max	32,0 °C
Avg	30,2 °C
Min	27,9 °C

(a) Furnace front view

(b) Furnace side view

Figure 32 – IR pictures of furnace taken at 11:30

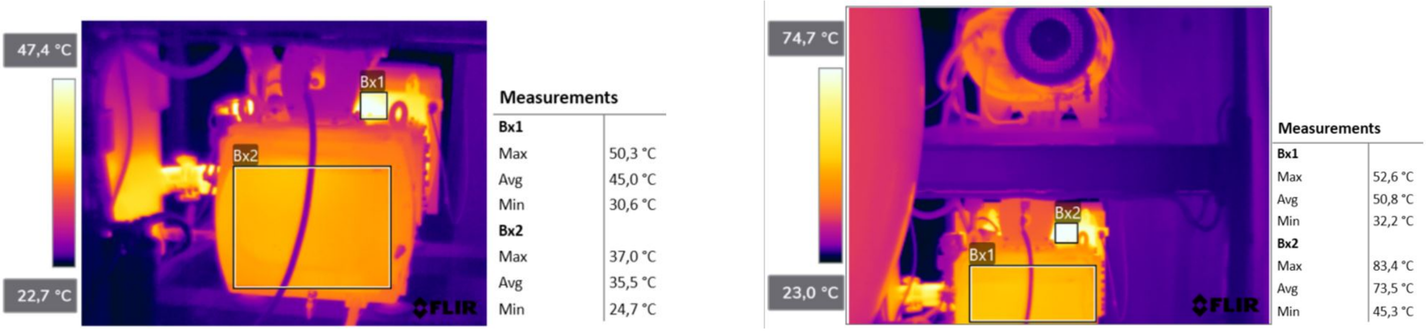


Measurements	
El1	
Max	41,4 °C
Avg	36,9 °C
Min	27,2 °C

(a) Rootspump at 09:53

(b) Rootspump (top) and fore/roughpump (bottom)

Figure 33 – IR picture of vacuum pump

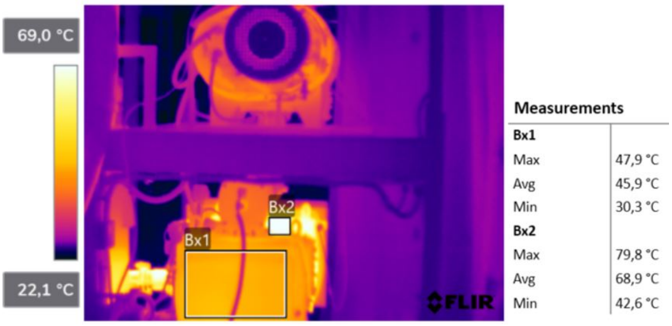


Measurements	
Bx1	
Max	50,3 °C
Avg	45,0 °C
Min	30,6 °C
Bx2	
Max	37,0 °C
Avg	35,5 °C
Min	24,7 °C

Measurements	
Bx1	
Max	52,6 °C
Avg	50,8 °C
Min	32,2 °C
Bx2	
Max	83,4 °C
Avg	73,5 °C
Min	45,3 °C

(a) Fore/roughpump at 08:00

(b) Fore/roughpump at 09:53



Measurements	
Bx1	
Max	47,9 °C
Avg	45,9 °C
Min	30,3 °C
Bx2	
Max	79,8 °C
Avg	68,9 °C
Min	42,6 °C

(c) Fore/roughpump at 11:00

Figure 34 – IR pictures of vacuum pumps

5 Analysis

5.1 Identified potentials for improvement

When mapping out the entire cooling system for the furnaces and analyzing results made from measurements, some interesting potentials for improvement were made. Furthermore this chapter will partly highlight system weaknesses and suggest more efficient alternative solutions to the current cooling system.

5.1.1 Increased cooling capacity

When examining the directions and markings of HEX 1, it shows a connection of a counter-current flow. On the other hand, it behaves as if it was co-current connected, (see Figure 12), where output flows from both circuits exits at nearly the same temperature. This results in a less efficient cooling sequence and longer cooling times during quenching, as well as reduced conditions for heat recovery. At this heat exchanger, the hot water outlet (purple) should be able to approach the cooled incoming (blue) water with a difference of about 2°C. Furthermore, the cold outlet water (orange) should approach the hot water outlet temperature of the furnace (yellow). By increasing the efficiency of the heat exchanger, the outlet temperature of the colder cooling water (orange) would be raised, which also would make heat recovery easier due to the increased temperature quality. The purple measurement series (cooling water entering the furnace) should therefore be able to be lowered by up to 6°C during the cooling phase. This is especially important due to the current critical state of the cooling process, where there are difficulties of bringing the load temperature down quickly enough. We believe that the heat exchanger itself is undersized, which could be solved by adding more plates or switching to a more efficient heat exchanger.

5.1.2 Increased temperature quality through recommended flows

After measurements during the two cycles, it can be stated that the flows of cooling water through the furnace, vacuum pump and circulation of the quick cooler are much higher than specified by company A, see Figure 14. The temperature increase of cooling water running through the furnace is currently about 4°C and could roughly be increased to about 8°C with a reduction of the water flow, referring to equation 3. It was also noted that the inlet water pressure is about 1-2 bar, even if it's specified as 3 bar according to company A. Thus, there is an opportunity to lower the flow, and thereby a second opportunity to increase the temperature quality, which further would simplify the heat recovery process of the work.

5.1.3 Cooling towers

When analyzing the temperature measurements of the two brazing cycles, we noticed that the water outlet temperatures of the cooling towers were high relative to the outside air temperature which was below 0°C. When calculating the efficiency for the cooling tower we found that it operated with a peak maximum efficiency of 41 % across the entire brazing cycle. Some reasons for the low efficiency results may be measurement errors, but also the fact that we measured the outlet temperature too far away from the cooling tower. The measurement of the water outlet temperature were done after it was mixed with the cooled water in tank 2, this can be seen in Figure 7. Another reason for the low efficiency is that the cooling fan situated on top of the cooling tower doesn't start until the inlet water reaches a temperature of 20°C. However, with respect to the stated arguments for the low calculated efficiency, it's still not close to the wanted efficiency of around 75 %.

5.2 Energy potentials

In this thesis, the brazing cycle has been divided into two different phases, heating and cooling. The cooling phase is at the time critical in the sense that the brazed load and furnace itself must be cooled quick enough to avoid unwanted structural changes of the load and longer overall cycle times. The cooling system struggled with these requirements due to vast amounts of energy needed to be cooled from the furnace, brazing load and the water tank containing $10m^3$ of cooling water, which all increases the systems thermal inertia. Slightly higher initial temperatures for the cooling system would according to Alfa Laval severely increase the time needed during the cooling phase. Therefore, suggestions were made to only increase the temperature quality and to recover energy in form of heat during the heating phase of the cycle. By separating the heating and cooling phase with their different need of cooling water temperatures, alternative suggestions had to be made for the design of the cooling system, which is further discussed in section 5.4. Another issue regarding the cooling phase was that during summer months, the cooling towers couldn't provide enough cooling effect to the systems, because of the higher outdoor temperatures. However, when analyzing the buildings need of heating, seen in Figure 24, it's clear that there are no need for heating recoveries during the summer months. During summer months district heating is only used for heating tap water in such small scales that it was seen as irrelevant when designing the new cooling system. The new cooling system would based on this section also need to be flexible to the extent that it could run both as the current cooling system, with cooler water temperatures during summer months and cooling phases, and with energy recovery from higher cooling water temperatures during heating phases, as proposed in the new system.

5.3 Clean-up test

From the alternative test procedures presented in section 3.6, tests on a furnace cooling system during a clean-up cycle were performed. A thing worth mentioning regarding the performed test is that it was carried out on a cooling system that only supplies one furnace with cooling water. Normally, a cooling system at Alfa Laval in Ronneby supplies two furnaces with cooling water. Secondly the tank size in that furnace circuit (Tank 1 in Figure 3) were only estimated to be around $2m^3$, compared to the standard used $10m^3$ tanks. The test were however done only to examine how the furnace would react to the increased cooling water temperature. Decreased thermal inertia due to less water in the system were desirable since it would speed up both the heating, and potentially the emergency cooling of the furnace water circuit and furnace itself.

At the start of the clean-up cycle, the pump that pumps water through the cooling towers water circuit was turned off. That would allow for temperatures of the cooling water, running through the different furnace channels, to increase above its' normal operating temperatures. The cycle was launched just before 08:00 with water temperatures around 23°C, seen in Figure 25 to 27. Internal temperatures inside the furnace where set well above regular operating temperatures for cleaning purposes. It took roughly one hour to reach the desired inside temperature of the furnace and after that the furnace internal temperatures were kept constant for a specified holding time.

Temperatures of the cooling water rose relatively slow during the heating phase which lasted one hour. At 09:00 an average temperature of around 27°C was measured based on the cooling water outlet connections. Once the furnace got to its' desired temperature of over 1000°C, temperatures of the cooling water started to increase with an exponential appearance. Temperatures for the outlet cooling water and the furnace surfaces reached a maximum average of 44°C and 37°C respectively, before the pump which circulates water in the cooling tower circuit was turned on again. Those cooling water temperatures measured during the cycle corresponds well with the same values from the furnace monitoring system, provided by company A.

What was limiting during the clean-up test in regards of temperature levels was the roughpump. According to the clean-up tests supervising furnace maintenance expert, the roughpumps outside bearings normally reached a maximum temperature of 70°C. However, those temperatures quickly rose above that with a peak temperature slightly above 83°C at 09:53, which resulted in the test being aborted. According to the furnace maintenance expert, the risk of causing any severe damage to the roughpump was too big at the time of the interruption. There was a discussion regarding connecting the roughpump with a separate water circuit when temperatures of the cooling water started to rise. Unfortunately the temperature levels rose faster than expected and due to time limitations there was no option but to turn on the secondary cooling circuit in order to cool the overall furnace cooling system. In future tests or implementations of a new cooling system, water supplies to temperature-sensitive parts are recommended to be cooled separately if possible, due to the quick raises of temperatures.

The clean-up test however provided a good basis for arguing that the furnace cooling system could be operated at higher temperature levels than current ones. During the test, no warnings, alarms or errors whatsoever were detected by the furnace safety system, which was a great success considering future increases in the furnace cooling circuits temperatures. Furthermore the furnace maintenance expert believed that the furnace itself (without the roughpump) could withstand higher temperatures than those maximums that were measured during the test. Another positive finding was the very quick temperature drop over the entire furnace cooling circuit, and all its nearby components once the cooling tower circuit pump was turned on. Less than 30 minutes after the cooling was activated, both the furnace surface and cooling water temperatures were back to normal operating temperature levels. A former concern had been that it would take vast amounts of added time to cool the furnace if temperatures were too high at the beginning of the cooling phase. As seen during the test, the furnace itself would not take much time to cool down. Considering the quick cooling of the furnace, it's no longer such a decisive factor as before to keep a lower cooling water temperature long before the cooling phase starts.

5.4 Implementation of waste heat to HVAC and improvements to cooling system

When investigating where to recover the waste heat from the furnace's cooling system, two placements of a heat exchanger seemed reasonable. The heat exchanger is named HEX 3, and the different placements are 1 and 2 in Figure 35. Placement 1 is on the closed loop of the cooling system. At this point, there would be one less heat exchanger between the furnace and where the waste heat could be connected to the HVAC system. The problem with this placement is that the furnace company A makes the closed loop of the cooling system. Placement 2 is on the cooling system that runs to water tank 1. This part was built by Alfa Laval and is easier to rebuild to retrofit a heat exchanger. The drawback is that there is one more heat exchanger before the recovery of waste heat, namely HEX 1. Although the added heat exchangers temperature drop would not make that much of a difference. The temperature difference between the two placements we took measurements of during the heating phase in the first cycle were though only 0.03°C, since the second placement is compensated by the quick coolers higher water temperature.

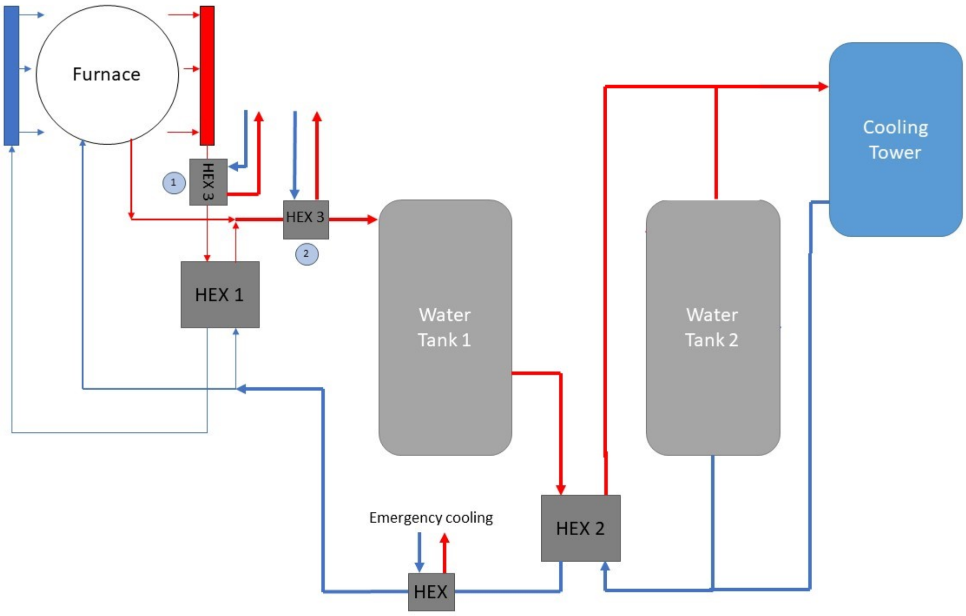


Figure 35 – Improved cooling system and potential heat recovery spots

During the project, the cooling systems were examined to see if anything could be improved. We observed that the emergency cooling is inserted directly into the cooling loop on water tank 1. This makes it hard to control the quality of the water that runs to the quick cooler and HEX 1. That could be mitigated if a heat exchanger were used instead, see HEX 5 in Figure 35. Another possible change is to re-do the piping for water tank 2 to be used as an accumulator tank. This could be done by making two separate water loops, the first loop would take the hot water from the top of the tank to the cooling tower, making tank 2 as cool as possible. The second loop would take the cooled water in the bottom of tank 2 and cool the furnaces. It would ensure that water tank 2 is always loaded with cool water when needed. That configuration can also be seen in Figure 35.

Alternative modifications to the current cooling systems have been discussed frequently during the writing of this thesis. Except for the suggested improvements, discussed in this section, we have thought of suggesting an installation of a bypass over water tank 1, seen in Figure 36. By implementing the bypass, 10 m^3 of cooling water could be removed which today only acts to increase the thermal inertia of the system. The bypassed water tank could instead be used in a different way than today. Alternatively, water could continuously run through the tank during the heating phase as it does today. Since our thesis wanted to increase the temperature quality of the cooling water, the tanks thermal inertia could be useful in order to avoid rampant temperature increases like we saw in the clean-up test. Instead the temperature could be risen in a more controlled manner were the overall water temperature of the tank would be met by the desired inlet temperature of the furnace. Problems would though arise at the start of the cooling phase, when all water in the furnace, the tank and the furnace itself are to be cooled as fast as possible. By then letting water run through the bypass instead, far less energy in the form of heat would have to be cooled off from the process. The hot water would then be stored in tank 1 during the cooling phase, ready to be reheated for recovery purposes during the upcoming brazing cycle.

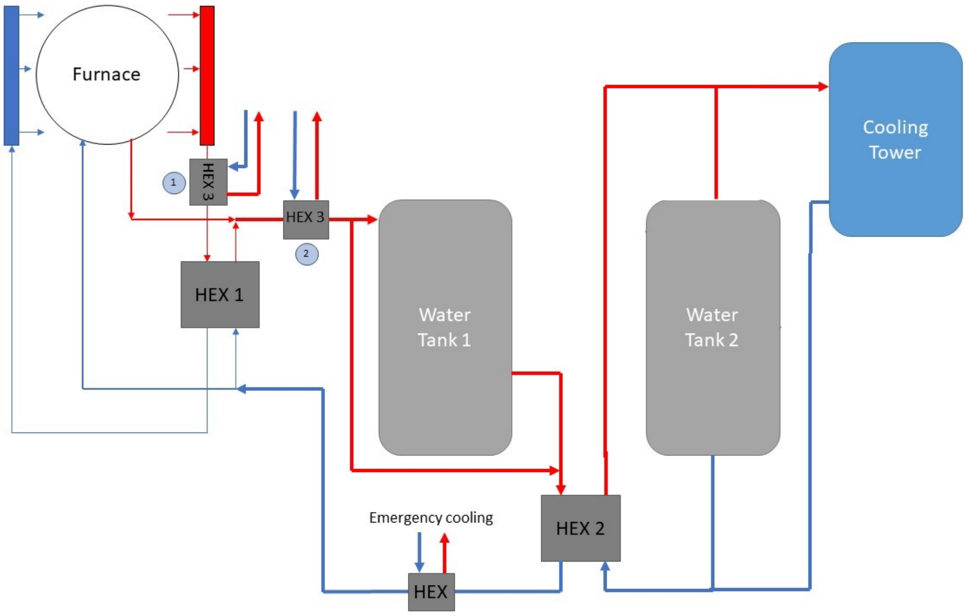


Figure 36 – Cooling system with bypass connection

In Section 3.8, two cases that depended on the temperature quality were presented. One for temperature lower than 55°C and one for more or equal to 55°C. For lower than 55°C, the chosen configuration can be seen in Figure 37, where we preheat the district heating return. The waste heat will come from the heat exchanger on furnaces in the industrial building.

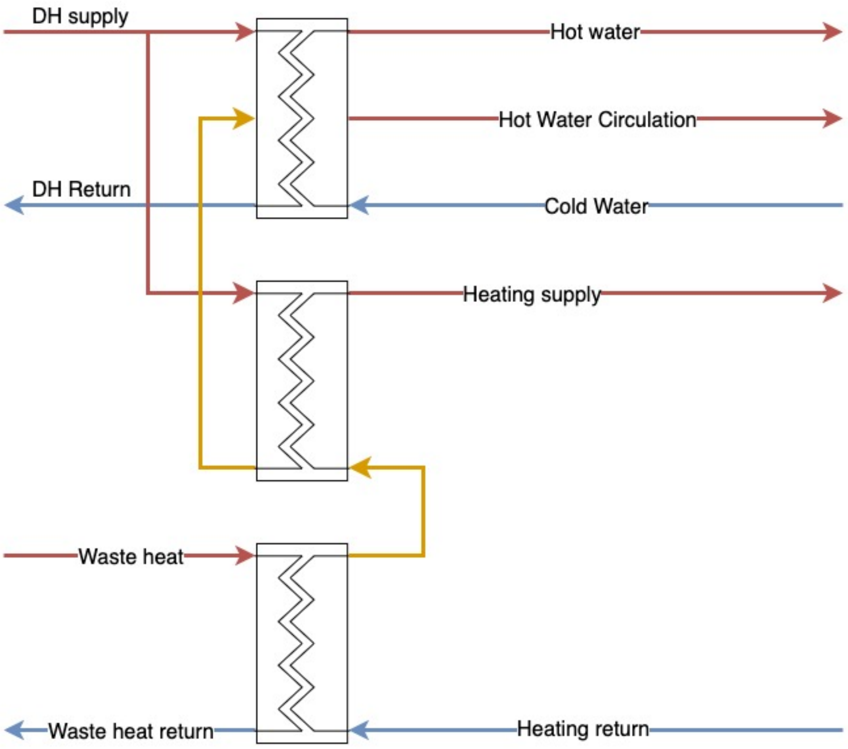


Figure 37 – Low temperature connection to the heating system

For the case where the temperature is more or equal to 55°C, the configuration chosen is presented in Figure 38. In this configuration, the waste heat will work parallel to the district heating, so when there is enough waste heat from the furnaces, the district heating is turned off.

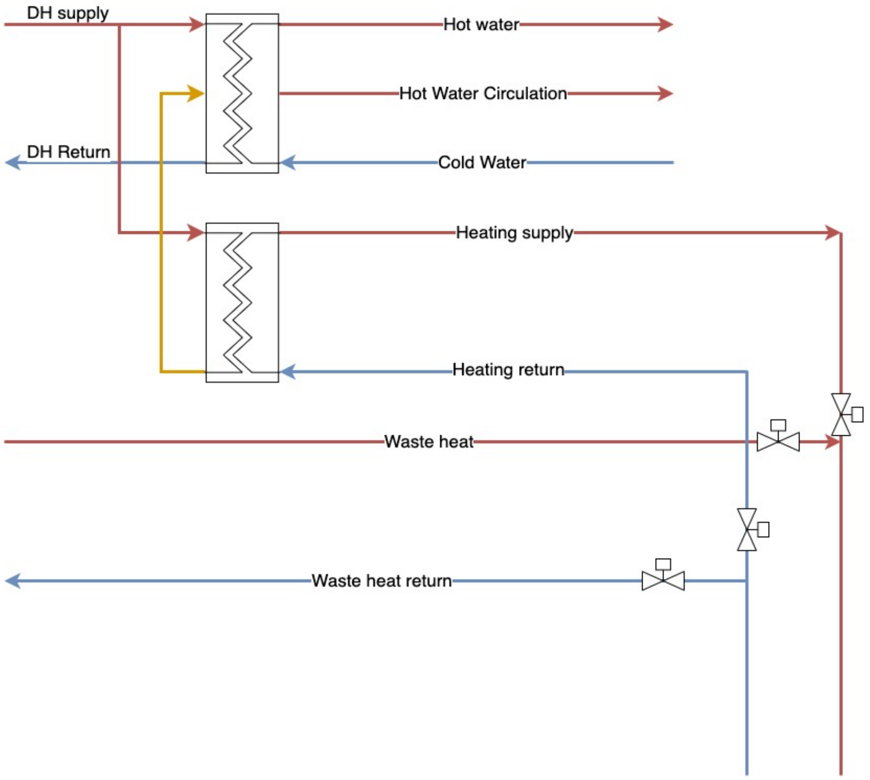


Figure 38 – High temperature connection to the heating system

Worth mentioning regarding the different connections is that the district heating company wants cold water in their return pipes to be used in their condensers or boilers. Since the low temperature connection uses waste heat from the furnaces to heat the buildings return water, the district heatings return water temperature in turn would be higher. Without sufficiently cool return water to the district heating's systems, they wont be able to produce as much electricity as wanted, or the pumping work will constitute to large parts of the process, leading to a drop in their processes efficiency. From their point of view, the low temperature connection is therefore not desirable.

6 Discussion

At Alfa Laval's production site in Ronneby, furnaces from two different companies were examined. Almost all of the focus during the work has been put in to the furnaces from company A, with only some IR-pictures taken of furnaces from company B. We although noticed that company B's furnaces had a relative higher average surface temperature of roughly 10°C during the first measurements of the furnaces, see Figure 39 to 41. The cooling water exiting the furnaces quick cooler circuit were simultaneously measured to 67°C. With a cooling water source capable of those temperatures we wouldn't need to try to increase the temperature quality of the cooling water like we did, which turned out to be a central part of this thesis. Instead, more focus could've been put on the actual implementation of the recovered heat from the cooling water. On the other hand, since the investigation and mapping of company B's furnaces quickly came to an end, we don't have any data to backup the energy potential of the furnaces, as was performed for company A's furnaces. Further it's also uncertain for how long the higher cooling water temperatures of around 60°C would be available. We most likely would've been in need of looking into increasing the cooling water temperature quality of company B's furnaces as well, but not to the same extent as were needed for furnaces from company A during this work.

As mentioned earlier the largest part of our thesis, and the most time consuming, consisted of trying to raise the temperature of the furnaces cooling water circuits. During our first measurements of a full brazing cycle it became clear that the cooling water circulating through the furnace only experienced a temperature increase of around 4°C. Since the aim of the thesis was to integrate the reused heat to the buildings heating system, with a preferred minimum temperature of 55°C, we started the investigation of trying to increase the temperature quality. During the first meeting with the furnace manufacturing company we were strongly told that the cooling temperature of the water couldn't be risen any further than current levels. This was further confirmed when getting a hand of, and reading the furnaces user manual, stating the maximum inlet temperatures of the furnaces cooling circuits to 30°C. When discussing the direct reasons for those limiting specifications and why they were set so low, relative to a furnace which is capable of temperatures well above 1000°C, a lot of different, and sometimes strange reasons appeared. At the same time furnace parts that are sensitive to overheating were mentioned, including the vacuum pump, cooling fan with its motor and the power cables, which all stood for some uncertainties considering the furnaces safety. Furnace experts working at Alfa Laval were also worried for risks of the furnaces overheating when we started proposing higher cooling water temperatures, as described in section 3.6.3. Our opinion however were that most of those standards had been written with a lot of margin for safety, and that the actual maximum temperatures for the cooling water were much higher. These unknown maximum temperatures would according to us have to be examined through practical tests. By trusting the safety systems of the furnace during higher operational temperatures than normal, we could pinpoint the exact conditions for when the furnace really started to overheat. After a number of meetings involving suggestions and clarifications of what we wanted to achieve, we dicided to run the clean-up test.

In future investments of new vacuum furnaces and cooling systems, a vital requirement should be the possibility of recovering energy efficiently. A key factor for minimizing carbon footprints and reducing energy usage is to have these things already in mind at the requirement specification when discussing with potential suppliers. By addressing these energy recovery potentials in an earlier stage, a lot of time and money consumed on efficiency improvements could be spared. For example, equipment which the cooling system and furnaces consists of could be designed to be more resilient of higher temperatures. Sensitive parts could be cooled with separate water sources or loops, which then would allow for a higher temperature quality on the cooling water that's used for heat recovery. We believe that furnace suppliers would be much more eager of discussing questions like these when the choice of a future supplier lies ahead.

After the clean-up test we can conclude that the furnaces have the possibility of operating at higher cooling water temperatures. During the test we found the limiting factor to be the roughing pump, which also in the future could be cooled separately. What we unfortunately missed during the test were to measure the temperature of the bi-metals, which will interrupt all heating of the furnace if they exceed 90°C. Those bi-metals are placed on the power feedthrough cables on top of the furnace and underneath some cover, which makes them hard to thermograph from the ground. If we had measured them at the time we interrupted the test, we could also have come to some form of conclusion of how far away from a heating stoppage we were when the maximum temperatures were measured. What is clear though is that the outlet temperature of the water that's cooling the power cables was well below 90°C, with maximum temperatures of 41°C. However, what complicates the analyzes of the clean-up test is the particular conditions that applied. The clean-up test differs from a production cycle in terms of load, heating required, the cooling phase, amount of time needed and the cooling systems different thermal inertia. All stated factors accounts for making it more difficult to directly translate the results from the test to a real production cycle. On the contrary, with the newly acquired information regarding what the furnaces can withstand in terms of water temperatures, future tests and implementations on real cycles will be easier.

One problem with the clean-up test was that there was no supplied cooling at all from the cooling towers to the furnace cooling system. That means that we could only see how the furnaces react to a higher temperature momentarily and when or if the safety alarms would go off. When doing the test plan, we hoped it would be done with cooling at a specific temperatures, so the furnace cooling system could reach a steady state, and temperatures increased gradually. The test was successful, even if we hoped to reach a steady state for the furnace. That could have been a communication error, or that we needed to be clearer about how we wanted the test to be performed in the first place. If we were to redo the test, or if someone else would do it at a later time, cooling is required to reach a steady state. It would then be interesting to see how the furnace reacts to higher temperatures for a longer time period during the heating cycle.

Other sensitive parts except for the roughpump are primarily the power feedthroughs and cooling fan motor, which also should have separate cooling circuits if temperatures of the cooling water are to be risen. Instead of being connected to tank 1, (see Figure 36), temperature sensitive parts could be directly cooled through water tank 2's cooling loop. Separating parts of the furnace in order to have different inlet cooling water temperatures would allow higher temperatures and a higher heat recovery efficiency from the parts that can withstand those higher wanted temperatures of 55°C.

A second alternative use of tank 1, like the suggestion in 36, would be to disconnect tank 1 and tank 2 from each other. Both tanks could then work as accumulators where each would be supplying separate furnaces, instead of the system today where 2 tanks together generally supply 2 furnaces. The tanks would then also be directly connected to the cooling towers which further would raise the temperature of the cooling water that enters the cooling towers. This would also increase the efficiency for the towers, especially during warmer days of summer when the ambient air wet bulb temperature which impacts the efficiency raises.

In this thesis, everything is done on an old ventilation system with no heat exchangers to save energy. During our thesis, there have been plans to remake the ventilation system in Ronneby with heat recovery and adjustments to be able to accept lower temperatures for heating. The use of energy recovery would lower the energy needed from district heating. In addition, this could make it possible to heat the building with the waste heat from the furnaces alone. Building the ventilation system to accept lower temperatures would mean that the temperature from the furnaces would not need to be raised to 55°C. The temperature achieved during the clean-up test would then be enough to heat the entire building with the newly installed ventilation system.

Up until now there have been discussions, suggestions for implementations and analyses regarding raising the cooling water temperatures, extracting heat from the processes and how to connect the incoming heated water to the buildings current heating central. However, what needs to be reviewed more is how the hot water is to be transported from the furnaces, which are located around the building in Ronneby. The current ventilation system is according to Alfa Laval inefficient and will in the near future be replaced with a newer one that can handle lower temperatures of distributed water. One alternative is thereby to use the old ventilation systems pipelines, seen in Figure 5. The heat exchangers which accounts for collecting the waste heat in the furnace loops could be connected to the closest return pipe of the old system. Regardless of the temperatures extracted from the furnaces, that distribution system, or old ventilation system, could supply heated water to the heating central according to Figure 37 or 38. What's still uncertain though is the inner diameters of the pipings, what pumps that currently are installed and if the total distribution system in general would be able to support this suggestion.

7 Conclusions

The temperature quality of the brazing furnaces cooling water at Alfa Laval in Ronneby can be risen to at least 44°C, which further will increase the possibility of recycling waste heat. The heat recovery temperature though is not limited to only 44°C, the maximum value of 44°C shown in this thesis is still with high safety precautions for the overall cooling systems used.

A way of integrating the recovered heat to the buildings HVAC system on site at Alfa Laval Ronneby has been suggested, and can be seen in section 5.4. During the writing of this thesis and mapping of the current cooling systems used for the furnaces, it became clear that the suggested cooling system changes are necessary. If the temperature quality of the cooling water is to be raised, and heat recovered in an efficient way, the old systems are not sufficiently adapted.

We believe that during further expansions of Alfa Laval in Ronneby, one should plan for heat recovery from processes at an earlier stage compared to the current situation. By adapting processes for energy recovery purposes at an earlier stage, a lot of time consuming supplementary work to make heat recovery more efficient can be spared.

7.1 Future work

During this thesis, there was only enough time to execute the clean-up test, where we reached an outlet cooling water temperature of 44°C. The goal was to reach higher temperatures and see if these temperatures were viable in a steady state condition. In a future project/master thesis, the next step would therefore be to test the maximum temperature for steady-state operations and try the same temperatures on an actual cycle.

There is more heavy equipment on site in Ronneby that could be used to recover waste heat from. For example hydraulic presses that uses oil cooling with temperatures above 55 °C, there is also drying ovens that use hot air. So in the future there could be an alternative to look in to more possibilities of waste heat recoveries at the site.

The work of increasing the furnaces cooling water temperatures took longer than expected, so the time spent on the alternatives for implementations of waste heats were less than planned. More work needs to be put into investigating what type of piping integration that could be used for collecting and distributing the furnaces waste heat water.

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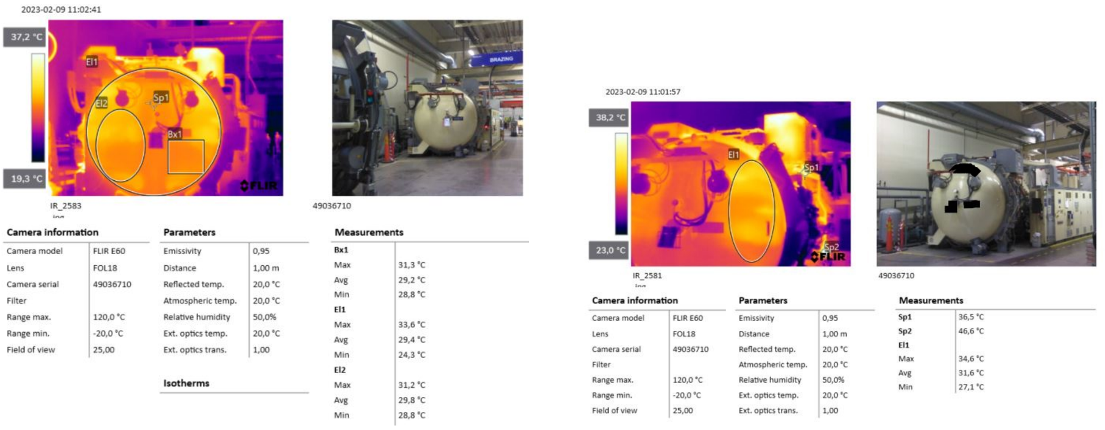
Appendices

Appendix A IR pictures



Camera information

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Range min.	-20,0 °C
Field of view	25,00

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Reflected temp.	20,0 °C
Atmospheric temp.	20,0 °C
Relative humidity	50,0%
Ext. optics temp.	20,0 °C
Ext. optics trans.	1,00

Isotherms

Measurements

Bx1	
Max	31,3 °C
Avg	29,2 °C
Min	28,8 °C
El1	
Max	33,6 °C
Avg	29,4 °C
Min	24,3 °C
El2	
Max	31,2 °C
Avg	29,8 °C
Min	28,8 °C

(a) Furnace front side

[redacted] [redacted] [redacted]

Camera information

Camera model	FLIR E60
Lens	FOL18
Camera serial	49036710
Filter	
Range max.	120,0 °C
Range min.	-20,0 °C
Field of view	25,00

Parameters

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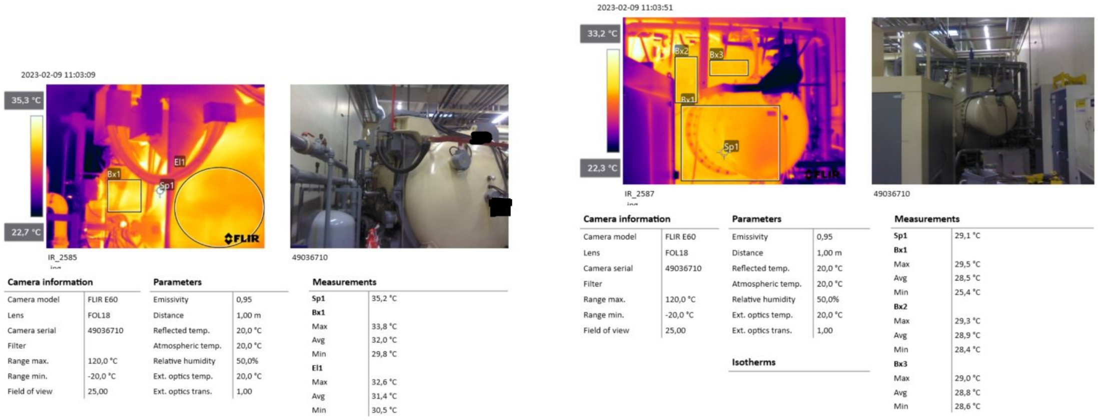
Distance	1,00 m
Reflected temp.	20,0 °C
Atmospheric temp.	20,0 °C
Relative humidity	50,0%
Ext. optics temp.	20,0 °C
Ext. optics trans.	1,00

Measurements

Sp1	36,5 °C
Sp2	46,6 °C
El1	
Max	34,6 °C
Avg	31,6 °C
Min	27,1 °C

(b) Furnace front side



[redacted] [redacted]

Camera information

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Camera serial	49036710
Filter	
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Range min.	-20,0 °C
Field of view	25,00

Parameters

Emissivity	0,95
Distance	1,00 m
Reflected temp.	20,0 °C
Atmospheric temp.	20,0 °C
Relative humidity	50,0%
Ext. optics temp.	20,0 °C
Ext. optics trans.	1,00

Measurements

Sp1	35,2 °C
Bx1	
Max	33,8 °C
Avg	32,0 °C
Min	29,8 °C
El1	
Max	32,6 °C
Avg	31,4 °C
Min	30,5 °C

(c) Furnace side

Camera information

Camera model	FLIR E60
Lens	FOL18
Camera serial	49036710
Filter	
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Range min.	-20,0 °C
Field of view	25,00

Parameters

Emissivity	0,95
Distance	1,00 m
Reflected temp.	20,0 °C
Atmospheric temp.	20,0 °C
Relative humidity	50,0%
Ext. optics temp.	20,0 °C
Ext. optics trans.	1,00

Isotherms

Measurements

Sp1	29,1 °C
Bx1	
Max	29,5 °C
Avg	28,5 °C
Min	25,4 °C
Bx2	
Max	29,3 °C
Avg	28,9 °C
Min	28,4 °C
Bx3	
Max	29,0 °C
Avg	28,8 °C
Min	28,6 °C

(d) Furnace back side

Figure 39 – IR pictures of furnace D

2023-02-09 11:05:25

IR_2589

49036710 [redacted]

Camera information	
Camera model	FLIR E60
Lens	FOL18
Camera serial	49036710
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Range min.	-20,0 °C
Field of view	25,00

Parameters	
Emissivity	0,95
Distance	1,00 m
Reflected temp.	20,0 °C
Atmospheric temp.	20,0 °C
Relative humidity	50,0%
Ext. optics temp.	20,0 °C
Ext. optics trans.	1,00

Measurements	
Bx1	
Max	42,4 °C
Avg	40,2 °C
Min	38,2 °C
Bx2	
Max	42,7 °C
Avg	41,1 °C
Min	39,8 °C
El1	
Max	64,1 °C
Avg	38,8 °C
Min	23,6 °C

(a) Furnace front side

2023-02-09 11:07:41

IR_2593

49036710

Camera information	
Camera model	FLIR E60
Lens	FOL18
Camera serial	49036710
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Range min.	-20,0 °C
Field of view	25,00

Parameters	
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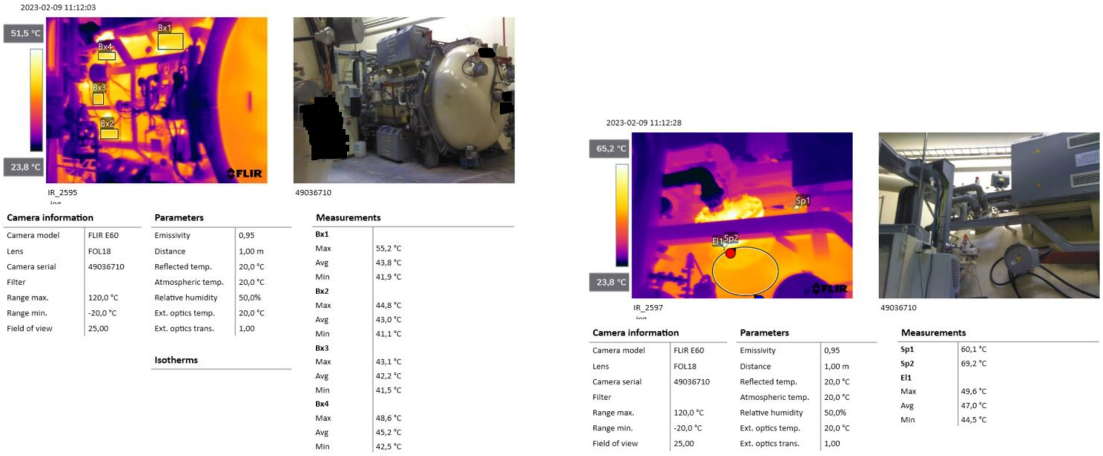
Distance	1,00 m
Reflected temp.	20,0 °C
Atmospheric temp.	20,0 °C
Relative humidity	50,0%
Ext. optics temp.	20,0 °C
Ext. optics trans.	1,00

Measurements	
Sp1	44,3 °C
Sp2	43,1 °C
Sp3	44,0 °C
Bx1	
Max	44,9 °C
Avg	41,2 °C
Min	38,9 °C

(b) Furnace back side



2023-02-09 11:12:03

IR_2595

49036710 [redacted] [redacted]

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Field of view	25,00

Parameters	
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Distance	1,00 m
Reflected temp.	20,0 °C
Atmospheric temp.	20,0 °C
Relative humidity	50,0%
Ext. optics temp.	20,0 °C
Ext. optics trans.	1,00

Isotherms

Measurements	
Bx1	
Max	55,2 °C
Avg	43,8 °C
Min	41,9 °C
Bx2	
Max	44,8 °C
Avg	43,0 °C
Min	41,1 °C
Bx3	
Max	43,1 °C
Avg	42,2 °C
Min	41,5 °C
Bx4	
Max	48,6 °C
Avg	45,2 °C
Min	42,5 °C

(c) Furnace side

2023-02-09 11:12:28

IR_2597

49036710

Camera information	
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Lens	FOL18
Camera serial	49036710
Filter	
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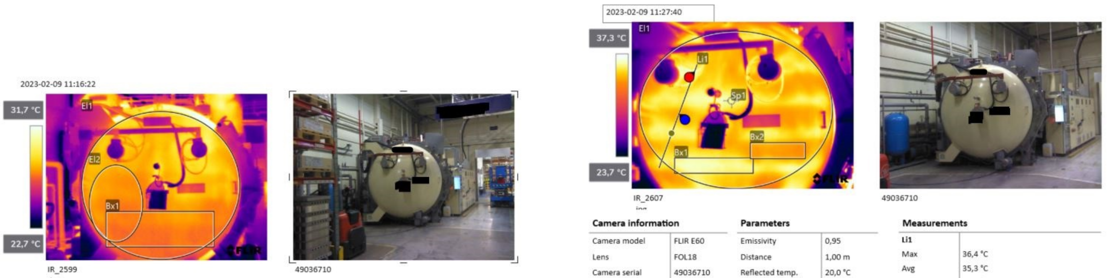
Range min.	-20,0 °C
Field of view	25,00

Parameters	
Emissivity	0,95
Distance	1,00 m
Reflected temp.	20,0 °C
Atmospheric temp.	20,0 °C
Relative humidity	50,0%
Ext. optics temp.	20,0 °C
Ext. optics trans.	1,00

Measurements	
Sp1	60,1 °C
Sp2	69,2 °C
El1	
Max	49,6 °C
Avg	47,0 °C
Min	44,5 °C

(d) Furnace side

Figure 40 – IR pictures of furnace E



[redacted]

[redacted]

[redacted]

[redacted]

Camera information

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Camera serial	49036710
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Range min.	-20,0 °C
Field of view	25,00

Parameters

Emissivity	0,95
Reflected temp.	20,0 °C
Atmospheric temp.	20,0 °C
Relative humidity	50,0%
Ext. optics temp.	20,0 °C
Ext. optics trans.	1,00

Measurements

Bx1	
Max	28,2 °C
Avg	27,5 °C
Min	26,3 °C
El1	
Max	30,4 °C
Avg	27,6 °C
Min	22,9 °C
El2	
Max	28,4 °C
Avg	27,7 °C
Min	27,2 °C

Camera information

Camera model	FLIR E60
Lens	FOL18
Camera serial	49036710
Filter	
Range max.	120,0 °C
Range min.	-20,0 °C
Field of view	25,00

Parameters

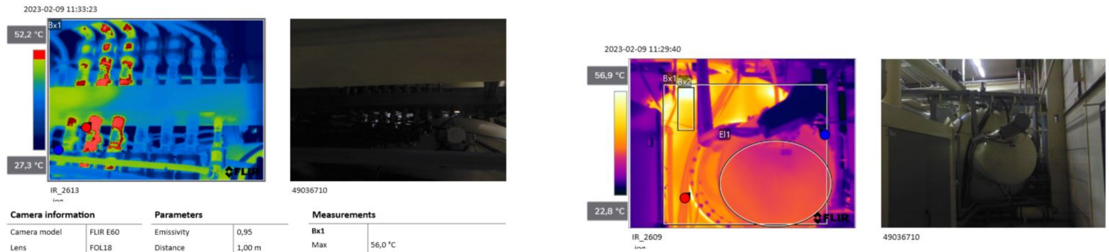
Emissivity	0,95
Distance	1,00 m
Reflected temp.	20,0 °C
Atmospheric temp.	20,0 °C
Relative humidity	50,0%
Ext. optics temp.	20,0 °C
Ext. optics trans.	1,00

Measurements

Li1	
Max	36,4 °C
Avg	35,3 °C
Min	34,2 °C
Sp1	35,9 °C
Bx1	
Max	36,4 °C
Avg	35,9 °C
Min	34,2 °C
Bx2	
Max	34,9 °C
Avg	34,1 °C
Min	33,5 °C
El1	
Max	36,7 °C
Avg	33,6 °C
Min	23,2 °C

(a) Furnace front side

(b) Furnace front side 11 min later



Camera information

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Lens	FOL18
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Range min.	-20,0 °C
Field of view	25,00

Parameters

Emissivity	0,95
Distance	1,00 m
Reflected temp.	20,0 °C
Atmospheric temp.	20,0 °C
Relative humidity	50,0%
Ext. optics temp.	20,0 °C
Ext. optics trans.	1,00

Isotherms

Above	
Above	50,0 °C
Percentage	3,6%

Measurements

Bx1	
Max	56,0 °C
Avg	40,1 °C
Min	25,6 °C

Camera information

Camera model	FLIR E60
Lens	FOL18
Camera serial	49036710
Filter	
Range max.	120,0 °C
Range min.	-20,0 °C
Field of view	25,00

Parameters

Emissivity	0,95
Distance	1,00 m
Reflected temp.	20,0 °C
Atmospheric temp.	20,0 °C
Relative humidity	50,0%
Ext. optics temp.	20,0 °C
Ext. optics trans.	1,00

Isotherms

Measurements

Bx1	
Max	63,4 °C
Avg	37,9 °C
Min	23,6 °C
Bx2	
Max	57,9 °C
Avg	49,9 °C
Min	39,2 °C
El1	
Max	39,0 °C
Avg	37,3 °C
Min	30,7 °C

(c) Cooling water entering (cold) and exiting (hot) outer shell

(d) Furnace back side

Figure 41 – IR pictures of furnace F