CHALMERS

Energy Management in Heat Treatment

Master's Thesis within the Sustainable Energy Systems programme

PONTUS BERG

Department of Energy and Environment
Division of Heat and Power Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2014

MASTER’S THESIS

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Cover:
Example picture of a roller hearth furnace (Product direct industry , 2014).

Chalmers Reproservice
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ABSTRACT

This master thesis report looks into the energy usage of a modern heat treating facility at the bearing manufacturer SKF in Gothenburg. In this report background studies on heat treatment, furnace technologies and energy aspects have been performed and compiled into a theoretical base. The main body of the work has revolved around the two approach methods, interviews with experts in the field energy and heat treatment and empirical data gathering, and the outcome of this approach method. The study has covered all the stages involved in heat treatment such as pre-washing, to post washing. The type of heat treatment that has been performed in this facility has mainly been bainitic hardening. In order to compare the results an overviewing study of another bainitic hardening facility on SKF was made.

The outcome of the study was that the important factors to consider when improving energy efficiency on a heat treating facility is to first of all to establish what the current situation is, and use this as a base line. Areas which are important to address to optimize the energy performance of the facility is to make sure the burners are efficient, have low surface losses, keep the utilization of the facility high and recover as much as possible of the waste heat. The most suitable way to do this is to use the waste heat from the flue gases in the pre- or post-wash.

For this particular facility it was found that the most energy effective measure would be to upgrade burner to regenerative models, lower the surface temperature with 20 K, pre heat ingoing atmospheric gases with the hot outgoing atmospheric gases and finally heat exchange the flue gases with the post wash. This will lead to energy savings of about 18 %.

Key words: Heat treatment, Energy, Energy efficiency, Furnace, Hardening

Energihantering inom värmebehandling

Examensarbete inom masterprogrammet Sutainable Energy Systems
PONTUS BERG
Institutionen för Energi och Miljö
Avdelningen för Värmeteknik och maskinlära
Chalmers tekniska högskola

SAMMANFATTNING

I detta mastersexamensarbete studeras energianvändningen på en modern värmebehandlingsanläggning hos lagertillverkaren SKF i Göteborg. I rapporten har bakgrundsstudier av härdugnstekniker, värmebehandling och energibalanser studerats och utgör den teoretiska basen. Kärnan i rapporten fokuserar främst på de två tillvägagångssätten, intervjuer och empiriska studier, och utfallen av dessa. I studien har alla delar av värmebehandlingsprocessen studerats. Det innebär att allt från förtvätt till eftertvätt har behandlats. I den anläggning som har studerats så har främst bainitisk värmebehandling genomförts. En enklare jämförelse med en liknande anläggning på SKFs område gjordes också.

Resultatet av studien var att de faktorer som är viktiga att ta hänsyn till vid energieffektiviseringar av en värmebehandlingsanläggning var: Etablera en tydlig bild av hur situationen ser ut i dagsläget och använd denna som en utgångspunkt för de förbättringar som föreslås. , att ha effektive brännare, små värmeförluster från ugnens yta maximera utnyttjandegraden av anläggningen och återvinn så mycket som möjligt av spillvärmen. Det bästa sättet att ta tillvara på spillvärmen var att utnyttja den i tvättarna.

För just den specifika anläggning som har studerats här är den bästa energieffektiviseringen av anläggningen den följande: Uppgradera brännarna till den generativa modellen, sänk ugnens yttemperatur med 20 K, förvärm de ingående atmosfärsgaserna med den heta utgående atmosfärsgasen och till sists värmeväxla rökgaserna med eftertvätten. Dessa åtgärder skulle ge en energibesparing på ca 18 %.

Nyckelord: Värmebehandling, energi, energieffektivisering, härdning, härdugn.

Contents

Preface

The master thesis has been done in the Manufacturing Development Centre in SKF Gothenburg from February 2014 to June 2014. The furnace facility studied was known as Heaton II and is located on the SKF site in Gothenburg region. The project has been performed at the division of Heat and Power Technology at Chalmers University of Technology in Gothenburg.

During this project I have received help and support from many people and I would like to thank all who participated in the interviews and guided me around in the facilities. A very big thanks to Johan Sandberg, Peter Neuman, Lars Arvidsson, Jerry Håll and Stephan Hägeryd who helped me preform a lot of the measurements, advise me in my calculations and explain the inner working of the facility. Finally a big thanks to my supervisor Walter Datchary and my examiner Mathias Gourdon.

Göteborg October 2014

Pontus Berg

Notations

Abbreviations

$BCC: Body\ Centered\ Cubic$

$CCT: Continous\ Cooling\ Transformation$

$FCC: Face\ Cenered\ Cubic$

$HHV: Higher\ Heating\ Value$

$MDC: Manufacturing\ Dvelopment\ Centre$

$NG: Natural\ gas$

$ppm: Parts\ Per\ Million$

Roman upper case letters

$A: Surface\ area\ [m^2]$

$E: Energy\ [J]$

$L: Characteristic\ length$

$Nu: Nusselt\ number$

$Pr: Prandtl\ number$

$P: Perimiter\ [m]$

$P: Pressure\ [Pa]$

$Q: Heat\ [J]$

$Ra: Rayleigh\ number$

$T: Temperature\ [K]$

$\dot{V}: Volume\ flow\ \left[\frac{m^3}{s}\right]$

$W: Work\ [J]$

Roman lower case letters

$c_p: Specific\ heat\ \left[\frac{kJ}{kgK}\right]$

$h: Heat\ transfer\ coeffeficient\ \left[\frac{W}{m^2K}\right]$

$k: Thermal\ conductivity\ \left[\frac{W}{mK}\right]$

$m: Mass\ [kg]$

$\dot{m}: Mass\ flow\ \left[\frac{kg}{s}\right]$

$q: Thermal\ energy\ [W]$

$q'': Heat\ flux\ \left[\frac{W}{m^2}\right]$

$x: Distance\ [m]$

Greek lower case letters

$\beta: Volumetric\ thermal\ expansion\ coefficient$

$\varepsilon: Emisivity$

$\rho: Denisty\ \left[\frac{kg}{m^3}\right]$

$\lambda: Air\ to\ fuel\ ratio$

$\sigma: Stefan\ boltzman\ constant\ \left[\frac{W}{m^2K^4}\right]$

1 Introduction

This master thesis is performed at the research and development department at SKF in Gothenburg, Sweden. More specifically it is the department called Manufacturing Development Centre or MDC for short. This section will give a short introduction to the project containing its background and the purpose of the project.

1.1 Background

Global warming is one of our times biggest challenges and almost all governments and people in power are trying to find a solution for it. However it is not only up to governments to solve this problem, single individuals and private companies could all make more or less substantial contributions to prevent the warming of our planet.

The greenhouse effect is the phenomena where greenhouse gases are emitted to the atmosphere and prevents heat radiating out from the surface of the earth. This leads to a temperature rise and it is this temperature rise that is known as global warming.

There exist several greenhouse gases, among which the most important in the context of this text is carbon dioxide. This gas is released first and foremost from the combustion of carbon rich fuels, in particular fossil fuels which are used extensively in the energy and transport sector. Industries that are energy intense contribute to the increasing demand of energy and hence the emissions of carbon dioxide. With the carbon dioxide emissions still on the rise and fossil fuels becoming more and more expensive and to some extent even scarce (Azar, 2009) (Sustainable energy futures Course compendium, 2012), it has become a bigger concern for more and more companies to lower their energy use. Partly as a consequence to reduce energy costs and remain competitive, partly as a form of branding where they could pride themselves in making a very good product in an environmentally sustainable way.

For a company like SKF, where the essence of their product is to reduce energy consumption through reduction of friction in rotating parts, it is of great importance to look to their own factories and make sure they live up to the same standard as their product.

SKF have set the target to reduce their carbon dioxide emissions with 5 % by the year 2016 compared to 2006 levels and to do so, efforts could be made on two fronts. The first one is to reduce direct emissions such as flue gas losses from heat treatment furnaces and boilers. The second one is to reduce indirect emissions such as the ones produced by the power plants that supply the electricity to the wide range of production equipment. (SKF own operations, u.d.).

Heat treatment is a crucial step in the making of many of industrial products and at the same time one of the most energy intense process steps in the production line. Furnaces operating at temperatures of about 900 ℃ consume plenty of energy both in form of electricity and combustible gases, hence generating a corresponding amount of carbon dioxide. With heat treatment being such an important and energy consuming part of the production, it is a crucial point to which attention should be paid in order to reduce a company’s energy consumption and carbon dioxide emissions.

1.2 Purpose

Considering the background above, the purpose of this master thesis is to study the energy consumption in two of SKFs heat treatment facilities as it is today, suggest improvements to the current layout and provide an information base of text, measurements and calculations which could be used in the planning of future production facilities.

1.3 Boundaries

In this master thesis the energy flows connected to the heat treatment process will be looked into. This involves all the energy flows that originate from a heat treatment, including for example ventilation of the building where the furnace is located. Whatever happens to a component prior or post heat treatment is not dealt with in this master thesis.

Since SKF is a global company and have heat treating facilities all over the globe it is difficult to state any cost related to the energy use in heat treatment. This is because energy prices and energy carriers could vary extensively from site to site. This means that no financial figures will be presented.

1.4 Task definition

A furnace facility in Gothenburg will be studied and used as a benchmark to determine the energy use of a modern heat treating facility at a mechanical engineering company. From this benchmark it will be determined what could be improved in this particular furnace installation and also give an overviewing picture of what is important to take in to consideration when designing new facilities and also what could be done to improve older facilities.

The three objectives could be summarized to:

- How much energy is the furnace using today?
- Provide recommendations on what are the important factors to consider when working with energy management in heat treatment.
- Give suggestions on improvements for the facility.

The study will consist of two parts. The first part will be to interview people who are involved in heat treatment at the company. This is to gather firsthand information on the energy situation of the facility as it is today. The second part will be to take actual measurements of the facility, partly to confirm the information that has been gathered during interviews and partly to be able to obtain all the data that is needed to make an energy analysis.

1.5 The company

SKF is a mechanical engineering company who started in the bearing business in 1907. Since then the company has grown to be a big international company with 46 775 employees spread over 140 sites in 28 countries all over the globe. The portfolio of product has grown from bearings to also incorporate seals, lubrication, services and mechatronics just to mention a few of the branches.

1.6 The facility

The heat treatment facility that has been studied is a modern heat treating facility used mainly for bainitic hardening but also have the capability of martensitic hardening. Figure 1 shows all the process streams that are involved in this study and how they relate to each other.

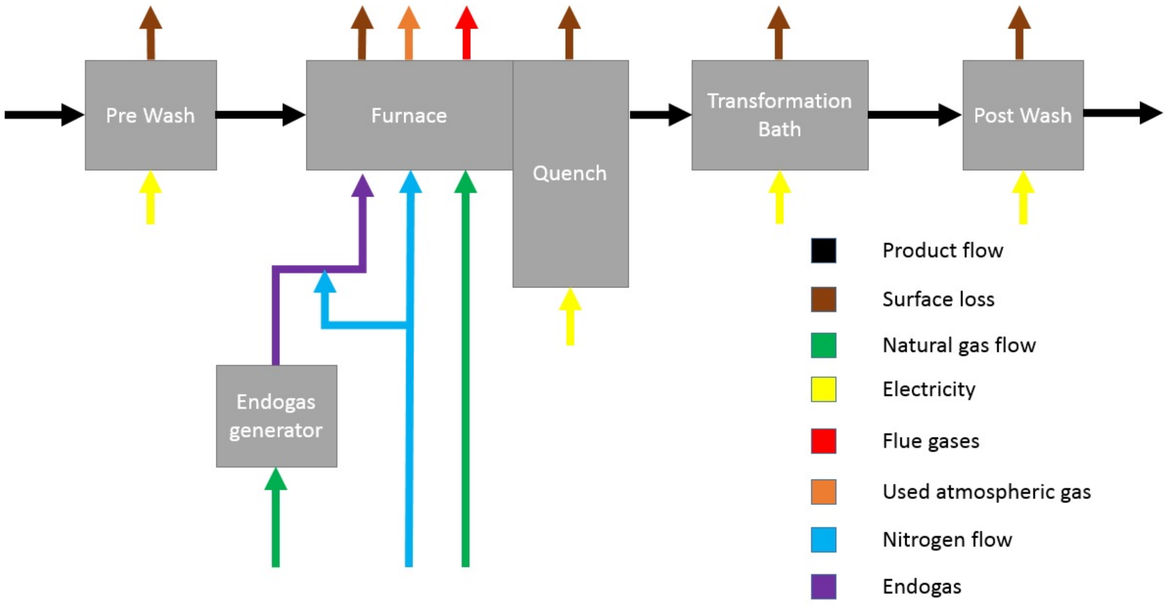

Figure 1. The studied heat treating facility known as Heaton II

2 Theory

2.1 Energy and the environment

Today it is widely acknowledged that humans have a significant impact on the composition of the atmosphere of the earth and hence also an effect on the planets climate. The consequence of this is that the global temperature has risen slightly and is predicted to rise even more in the future. This warming of the climate is created from something known as the greenhouse effect and the most debated greenhouse gas is carbon dioxide. The emissions of carbon dioxide originate from the combustion of fossil fuels such as natural gas, oil and coal. The biggest user of these fossil fuels is first and foremost the heat and power sector followed by the transport sector but even the industrial sector contributes considerably to the carbon dioxide emissions see Figure 2.

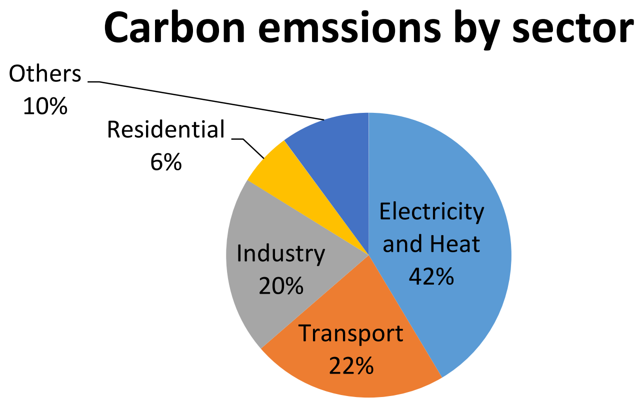

Figure 2. A pie chart showing the sources of carbon dioxide emissions in the world (International Energy Agency, 2012)

In the begging of the eighteen hundreds the carbon dioxide concentration in the atmosphere where slightly below 300 ppm, as of January 2014 the concentration is 397.8 ppm and is still rising. Some of the consequences that may arise from a warmer climate is sea level rise that threatens low lying countries and cities, deserts will spread and more extreme weather just to mention a few. Recently John Kerry, the United States Secretary of State, said that the climate change now ranks among the world's most serious problems alongside disease, poverty and terrorism (Almasy, 2014).

2.2 Brief about metallurgical theory

In order to get a brief understanding of why heat treatment is needed and why it is performed in the way it is, some basic knowledge of how metal works is needed. A metal is what's called a crystalline material; that means that all the atoms are placed in an orderly and repeating fashion in what is called a lattice. The atoms could be arranged in a number of different ways in this lattice and hence the name lattice structures to describe in what manner the atoms are placed, one lattice structure is for example the FCC structure (Face Centered Cubic).

The first step that happens when a metal solidifies is that a *nucleus* is formed with a certain lattice structure (Figure 3 a). As more and more of the material starts to solidify more and more atoms attach themselves to the original nucleus and adopt the same lattice structure and orientation as the nucleus (Figure 3 b). As the nucleus grow it starts to form an individual crystal called a *grain* (Figure 3 c). As the metal solidifies more and more, the grain grows and finally the grains will meet and since there is a mismatch in the crystallographic orientation between each individual grain, a *grain boundary* is formed where they meet (Figure 3 d).

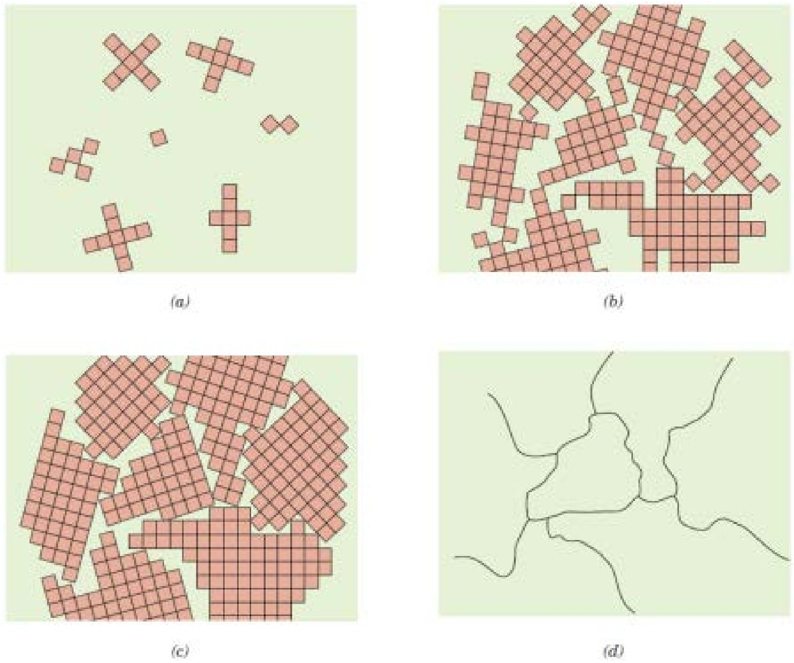

Figure 3. Shows the solidification process of a crystallographic material (William D. Callister, 2007)

It is important to know that there does not exist a perfect solid, there is always some kind of anomaly in the crystal lattice. This could be a vacancy i.e. an empty spot in the lattice or it could be what is called a *solid solution* which is a “foreign” atom that occupies a lattice site. These are of big importance for the properties of the steel and there are mainly two types of solid solutions: *interstitial* and *substitutional*. The interstitial solid solution is when a small atom “squeezes” in between the host atoms and the substitutional is when a host atom is replaced with a foreign atom. All of the above anomalies are called point defects. There are also so called *linear defects* where a number of atoms are misaligned or somehow different from the main lattice, one example could be a half plane appearing in the lattice. These defects cause strains and stresses in the lattice which are of big importance when it comes to the performance of the metal or alloy in question. (William D. Callister, 2007).

The main phenomenon that governs over all these processes is diffusion. It is the process where the random movements of molecules cause them to drift from one place to another. There are three things that are needed for this to happen: first the atom must have sufficient energy to break the bound with its neighboring atoms, secondly there has to be some form of vacant location available in the vicinity and thirdly there must be enough time to allow the atoms to relocate. This gives two options, either the atom could diffuse from vacant lattice site to vacant lattice site, *vacancy diffusion*, or, if the atom is small enough, it could diffuse between interstitial positions in the lattice, *interstitial diffusion*. The latter of these is the dominant since the number of interstitial points in a lattice is much greater than vacancies. In order to give the atom the energy needed to break its bonds it is simply to raise the temperature and hence increasing the atoms kinetic energy.

What happens on a microscopic level when a metal plastically deforms and finally break is that the crystal lattice moves along what is called slip planes in the lattice. In order to make a material harder and tougher the movements along these slip planes must be obstructed. This could be done in a number of ways: *solid solution strengthening* is as mentioned before the presence of foreign atoms causing strains in the lattice that prevent the movement of the slip planes, other types of defects, a different lattice orientation like a grain boundary, different crystallographic orientation such as a different phase or even a another slip plain could prevent this movement.

This comes down to that in order to create these obstacles for the slip plane the crystallographic properties of the material have to change and as mentioned before these changes could only occur at practical rates at higher temperatures end hence the process known as ***heat treatment*** is required to achieve this. This also leads to the use of steel which is an alloy from Iron and carbon where carbon forms an interstitial solid solution which makes the metal much stronger than pure Iron. Other alloys could of course also be heat treated but the focus in this report is on steel.

2.2.1 Steel and its equilibrium phase diagram

As mentioned above, steel is an alloy consisting of the two elements iron (Fe), carbon (C) and other alloying elements. There is a large variety of different steels with number of different alloying elements besides carbon. The amount of carbon that is mixed in with the iron could vary, usually concentrations from $0.008\, wt\,\%\, C$ to $2.14\, wt\,\%\, C$ are called steel and alloys that lies between $2.14 - 6.7\, wt\,\%\, C$ are called cast iron (William D. Callister, 2007). For higher concentrations of carbon, compounds with poor mechanical properties are formed and for that reason they are of very little interest in the mechanical industry.

Steel could appear in different phases depending on the concentrations of the components and the temperature of the mixture. This is similar to other elements such as salt and water mixtures where solidification and vaporization varies with the salt concentration. The representation of these phases and where the changes between them occur is represented in a phase diagram, see Figure 4.

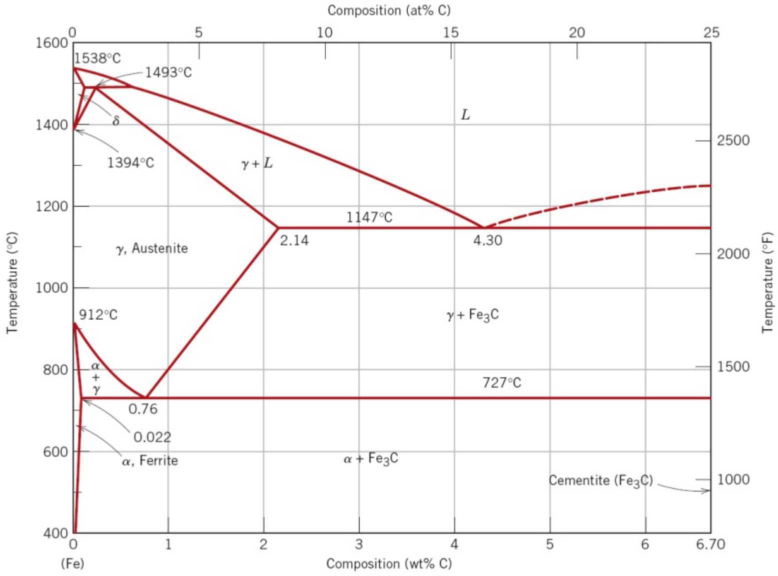

Figure 4. The iron carbon phase diagram (William D. Callister, 2007)

In the steel the phase changes are not only dependent on melting and solidification but also on changes in the crystalline structure of the material. For example the α (Ferrite) has a BCC structure (Body Centered Cubic) and γ has a FCC structure (Face Centered Cubic). These changes take place due to diffusion of atoms and are hence dependent of the temperature, which is specified in Figure 4.

One important point in the phase diagram is the *eutectoid* points. These are the points where three phases are present at the same time. When heat treating steel in the industry the eutectoid point in the diagram where the Carbon concentration is $0.76\, wt\, \%\, C$ and the temperature is $727℃$ is of big interest (William D. Callister, 2007). This is because it is the lowest temperature austenite could be obtained. The Austenite phase is the starting point for a hardening process hence reaching it is important in order to be able to harden steel.

2.2.2 Heat treatment

The reason for heat treating is to alter the performance of a metal. There are mainly four aspects that are of interest when trying to do this (MacKenzie):

- Hardness
- Ductility
- Strength
- Toughness

Different applications require different priorities between these aspects. For example a sharp edge like a razor or a kitchen knife needs to be hard to keep its sharpness but it is not required to be very ductile.

These properties are strongly linked to the *microstructure* of the material. When steel cools after being at austenisation temperatures of more than 700 ℃, different types of these microstructures are formed. The most common of these are *pearlite*, *bainite* and *martensite*. There exist other types of microstructures then pearlite, bainite and martensite but those three are the most common (William D. Callister, 2007). Which one of them that is formed depends on the rate of cooling of the material. As mentioned previously, microstructures are dependent on diffusion which in turn is dependent on time and temperature. If a steel is austenitised, i.e. raised above 727 ℃ for an eutectoid steel, and then cooled during what is called *equilibrium cooling* (very slow cooling) the atoms will have time to rearrange themselves in accordance with the phase change and the microstructure called pearlite will be formed. If the cooling is rapid the atoms will have very little time to adapt to the phase changes and the cooling curve will miss the pearlitic nose in Figure 5 and bainite will be formed if the part is left at this temperature for some time. Finally, if the cooling is extremely rapid there is no time for diffusion and the microstructure martensite will form. To display the exact times and temperatures that are needed to reach these microstructures something called *Continuous Cooling Transformation diagrams*, or CCT-diagrams for short, is used, see Figure 5

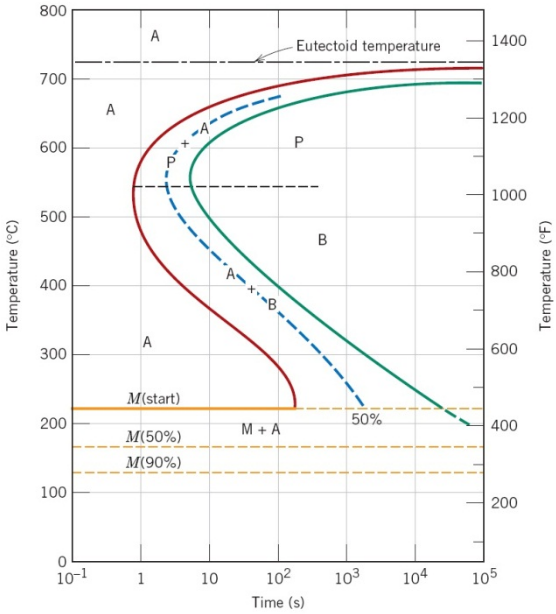

Figure 5. A Steel Continuous Cooling Transformation (CCT) diagram (William D. Callister, 2007) The letters A,B,P and M stands for austenite, bainite, pearlite and martensite respectively, the dashed black line marks what is called the *pearlitic nose,* this should be avoided in order to not form pearlite.

As could be seen in the diagram for this specific steel is that in order to avoid the pearlitic nose the steel has to be cooled from the eutectoid temperature of 727 ℃ down to close to 500 ℃ in less than a second. This form of rapid cooling is called *quenching*.

Martensite is the hardest form of microstructure a metal could get and it is also very brittle. This makes it unsuitable for many applications in engineering and in order to improve its ductility, strength and toughness it is put through a process called tempering in order to improve these properties.

To summarize what heat treatment is about it could be said that the material is first austenitized at somewhere between 700 ℃ *and* 900 ℃ and then rapidly cooled, quenched, to form bainite or martensite and finally the material is put through some sort of annealing/tempering process.

2.3 Heat treatment equipment

A modern heat treatment production line includes several pieces of important equipment. The most relevant of these will be looked at more closely in this chapter and it includes; the furnace with its burners and insulating material, the quench and quenching media, in this case a transformation bath and washing baths. Equipment such as conveyors and production robots will not be described in detail.

2.3.1 Furnace

Furnaces come in many shapes and sizes. They could be sorted in different categories depending if they are fuel fired or electrically powered, if it is a batch furnace or a continuous furnace and if it has protective atmosphere or not. It is important to understand that these different categories could be mixed. That is that a continuous furnace could be either electrically heated or heated with fuel. In the same sense it could be either with or without protective atmosphere. This of course also applies to batch furnaces and other furnace types as well. This section will treat some of the categories and type of furnaces that are available and of relevance for this thesis. The factor that determines what furnace is used is the operating cost over several years, investment cost and that it is able to perform the task at hand. (Andersson, o.a., 2012).

2.3.1.1 Electrical furnaces

This type of furnace is heated by passing an electrical current through an element with high resistance and the element is heated as a consequence of the high resistance (see Figure 6). The heat is then transferred to the furnace's walls and the component(s) via radiation. Some of the properties of an electrical furnace are listed below:

Advantages

- Operation is clean and locally environmentally friendly.
- No need for flue gas stack.
- Low noise due to absence of burners.
- Uniform temperature distribution.
- High efficiency due to sealed furnace.

Disadvantages

- Large installation, i.e. capital cost for large units.
- Exceeding peek electrical power may be very costly. This usually happens in the startup phase.
- High operating cost compared to fuel fired.

Typical efficiencies for electrically heated furnaces are about 85% (Andersson, o.a., 2012). The definition of furnace efficiency is, regardless of furnace type:

$$\frac{Heat\ in\ to\ products}{Heat\ in\ to\ furnace} = \eta$$

where η is the efficiency.

Figure 6. Electrical resistance heating elements

2.3.1.2 Fuel fired Furnace

Depending on location and availability of fuels, fuel fired furnaces could use a number of different fuels. Liquid or gaseous fuels are typically used in these furnaces and the most common is to use natural gas.

The fuel could be burnt directly into the furnace or it could be burnt in what is called a radiant tube. Direct fired burners (see Figure 7) are simple and cheap but have the drawback of having a poor temperature distribution and that flames could be impinged on the components in the furnace (MacKenzie). It is not possible to have a protective gas environment since the flame will introduce pollutants into the furnace. A radiant tube (see Figure 7) works by burning the gas inside a pipe, heating the pipe. The hot pipe then radiates to the surrounding furnace and consequently heats it. Advantages with this technique are that the combustion atmosphere and the furnace atmosphere is separated, there is no flame impingement and the temperature distribution is more uniform. A radiant tube is however more expensive, can't tolerate as high temperatures and it needs to be replaced from time to time. There are different shapes of radiant tubes depending on how much recirculation of flue gases that is utilized (MacKenzie).

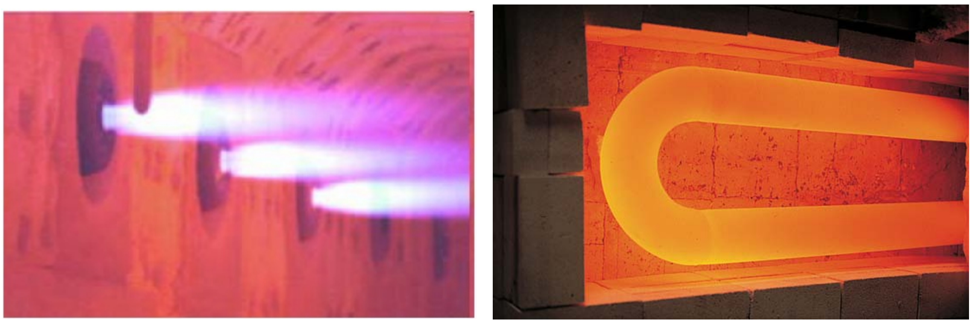

Figure 7. On the left is direct fired burners (MacKenzie) and on the right is a radiant tube (Encyclopedia Britannica Kids, u.d.)

The efficiency of a fuel fired furnace could vary between 50 to 70%. This is largely depending on what type of burners that are installed (see section 2.3.1.5). Below is a list with some of the properties of fuel fired furnaces (Andersson, o.a., 2012):

Advantages

- If accessible, combustible waste fluid could be utilized as fuel.
- Energy peaks are easily managed.

Disadvantages

- High installation cost for small units.
- Startup sequence is required if there is an interruption in production.
- Complex safety and control systems.
- Equipment like heat exchangers and flue gas stack requires a lot of space.
- Maintenance costs.

2.3.1.3 Batch furnace

These furnaces come in a wide range of sizes and most of the normal heat treating processes could be performed in them (Andersson, o.a., 2012). To generalize a bit it could be said that a batch furnace utilizes the same door to put in the product that is to be heat treated as to withdraw the one that is finished. Typically batch furnaces are good to use for example:

- Short series.
- Treating parts of with a shape and size which is not suitable for a continuous furnace due to technical reasons for example long shafts.
- Very large single objects.

The amount of manpower used to operate a batch furnace could vary with different levels of automation. Examples of Batch furnaces are for example:

- **Chamber furnace (**Figure 8**).** The simplest form of heat treating furnace which is a refractory lined chamber fitted with a hatch thru which the components are placed in the furnace.
- **Pit furnace (**Figure 8**).** Typically exists in two versions, with or without gastight chamber. Typically these furnaces are fitted with a lid that could either be lifted by a crane or swung aside. Pit furnaces are used for example in slab heat treatment.

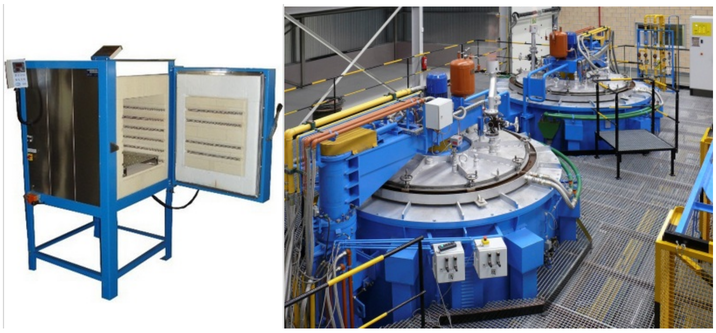

Figure 8. On the left is a chamber furnace (Borel, 2013) and on the right is a pit furnace (Seco/Warwick, u.d.)

2.3.1.4 Continuous furnaces

These furnaces are very well suited for very large production volumes. They could be incorporated into the production line itself. The principle behind them is that the parts that are to be heat treated are moving continuously through the furnace,that means it enters through one hatch in one end and exits through a hatch at the other end. Like batch furnaces the continuous furnaces comes in a large variety of shapes and sizes. (Andersson, o.a., 2012). Continuous furnaces are particularly suited for:

- Heat treating standardized material with the intention of producing even quality.
- Large quantities.
- Integration in continuous production lines.

Several types of continuous furnace exist. Below some examples are presented

- **Roller heart furnace.** The parts are loaded onto a hearth which is transported on rollers through the furnace see Figure 9. The hearth is the load carrier.

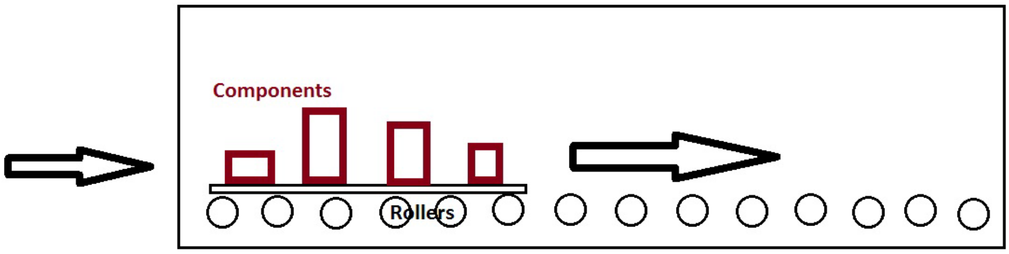

Figure 9. A schematic drawing of a roller heart furnace

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- **Pusher type furnace.** The incoming charge is used to push the charges in front of it through the furnace (see Figure 10). The components are placed on trays which are then pushed. The charge then consists of the components plus the trays or load carriers.
- In both cases above the trays must be heated together with the components and hence requires heating energy.

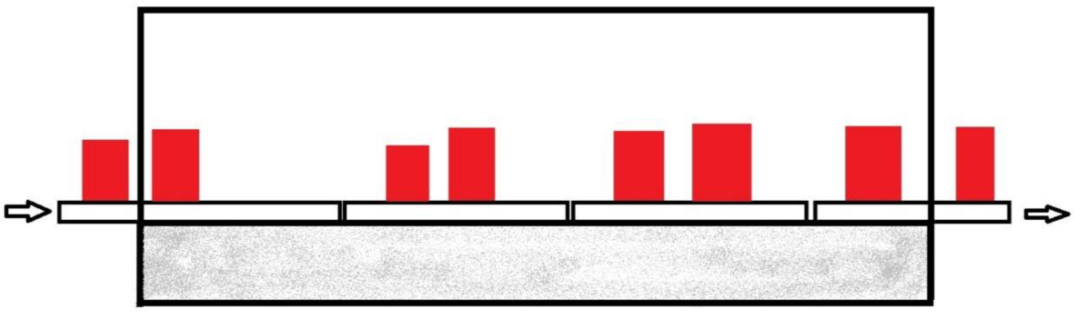

Figure 10. A schematic picture of a pusher type furnace

- **Conveyor type furnace.** The charges are placed on a conveyor belt and transported through the furnace (see Figure 11). In this type of furnace one has to be observant so that no parts get stuck in the belt or falls through it and end up on the bottom of the furnace.

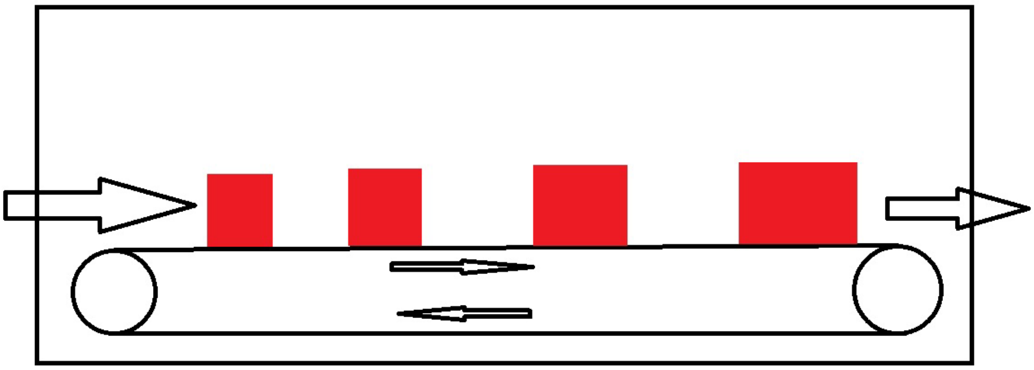

Figure 11. A schematic picture of a conveyor type furnace

2.3.1.5 Burners

Burners come in many shapes and sizes and are utilized in a variety of different applications from simple Bunsen burners (see Figure 12) to highly advanced burners in gas turbines, furnaces and power plants (see Figure 12). The purpose of them is to make sure that the combustion is made as efficiently as possible by ensuring that the fuel and the oxidizer are properly mixed.

Figure 12. (Left) Bunsen burner is a good example of a cold air burner (Humboldt, u.d.). (Right) A Regenerative FLOX (Flame Less Oxidization) burner is an example of a modern highly advanced burner with preheated combustion air (Flox, u.d.).

Combustion

In combustion a fuel and an oxidizer is mixed and ignited in order to release the chemically bounded energy as heat. According to (Thunman, 2013) it could be seen that if propane is burnt in pure oxygen the flame temperature exceeds 5500 K but if it is burnt in air where the composition is roughly 21 % oxygen and 79 % nitrogen the flame temperature is about 2400 K.

What this demonstrates is that when a fuel is burnt in pure oxygen, all the energy released goes into increasing the flame temperature and hence providing more energy to the surrounding environment. When burnt in air there is the presence of the non-reacting nitrogen which brings the flame temperature down. This is because some of the energy released in the reaction is spent heating the nitrogen.

In the example above the reaction is stoichiometric, in reality this is very difficult to achieve since it requires very god mixing. In order to avoid incomplete combustion, that is everything can’t react and release its energy, combustion is therefore in many cases aimed to take place at a fuel to air ratio (λ) of 1.1. That is for every mole of fuel an extra 10 mole% of air is added in order to ensure complete combustion. Just like the nitrogen this air is also needed to be heated from the energy that is released from the fuel that reacts.

One very efficient way of getting around this problem is to pre-heat the combustion air. This implies that the air is heated from room temperature to a temperature much closer to the flame temperature and hence reducing the amount of the released energy that is spent on heating non-reacting molecules.

The type of fuel that is of most significance for this report is gaseous fuels. There are a big variety of burners for gaseous fuels, everything from a simple pipe to burners that are designed with air and fuel staging, pressure nozzles that also provide swirl to the flow, all in order to give as a good mix as possible of fuel and oxidizer.

In heat treating furnaces there are three categories of burners: Cold air burners, regenerative burners and recuperative burners (Arvidsson, 2014). Cold air burners are, as explained above are not very good and hence is only in use on older furnaces. Recuperative burners use some of the energy content in the flue gases from the combustion to pre heat the combustion air. Typically the preheated combustion air reaches about half the flame temperature. The most advanced type of burner is a regenerative burner (see Figure 12). This also utilizes the heat in the flue gases to pre heat the combustion air but it is much more efficient in doing so. It could raise the ingoing combustion air temperature to about 90 % of the flame temperature, hence making it very efficient (Arvidsson, 2014).

2.3.2 Refractory

In principle a furnace consist of a metal shell whose main purpose is to support the systems that are installed in and on it. To mention a few of these systems there is the hearth that caries the parts, burners or other heating equipment is usually attached to the shell and finally the refractory has to be mounted to something.

Refractory is simply another term for insulation. Typically the refractory is bricks or porous ceramic material. The main purpose of the refractory is to insulate the furnace and store the heat. To do this it needs to be able to withstand the temperatures typically found in a furnace, i.e. from 600 to in some cases over 1000 ℃ Further away from the hot hearth cheaper insulating material like fibrous wool could be used (Andersson, o.a., 2012).

The function of the refractory is to minimize the heat conduction from the inside surface of the wall to the outside surface of the wall. The equation that governs this is the equation of heat conduction:

$$q'' = -k\frac{dT}{dx} \qquad (1)$$

Where q'' $\left[\frac{W}{m^2}\right]$ is the heat flux per unit area, k $\left[\frac{W}{m*K}\right]$ is the thermal conductivity, $dT = (T_1 - T_2)$ $[K]$ is the temperature between the positions of interest and $dx = (x_1 - x_2)$ is the distance between the position of interest (Incropera, Dewitt, Bergman, & Lavine, 2007).

As can be seen from equation (1) the properties of the furnace wall are dependent on the thermal conductivity k and the wall thickness dx. This means that in order to improve the performance of the refractory it could be changed to something with a lower thermal conductivity or the thickness of the furnace walls could be increased. However there is a practical limit to how thick a furnace wall could get. A wall thickness of several meters is both cumbersome and uneconomic (Andersson, o.a., 2012). A typical temperature of the metal skin of a furnace is about $40\,^{\circ}\mathrm{C}$ which would correspond to about $200\,\frac{W}{m^2}$ of heat being released (Andersson, o.a., 2012).

2.3.3 Endogas

Endogas, or endothermic gas, as it is more correctly called is a type of atmospheric gas. The name comes from that the gas is created from an endothermic process, i.e. energy has to be added to the process. Endogas is more generally speaking an atmospheric gas which is used to create a certain atmosphere inside a heat treating furnace.

There are two main reasons for the need of a different atmosphere in a furnace (Andersson, o.a., 2012):

1. A so called protective atmosphere is applied in order to protect the components from oxidization and from decarburizing. The latter is caused by diffusion and in order to prevent carbon from diffusing out of a part, a carbon rich atmosphere is required.
2. The second reason is for thermochemical process where the diffusion phenomenon is used to add certain substances to the surface of a part. This is typically preformed in so called carburizing, carbonitriding, nitro carburizing and nitriding where carbon and/or nitrogen is added by diffusing from the high concentrations in the atmosphere into the surface of the component.

To summarize it could be said that the atmospheric gas or endogas should fulfill the following properties:

- Control the oxidization of the steel during heat treatment.
- Achieve the correct surface content of carbon or nitrogen.
- Be able to flush out unwanted gases such as water vapor from the furnace.
- Ensure a slight overpressure to prevent air entering the furnace.

2.3.4 Quench

Quenching is the step that follows after the furnace. This is where the desired properties of the material are achieved. In order to lower a parts temperature it is quenched in some kind of fluid. The quenchant could be applied in several ways, for example the part could be lowered in to the quenchant or the quenchant could be sprayed on the hot part in great quantities. In order to have a repeatable process the temperature of the quenchant has to be controlled. This means that after a hot part has been lowered into the quenchant, or the quenchant have been sprayed on the part, the temperature of the quenchant has risen and is needed to be cooled in order to be able to recreate the same quenching conditions.

2.3.4.1 Quenching media

There are several types of quenchant media and their properties are different depending on the type of heat treatment that is being performed and the requirements on the product. It could also depend on the properties of the steel. If for example the steel is of such a character that the pearlitic nose does not appear until after quite long times, a quenchant that conducts heat poorly is sufficient but if the pearlitic nose is early a quenchant that could drop the temperature quickly is needed. Below is a list of the quenching medias used in the industry today (Andersson, o.a., 2012):

- Water
- Polymer quenchant
- Quenching oil
- Salt bath
- Gas, for example nitrogen
- Air

2.3.5 Transformation

Since the process that is studied is first and foremost bainitic hardening, bainitic transformation is an important step. As discussed in section 2.2.2 the part is quenched in order to avoid the pearlitic nose and then it needs to be kept at an elevated temperature to fully form bainite (Andersson, o.a., 2012). In the case of this study this is done in heated salt baths called transformation bath.

2.3.6 Washing

The heat treatment process could be performed at different stages in the manufacturing process and both heat treatment and succeeding operations need the components to be clean and free of various contaminants. In order to ensure this the components are washed both before and after heat treatment. Before is important due to the sensitivity of the protecting atmosphere in the furnace and after is needed to get rid of residues from quenching and in some cases residues from transformation baths.

2.4 Energy flow theory

This section gives a brief description of the theory behind heat transfer calculations and energy flows.

2.4.1 Energy conservation

The first law of thermodynamics reads (Incropera, Dewitt, Bergman, & Lavine, 2007):

> *"The increase in the amount of energy stored in a control volume must equal the amount of energy that enters the control volume, minus the amount of energy that leaves the control volume."*

This says that the total amount of energy in a system is conserved unless there is energy flows across the system boundaries. In a closed system there is only two ways for energy to be transferred to or from the system. That is either by heat transfer across the boundaries or work done on or by the system. This leads to the equation:

$$\Delta E = Q - W \qquad (2)$$

Where ΔE is the change in total energy stored in the system, Q is the net heat transfer to the system and W is the work done by or on the system, see Figure 13.

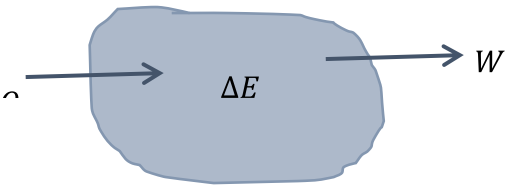

Figure 13. Conservation of energy

The total energy of the system could be summarized as:

$$\Delta E_{stored} = E_{in} - E_{out} + E_{generated} \qquad (3)$$

Here E stands for both mechanical energy and thermal energy. When we are dealing with heat transfer, mechanical and atomic energies could be neglected and if we assume steady state the energy flow over the boundary of the system could be expressed as

$$q = \dot{m}\, c_p\, \Delta T \qquad (4)$$

Where q is the thermal energy in $[W]$, $\dot{m}$ is the mass flow in $\left[\frac{kg}{s}\right]$, c_p is the specific heat in $\left[\frac{kJ}{kgK}\right]$ and ΔT is the temperature difference over the region where the heat transfer happens.

2.4.2 Convection

Convection is a heat transfer mode that is the combination of two principles. The first one is from heat being transported by the random molecular motion known as diffusion. The second one is the more significant bulk movement of a fluid over a surface. This bulk movement is connected to the collective movement of a large number of atoms.

There are two forms of convection, *natural* and *forced*. Natural convection is when a fluid starts to flow due to buoyancy effects. For example it is possible to feel an updraft of warm air if you put your hand close to a hot metal plate. On the other hand forced convection is when the flow of the fluid is induced by some kind of external effect like a pump, fan, or winds.

It does not matter what type of convection that is in question the equation is the same (Incropera, Dewitt, Bergman, & Lavine, 2007):

$$q'' = h\left(T_{surface} - T_{surronding}\right) \qquad (5)$$

Where q'' is the convective heat flux $\left[\frac{W}{m^2}\right]$, h is the convection heat transfer coefficient $\left[\frac{W}{m^2K}\right]$ and $T_{surface}$ and $T_{suronding}$ is the respective temperatures.

For a furnace placed in an indoor environment, the form of convection that occurs are natural convection. In order to calculate the free convection of a furnace it could be simulated as a box. In this way the equations governing free convection on horizontal surfaces could be used on the top and bottom surface and the equations governing convection on a vertical surface could be used on the sides.

General equations for free convections are (Incropera, Dewitt, Bergman, & Lavine, 2007):

$$Nu_L = \frac{hL}{k} \tag{6}$$

Where Nu_L is the Nusselt number h is the convection heat transfer coefficient and $k$is a material dependent heat transfer coefficient.

$$Ra_L = \frac{g\beta(T_s - T_\infty)L^3}{\nu\alpha} \tag{7}$$

Where Ra_L is the Rayleigh number, β is the volumetric thermal expansion coefficient which for ideal gases could be expressed as $\beta = \frac{1}{T}$, υ and α are material constants and L is the characteristic length of the surface.

For a vertical plate the Nusselt number could be obtained with two equations for laminar flow $(10^4 \leq Ra_L \leq 10^9)$ and for turbulent flows$(10^9 \leq Ra_L \leq 10^{13})$.

$$Nu_L = \left(0{,}825 + \frac{0{,}387 Ra_L^{\frac{1}{6}}}{\left[1 + \left(\frac{0{,}492}{Pr}\right)^{\frac{9}{16}}\right]^{\frac{8}{27}}} \right)^2 \tag{8}$$

Equation 9 gives slightly better accuracy with laminar flows

$$Nu_L = 0{,}68 + \frac{0{,}670 Ra_L^{\frac{1}{4}}}{\left[1 + \left(\frac{0{,}492}{Pr}\right)^{\frac{9}{16}}\right]^{4/9}} \tag{9}$$

where Pr is the Prandtl number.

For a horizontal plate you have to different correlations, one for the upper surface of a hot plate and the lower surface of a hot plate. In this case this would apply to the top and bottom of the furnace.

Upper surface of a hot plate:

$$Nu_L = 0{,}54 Ra_L^{\frac{1}{4}} \quad (10^4 \leq Ra_L \leq 10^7) \tag{10}$$

$$Nu_l = 0{,}15 Ra_L^{\frac{1}{3}} \quad (10^7 \leq Ra_L \leq 10^{11}) \tag{11}$$

Lower surface of hot plate:

$$Nu_L = 0{,}27 Ra_L^{\frac{1}{4}} \quad (10^5 \leq Ra_L \leq 10^{10}) \tag{12}$$

For the horizontal plate the characteristic length could be expressed as

$$L = \frac{A_s}{P} \tag{13}$$

where A_s is the surface area and P is the perimeter of said area.

2.4.3 Radiation

In contrast to convection (and conduction), radiation does not require the presence of a material medium. Heat could be transferred over a complete vacuum via radiation; in fact radiation is as most efficient in a vacuum. This is due to the fact that radiation emission is down to changes in the electron configuration of the constituent atoms and the radiation field is transported by electromagnetic waves. The emissive power for an ideal black body ($E_{black\ body}$) could be described as:

$$E_{black\ body} = \sigma T_{surface}^4 \tag{14}$$

Where $\sigma = 5.67 * 10^{-8} \left[\frac{W}{m^2 K^4}\right]$ is the Stefan-Boltzmann constant. However the emissive power of a real body is less than that of a black body and is given by:

$$E_{black\ body} = \varepsilon \sigma T_{surface}^4 \tag{15}$$

Where ε $(0 \leq \varepsilon \leq 1)$ is called the emissivity and depend strongly on the surface material and its finish. The energy that is emitted via radiation could be expressed as:

$$q''_{rad} = \varepsilon \sigma (T_s^4 - T_{sur}^4) \tag{16}$$

Where T_s is the surface temperature in Kelvin and T_{sur} is the surrounding temperature in Kelvin.

2.5 The General gas equation

The general gas equation could be derived from the ideal gas law.

$$PV = nRT \tag{17}$$

The general gas law relates the properties of gas at different states and is as follows:

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \tag{18}$$

3 Earlier research

There is limited research regarding the topic of energy efficiency and heat treatment. This contributes to make the study in SKF important to help in better understanding of the energy aspects of the heat treatment process.

(Lawler, 2012) have looked at heat treating in the electronics and nanotechnology industry and states that heating ovens and furnaces require a large amount of energy and that the carbon footprint of these process is relatively large. However manufacturers have started to address the problem and are working to reduce the environmental impact of their equipment. (Lawler, 2012) gives an example where a UK manufacturer of wire and strip has reduced their energy usage in heat treatment by switching from a steam heating system to a thermal fluid heating system. Another example given is from an electronics manufacturer that uses dual lane ovens to increase the throughput of the oven and by that decreasing energy usage.

(Mendikoa, o.a., 2013) have studied a method which could be used in optimizing the time temperature diagrams used in the heat treatment process. (Mendikoa, o.a., 2013) states that heat treatment is a sub-process in the metal processing industry it could account for more than a third of a company's energy usage and it is hence important to focus energy efficiency efforts on heat treatment in particular. (Mendikoa, o.a., 2013) describes the design of a heat treating process as starting with the choice of a suitable time temperature curve for the specific requirements the component have to fulfill. This is usually made from personal experience of experts but with the use of the suggested DEMI tool the design of this time-temperature curve could be more optimized for the product at hand.

Looking back in time, an anonymous writer (Anonymous, 1976) points out the difficulties the heat treating industry is facing. The paper mentions fuel shortages, the ever rising cost of fuel and the available techniques for reducing the energy consumption in heat treatment.

The importance of utilizing a heat treating furnace is emphasized by (A, P, J, & A, 1994) where they present a calculation model for determining the degree of utilization of a heat treating facility. What is mentioned to be of significant importance in this study is the charge weights.

In a presentation from one of SKF's competitors (Seifert & Nathan, 2010) they found that reducing the number of burners in the soaking zones of the furnace have provided significant fuel savings with no impact on product quality. Replacing old burners for modern ones have, besides increasing energy efficiency, also increased the throughput of the facility. (Seifert & Nathan, 2010) have also shown that for their process improvements on reduced cycle times, improved furnace pressure control, added insulation etc. have reduced energy usage of their facilities.

Literature on good design of industrial furnaces (Mullinger & Jenkins, 2013) lists the following key points as important to consider when striving for improving the energy efficiency:

- Minimizing air in-leakage.
- Operate burners at low excess air to maximize heat transfer.
- Recover heat from the products and flue gases.

A similar study at a heat treating facility was made by (Källen, 2012) were measurements were taken and the energy usage was mapped. The largest energy consumers were identified and it was concluded that about 750 MWh/yr could be saved. Some or the suggested efficiency measures was switch lighting to low energy lamps, insulate hood doors and heat exchange flue gas waste heat with washes.

Yet another study of this kind was made at a vehicle manufacturer in Sweden by (Ångström, 2009). Similar to the work of (Källen, 2012) a mapping was performed of the facility and the findings were that approximately 35% of the losses originated from wasted flue gases. The concluding recommendation was to use heat exchangers to recover heat losses from flue gases and quenching baths. Better insulation was proved to be a critical factor to improve energy efficiency of the furnace.

Heling 2014 (Heling, 2014) has studied the impact of pre and post washing and systems in heat treatment. What was found was that the electricity consumption for the heating of the washes was the biggest energy user in the washing stage. Heling (Heling, 2014) concludes that using electricity from renewable source is the most effective way of reducing the climate impact of pre and post washing in heat treatment.

Davis and Nilsson (Davis & Nilsson, 2012) conducted an internal study in SKF where induction hardening was compared with conventional through hardening. It was performed on a specific type of bearing on a specific production site hence the result could only be considered valid for that specific case. What was found was that induction has is more energy efficient than the conventional through hardening in a regular furnace. Davis and Nilsson (Davis & Nilsson, 2012) discuss that the size of the component being heat treated have an impact on the result. Smaller rings could be packed more tightly in a furnace and hence there might be a potential for lower energy impact per ring, however this is uncertain.

Considering what has been done and brought up as important in earlier research it appears that it is important to get a clear picture of the current energy situation at a heat treating facility before looking into improvement options. Once the baseline is established it is clear that factors that are important are flue gas losses, insulation, burners and utilization.

4 The Sites

The site where this study has been performed is a large industrial site in Gothenburg. Some of the studied areas are located some distance away from each other and some of them are closer. Figure 14 gives a view of the layout of the studied equipment.

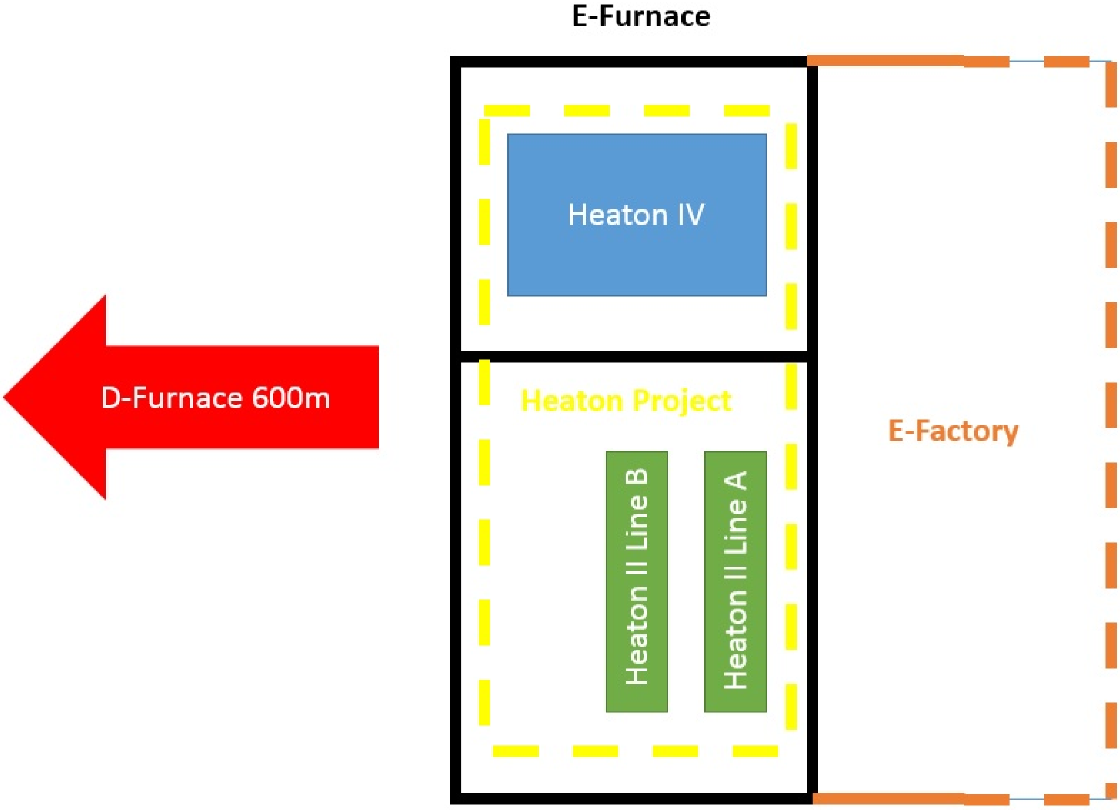

Figure 14 Geographical orientation of the furnace facility sites on SKF in Gothenburg

As the red arrow displays the D-furnace is on the other side of the site. The black building block is known as the E-Furnace, the orange building block right next door is the E-factory. There are two furnace facilities in the E-furnace; the Heaton IV furnace and the Heaton II furnace which consists of two lines, A and B. The dashed yellow line marks what latter is referred to as the Heaton project.

4.1 Heaton II

In this thesis the furnace facility named Heaton II has been studied in detail. The facility is a modern heat treating facility which commenced operation in 2008. It is mainly designed for SKF trademarked in house bainitic hardening but is also capable of performing martensitic hardening. The level of automation is high and both line A and B contains all the machinery necessary to complete the entire heat treating cycle, this includes:

- Pre wash equipment
- Drying equipment (included in the first wash block)
- Austenitizing furnace
- Quenching equipment

- Transformation baths
- Post wash equipment
- Atmospheric gas generator

Figure 15 gives a detailed view of one of the Heaton II lines and all the energy flows that is associated with the heat treatment process.

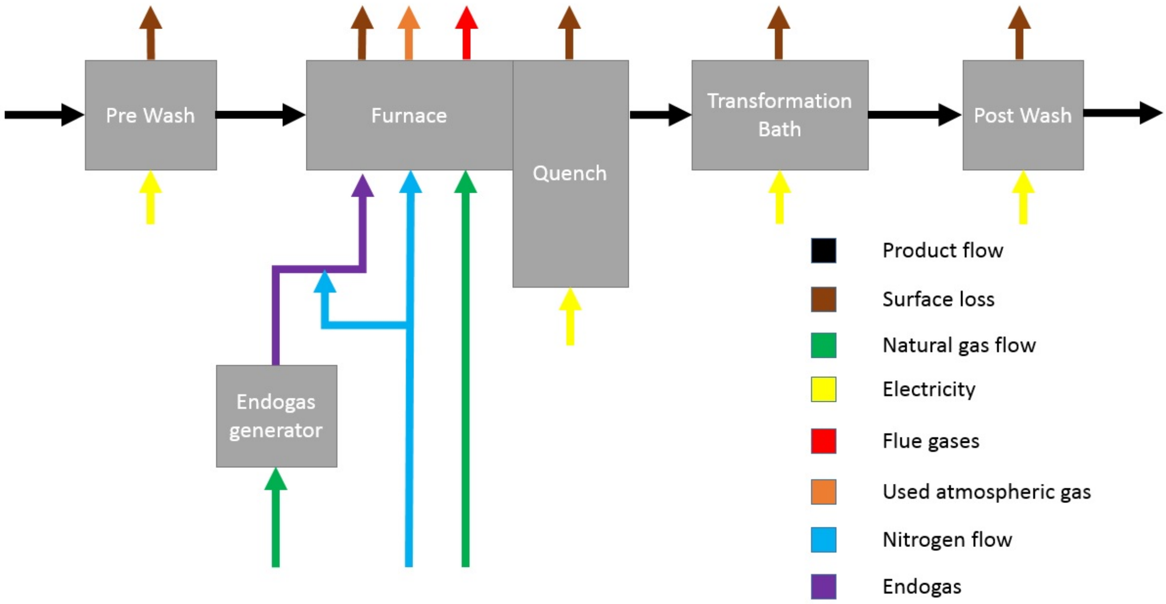

Figure 15. A schematic view of the Heaton II Facility

The principles of the bainitic hardening manly preformed in this facility is illustrated in a CCT diagram (Figure 16). The line starts were the component has just left the furnace and enters the quench. The temperature is dropped rapidly in order to avoid the pearlitic nose and then held at elevated temperature in the transformation baths to complete the bainitic transformation.

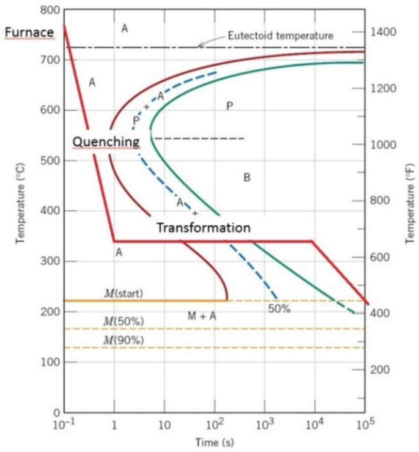

Figure 16 The red line marks a representative bainitic hardening process similar to what is done in Heaton II. Furnace marks the temperature at which the component comes out of the furnace. It is rapidly quenched and finally held at a constant elevated temperature under the transformation process.

Pre-washing is made at an elevated temperature using water with a detergent to remove residues of cutting fluid, oils, metal chips from previous processes and other contaminating matter. The washing is done to ensure a good quality of the product since unwanted contaminants could have a big effect on the heat treatment process. It is also an important safety aspect since foreign contaminants could cause an explosion if they enter the furnace. The elevated temperature is maintained with electrical heating elements.

Drying is needed since the water with detergent could be viewed as a contaminant if it enters the furnace. The consequences if the parts are still wet when they enter the furnace are the same as those described above.

The furnace is a continuous roller heart furnace with protective atmosphere. Components are placed in steal baskets in order not to get stuck in the rollers. A basket loaded with components is known as a charge.

The burner is a so called recuperative burner and has about 50% energy recovery in the form combustion air pre-heating (Flox, u.d.). The burners are on/off controlled where on means 100% and off means 0%. These are then fired in radiant tubes in order to keep the furnace atmosphere separated from the flue gases. The burners are placed both above and below the rollers in the furnace. The refractory used is fire resistant bricks. To increase temperature control the furnace is divided into several zones (see Figure 17). The furnace has individually controllable temperature zones that are placed along the length of the furnace and an extra zone which is the inlet vestibule that prevents the escape of atmospheric gas and unnecessary temperature loss.

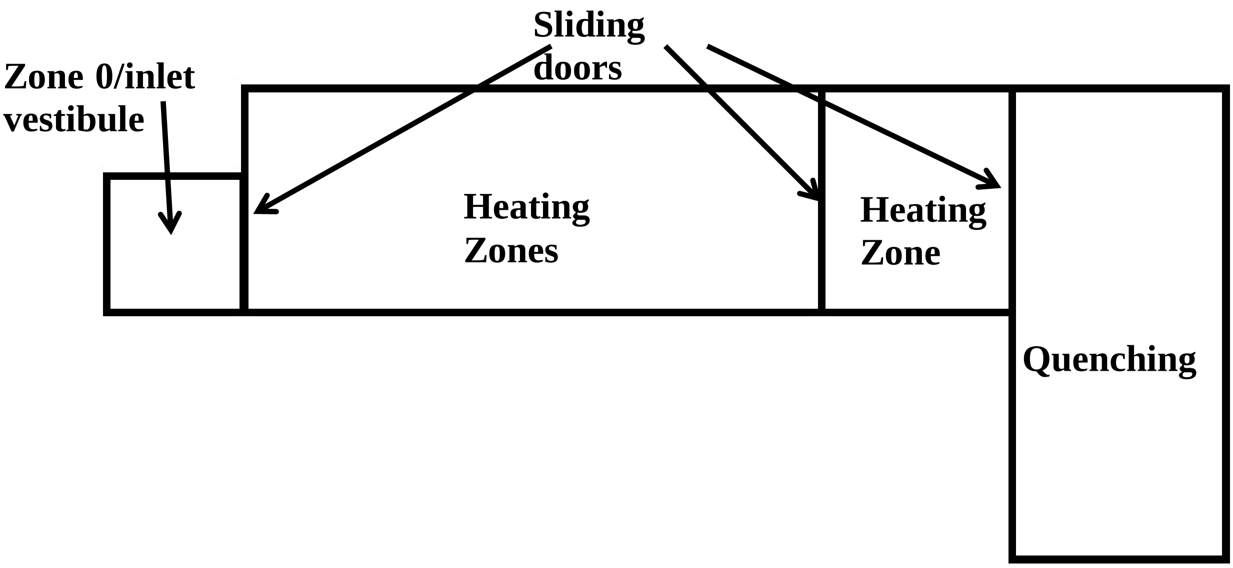

Figure 17. A detailed view of one of the Heaton II furnaces including quench

The quench is located right after the furnace and the quenching media is hot salt. The parts or the charges are submerged into a pool of quenchant that is in the lower part of the section named quenching in Figure 17. The quenching media is kept at a temperature high above the ambient temperature and is hence equipped with electric heaters to maintain this temperature. The quench is equipped with a heat recovery system that allows some of the heat from the quenched components to be recovered in the heating and ventilation system. This heat is then used to heat the incoming air to the furnace building and the factory next door.

The transformation baths are big tanks with hot liquid salt used to complete the bainitic transformation. The transformation baths are also kept at a temperature high above the ambient which requires them to be electrically heated. The tanks are open topped which means that a lot of heat escapes from the tanks. To avoid too much of this heat being wasted the salt tanks are secluded in a sealed area which allows the heat released from the tanks to be collected and to some extent recovered in the heating and ventilation system and reused in the same way as for the quench. Since the salt solidifies at room temperature there is a large heating capacity installed in order to re melt the salt after a longer stop.

The post washing is, similar to the pre-washing performed at an elevated temperature and the purpose of it is to remove salt that might have stuck from the quench or the transformation baths.

4.2 D-Furnace

The D-furnace facility is, similarly to the Heaton II facility, used for bainitic heat treatment. Therefore it is suitable to be used as a comparison to the Heaton II.

5 Method

5.1 Interview

The interviews were performed in such a way that people should feel free to speak their mind and all the questions that was not directly aimed to find a specific piece of information was open ended. The people that were selected for interviewing were representative for a cross section of all people involved in heat treatment in one form or the other. Both people in management positions and project leaders to factory workers were included in the study. To give an overview of what the interviewees' specific area of competence were they have been divided into four groups with the following competences in them:

- Process design and hardware development
    - Manager machine competence center
    - Senior engineer metallurgy and heat treatment
    - Heat treatment and laboratory manager
    - Senior engineer energy efficiency and heat treatment
    - Senior project expert
    - Team leader heat treatment
- Users in factory
    - Channel manager Heat treatment
    - Production technician heat treatment
    - Service technician
- Environmental
    - Team leader environment
    - Process specialist life cycle assessment
    - Development engineer
- Purchasing
    - Global category manager heat and surface treatment and cleaning.

As mentioned above the aim was to make the interviewees speak as freely as possible but in order to steer the interview in the right direction a template of basic open ended questions where used. This was split into two parts, the first was a very short general list of questions about the view on energy and environment in SKF and the second longer part deals with energy and heat treatment more specifically. The questions were of the character: how is the situation at the moment, what could be done to improve the situation, what will change in the long run, and what is the interviewees personal opinion on what has been done and what should be done.

The template was modified as the interviews proceeded as some questions turned out to be irrelevant and some topics that where missed in the beginning was added to capture yet another important angle. For the original template see Appendix 4.

5.2 Data gathering Heaton II

The system boundary is set to include all the energy consuming equipment which is directly linked to the heat treating process. It includes the steps: pre-wash, furnace, quench, transformation and finally the post-wash. Figure 18 shows what was measured in the facility. Some of the process streams could not be established from measurements but had to be established through calculations.

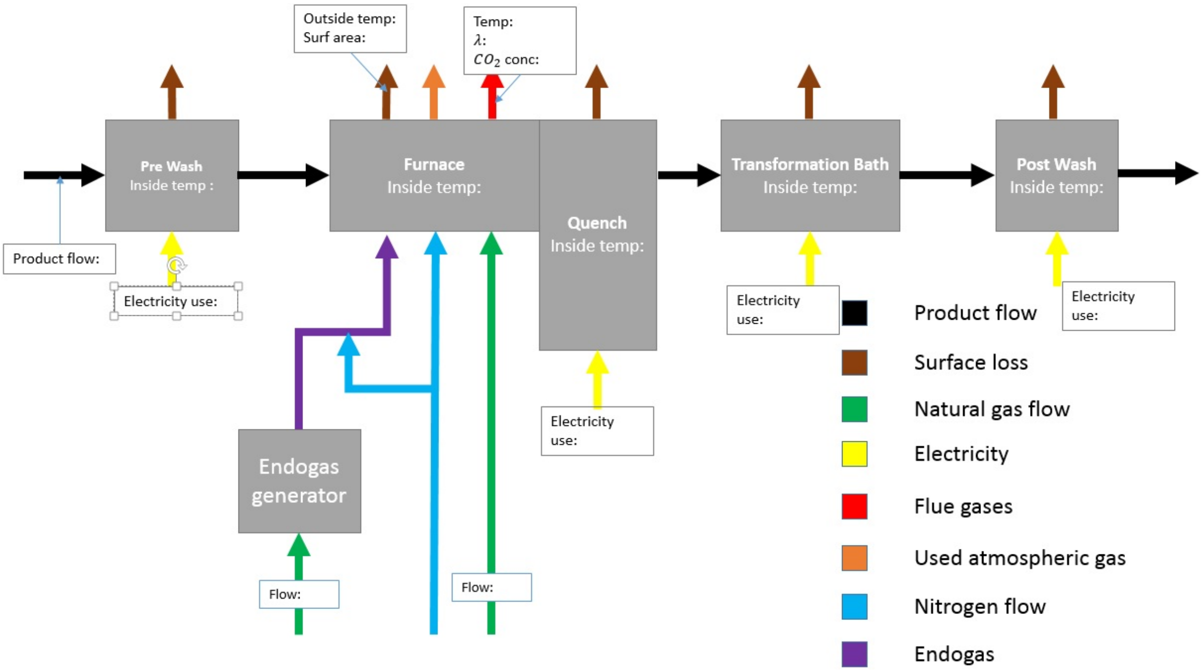

Figure 18. An overview of the Heaton II line and what was measured

The ambient temperature i.e. the inside temperature of the facility was established to be 25°C

5.2.1 Electricity

A mapping of the electricity consumption had been performed in the facility prior to this study. The mapping gives averaged values of the electricity use under three different conditions: i) Running, which is the regular operating mode of the furnace at the time the mapping was performed, ii) Fully loaded, which is the mode where the furnace is running at its maximum throughput capacity and iii) Maximum installed capacity which is only used under special conditions like start up, when components like transformation baths and washes need to be brought up to operating temperature quickly. This mapping was provided by an electrician in Heaton II. The mapping was last revised in 2011-03-31 and came from Electrical FDS-SKF Gothenburg 171.

The emissions from the electricity was calculated from two different values, one for the green electricity mix that SKF uses that was provided from the environmental team at MDC and one value for a typical European electricity mix.

$SKF\ green\ electricity\ mix$ (Davis, Energy management in heat treatment, 2014):

$$0.005\,\frac{kg_{CO_2}}{kWh_{electricity}}$$

$$EU27\ electricity\ mix\ (\text{The emission factors}):\quad 0.46\,\frac{kg_{CO_2}}{kWh_{electricity}}$$

5.2.2 Natural gas

The natural gas consumption was measured during a period of one week with the start date of 2014-05-09 and a finishing date of 2014-05-16. This was a regular working week with no holidays, production stops or any kind of anomaly. The logging of the gas consumption was made by taking readings of the pre-installed flow meters that are mounted on the furnaces main gas pipelines

This gas will be slightly pressurized which has to be compensated for when regarding the energy content per unit volume of the natural gas. The flow meter itself works like an odometer and records the amount of gas that has passed it since the start of the furnace. This means that in order to get the consumption for one week it is simply to subtract the value obtained at the beginning of the period from that obtained at the end of the period.

5.2.2.1 Natural gas data and assumptions

The gas used to power the furnaces where natural gas imported from Denmark. It was at the time not possible to acquire the exact composition of the gas so typical values used for Danish natural gas was obtained from literature (GasAkademin, 2006) The most relevant data is presented below, for more detailed information see Appendix 1.

$$Higher\ Heating\ Value, \qquad HHV = 43{,}96\,\frac{MJ}{Nm^3}$$

$$CO_2\ emissions\ at\ complete\ combustion, \qquad 57.16\,\frac{g}{MJ_{fuel}}$$

5.2.3 Surface losses

5.2.3.1 Radiation

In order to establish the radiation losses from the furnace, four aspects need to be measured: the surface area of the furnace, the emissivity of the surface, the surface temperature and finally the surrounding temperature.

The furnace area was established using the blueprints of the furnace. To obtain the skin temperature a thermal imaging camera was used. The Model and make was a Fluke Ti25.

A thermal imaging camera works by recording the thermal radiation coming of a surface. The emissivity is determined by the user, this means that in order to get a correct temperature reading the emissivity must be set to the correct value of the surface that is being studied. In this case the emissivity of the camera was set to $\varepsilon = 0.95$. In order to get a good average value, 19 measuring points were selected on each side wall of the furnaces. To make sure they were taken at regular intervals a tape measure was used to maintain an even distance between the points. At the end a total of 76 measuring points of the furnace walls was used to establish the skin temperature. No systematic measuring was made on the top or bottom of the furnaces because this area is more difficult to reach.

5.2.3.2 Convective

Only to things was required to establish the surface convection losses: surface temperature and surface area, both were collected during the data gathering for the radiation losses.

5.2.4 Flue gas losses

To establish the energy content of the flue gas the following must be known:

- Volume flow of the flue gases $\dot{V}$ $\left[\frac{m^3}{s}\right]$
- The heat capacity of the flue gases c_p $[\frac{kJ}{kgK}]$
- The density of the flue gases ρ $[\frac{kg}{m^3}]$
- The temperature of the flue gases $T_{flue\ gas}$ [°C]
- The air to fuel ratio λ

The flow of flue gas was calculated using the assumption that it was Danish natural gas that was used in the burner. With the air to fuel ratio λ known the flue gas flow could be calculated with correlations provided in Gas Akademin (GasAkademin, 2006) on how the flue gas flow related to the natural gas flow. A detailed description of the composition is provided in Appendix 1.

Values for the heat capacity and the density were found in literature and the values are available in Appendix 2. The equipment used to measure the flue gas values was a Testo 327-1.

Due to the complexity of the composition of the flue gases produced from the combustion in the furnaces a representative value for the combustion of a typical gaseous hydrocarbon fuel in air was used. The assumed composition was: CO_2: 13%, H_2O: 11%, N_2: 76% (Flue gases properties table - density, visocosity, u.d.)

The values for the relevant temperature interval is shown in Table 1 below, for the complete table see Appendix 2.

$Temperature\ [°C]$	$Density\ [kg/m^3]$	$Heat\ capacity\ \left[\frac{kJ}{kgK}\right]$
300	0.617	1.122
400	0.525	1.151
500	0.457	1.185

Table 1. A segment of the relevant values of from the flue gas table.

The burner operates in an on/off mode and had to be forced into "on" position for a couple of minutes to establish correct readings. This measurement was only performed on one of the total of 32 burners on a furnace.

5.2.5 Atmospheric gas losses

Since the atmospheric gas generators, or endogas generators, are not monitored and logged as meticulously as the furnace itself the values connected to this process are more based on calculations from expressions used to describe the process.

The Natural gas usage could be measured momentarily in the form of flow $\left[\frac{m^3}{h}\right]$ but it could also be calculated from the endogas flow which is more accurately measured and logged. The formulas used to calculate the flow is that the endogas has the following relation to natural gas and air:

$$\dot{V}_{endo\ gas} = 1.48\left(\dot{V}_{NG} + \dot{V}_{air}\right) \quad (19)$$

And air has the following relation to natural gas:

$$\dot{V}_{air} = 2.8\dot{V}_{NG} \quad (20)$$

This leads to the relation between natural gas and endogas in the following way:

$$\dot{V}_{endo\ gas} = 1.48\left(\dot{V}_{NG} + 2.8\dot{V}_{NG}\right) \quad (21)$$

$$\dot{V}_{endo\ gas} = 5.434\dot{V}_{NG} \quad (22)$$

$$\dot{V}_{NG} = \frac{\dot{V}_{endo\ gas}}{5.434} \quad (23)$$

Before the endogas is injected into the furnace it is diluted with nitrogen. There is no accurate way of measuring the amount of nitrogen used to this specific process but the final mixture is intended to contain $8 - 9\ \%_{vol}\ CO$ and the undiluted mixture was intended to contain $20\ \%_{vol}CO$ and from this it is possible to calculate the amount of nitrogen needed to mix the endogas.

Furthermore, nitrogen is not only used to dilute the endogas but is also sprayed on various components inside the furnace.

The amount of nitrogen that is used in the process is not logged in detail. From consultation with an expert on this field it was estimated that each furnace uses about $110\,\frac{m^3_{N_2}}{h}$ including the endogas. This comes to a total of $220\,\frac{m^3_{atmpspheric\ gas}}{h}$. Since the composition of the atmospheric gas leaving the furnaces is almost entirely made up from nitrogen, properties for the atmospheric gas losses has therefore been taken for that of pure nitrogen.

5.2.6 Production data

The production data used to establish material flows, utilization, temperatures, typical charge weights and similar information was obtained as raw data from the monitoring and logging program WinCC used in Heaton II. The provided data was logged over the period 2013-10-01 to 2014-04-07, corresponding to about 4500 hours. The following could be obtained from this data:

- All the id-numbers such as: charge number, batch number, product article number.
- The line number, if it was treated in furnace A or B.
- All the times for when a charge passes a zone such as the different zones in the furnace, in and out of wash, in and out of quench, in and out of transformation bath zones etc.
- Number of articles on a charge.
- Temperatures of all the process steps.
- Weight of each charge.

This data was then sorted using built in programs in excel.

The logging program sometimes made mistakes recording the weights of the charges. One charge had a maximum weight of 830 kg but the program have logged charges that whey over 10 tons and also charges of a total weight of 0.2 kg and have hundreds of parts on them, these data points where sorted out. Because of this problem an averaged weight of a charge had to be established and then multiplied with the number of charges in order to get the total production weight.

No clear definition of utilization of the furnace was defined so three types of definitions that could show different aspect of the furnace was created.

$$Utilization\ concerning\ time = \frac{Hours\ of\ operation\ with\ one\ or\ morge\ charge\ in\ furnace}{Totla\ amount\ of\ operating\ hours}$$

$$Material\ flow\ utilization = \frac{Material\ flow\ with\ and\ (without) carrier}{Normal\ operations\ flow\ capacity}$$

$$Weight\ utilization = \frac{Average\ weight\ of\ charge\ with\ and\ without\ carrier}{maximum\ weight\ per\ charge}$$

5.3 Data for D-furnace

Like the Heaton II facility, the D-furnace is also used for bainitic hardening and hence it is suitable for a comparison when it comes to energy usage. The mapping of the D-furnace was not as detailed as for that of Heaton II, only two pieces of information were needed to make the comparison.

5.3.1 Production data

Similar to the Heaton II facility the D-furnace has a system where charges are logged with plenty of information about temperatures, weights, times etc. However this is not done in the same convenient way as in Heaton II, the same practical overview is not readily available. In order to make the information more easily handled a separate program has been created in Excel to give a better overview. From this program one could read the production weights and the different utilization factors directly.

5.3.2 Gas use

The D-furnace is equipped with the exact same equipment as Heaton II when it comes to measuring the gas usage. That is an odometer that logs the total volume of gas that has passed through the main pipe to each furnace since operations first started. The pressure difference was readily available from a meter next to the gas meter.

6 Results

Results from the interviews and the measurements will be presented in this section. The results will be presented separately.

6.1 Interview results

It is clear that energy and environment is an important topic in SKF but unfortunately not that much have been done about this concerning the heat treating part of the manufacturing process. Despite heat treatment being the single largest energy user in the whole production line. However it seems like the wind has turned slightly over the past decade and now there has started to be a more prioritized topic even though it is considered to be far behind. One issue that was lifted is the lack of actual data of the current situation, without it is difficult to judge however an upgrade is an actual improvement.

Almost all of the interviewee mentions the new Heaton facilities when asked about what has been done lately to improve energy efficiency in heat treatment. The biggest effort on this facility have been in the heating and ventilation system where the waste heat from quenches and transformation baths are used for both heating the heat treatment building itself but also the nearby factory. There have been thoughts on making further improvements, the wasted flue gas heat has been considered for use in both wash- and transformation bath heating. One problem with the transformation bath that was that in order to use the waste heat effectively it needed to be transferred to a fluid based system and there is very few practical fluids that could mix well with hot salt. The risk of explosion like boiling in the event of a leak in a heat exchanger was considered too big. Other improvements were better burners, the ability to cover up transformation baths with lids, extra fiber insulation and the lowering of the temperature when the furnaces where not in use.

It is unanimous for most of the interviewees that the best way to save energy is not with better energy recovery but through better insulation. However when it comes to what means with better insulation opinions could differ. Some claim that thicker insulation would not be a problem, thicker walls do take more space and give the furnace slower dynamics but this would be countered by smaller load sensitivity and smaller losses. Others claim that it is too unpractical with the size of the furnace and claim that less bulky types of insulation should be used.

Equally unanimous is the opinions that in order to have a good energy efficiency the utilization factor needs to be high, preferably the furnace should run 24-7 all year round. Despite this the guide word is productivity and not energy management. This means that flows are optimized for latter stages of the production and this in turn leads to more changes in the furnace which lowers utilization and ups the energy consumption per kilogram produced.

Induction seems to be the new upcoming technology in heat treatment and it is believed that it will lower energy usage but how it should be utilized in the best way is not clear. Some claim that it is best used for small, high volume components and others claim that it should be used for big low volume components. It has been pointed out that technical difficulties prevent the use of induction on bigger low volume components but studies suggest that furnaces are best utilized for small high volume components.

Manufacturers need to be micromanaged in order not to take shortcuts when it comes to energy performance. They are also hesitant towards venturing out of there comfort zone and are hence not the most driving part when it comes to increasing the energy performance of furnaces. The amount of in house patch jobs that needs to be made on the furnaces after delivery wary much between different countries and between who is asked, if it is blue or white collar personnel.

SKF is a premium bearing company and this is what appears to drive the process and product development. If an energy saving investment is put against a product improvement investment the product improvement investment usually gets the upper hand. One reason for this seems to be that energy investments have longer payback periods then what is considered profitable in SKF so they are usually turned down. This has been brought up as a big trouble with all of the interviewees, a small and causes change in this could be sensed though.

To summarize:

- Energy and environment is an important topic but heat treatment is dragging behind. Not much data available.
- Much of the efforts on energy efficiency have been spent on the heating and ventilation system in the heat treatment facility.
- Better insulation is considered the best way to further improve the energy efficiency.
- Utilization is critical.
- Induction seems to be the new trend even though some doubt it and it is unclear how it should be utilized in the best way.
- Manufacturers needs to be micromanaged and are hesitant towards changes which makes them unwilling to be a driving partner in the energy efficiency work.
- Investments into energy savings are close to impossible due to long payback periods and that SKF is a premium bearing company which makes product investments more prioritized.

In the interviews a four point list of what is important to consider when preforming energy optimization of a furnace facility was provided, see appendix 7. This combining the result of all interviews this list could be expanded to:

- Measure everything
- Utilization factor
    - Even temperature
- How to heat (Burner performance etc.)
- Insulation
- Maintenance

6.2 Measurement results

An overview of the measured results will be presented in Figure 19. In the following subsection the result will be presented in greater detail, category by category.

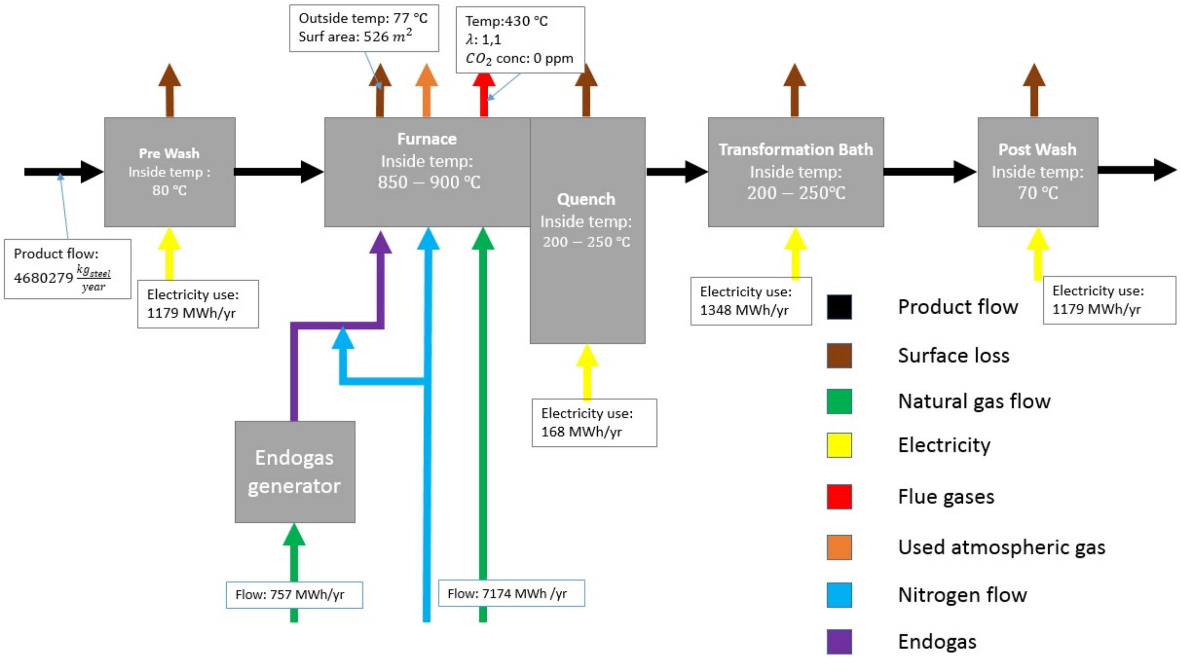

Figure 19. An overview of what data was gather at the different measuring points.

6.2.1 Electricity usage

In Table 2 the detailed result of the electricity data is presented. It is split into electricity for pure heating and for auxiliary equipment for all three modes; running, fully loaded and maximum installed capacity.

Total electricity usage for Line A and Line B				
Electrical heating				
Running	577	kW	4861	MWh/yr
Loaded 100%	2097	kW	17665	MWh/yr
Installed	4440	kW	37403	MWh/yr
Auxiliary equipment				
Running	425,4	kW	3584	MWh/yr
Loaded 100%	712,4	kW	6001	MWh/yr
Installed	906,5	kW	7636	MWh/yr

Table 2. Results from the electricity mapping

The corresponding amounts of carbon dioxide emanating from this electricity usage could be represented in three ways: If all the heating were to be conducted with natural gas, if all electricity came from a typical EU-27 electricity mix or finally from the electricity mix that SKF is using. The results are presented in Table 3 (Davis, Energy management in heat treatment, 2014) (The emission factors) (GasAkademin, 2006):

CO2 emissions [ton CO2/yr]			
	NG	**EU-27 mix**	**SKF-mix**
Running	1000	2236	24
Loaded 100%	3635	8126	88
Installed	7696	17205	187
Auxiliary equipment			
Running	-	1648	18
Loaded 100%	-	2761	30
Installed	-	3513	38

Table 3. The resulting CO_2 emissions from the electricity usage

For a detailed view of the electricity mapping, see Appendix 5. Table 4 and Figure 20 show the distribution of the electrical heating energy required from different parts of the heat treating facility.

Electricity used for heating to both furnaces lines						
	Running		100%		installed	
Pre-wash	1179	MWh	1179	MWh	1264	MWh
Drying	253	MWh	253	MWh	253	MWh
Quench	168	MWh	842	MWh	13731	MWh
Transformation	1348	MWh	13478	MWh	13478	MWh
Post-Wash	1179	MWh	1264	MWh	1264	MWh
Others	986	MWh	986	MWh	7666	MWh

Table 4. A table of the energy required for electrical heating during different operating scenarios

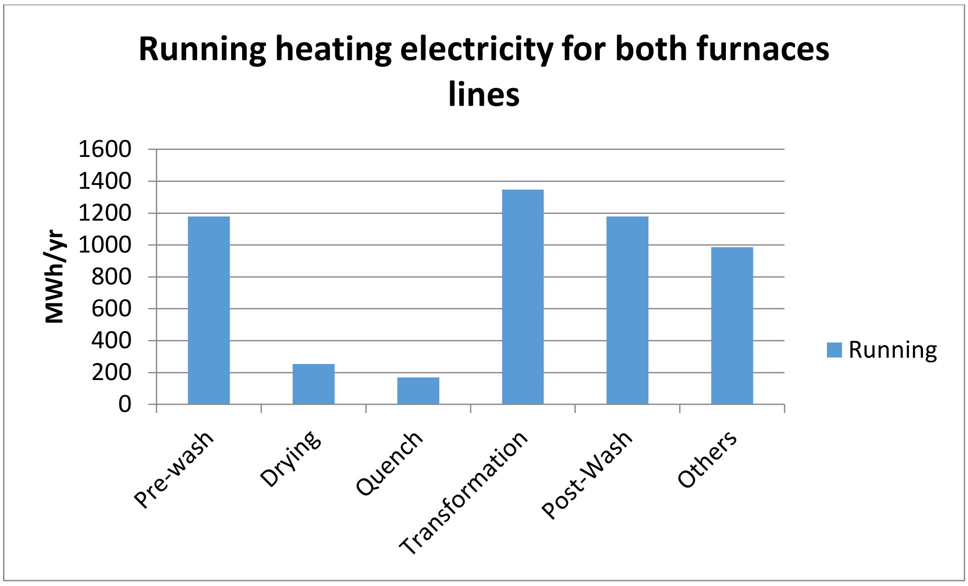

Figure 20. A bar chart showing a comparison of the electrical heating required at different parts of the heat treating line.

6.2.2 Natural gas usage

The gas meters were checked at three times, the first two times where within a quite close interval and the third and last time was about a week after the first measurement. During this time period there were no holidays or bigger anomalies planned in the production. The results are the following (see Table 5):

Description	Total gas use in a year $\left[\frac{m^3}{yr}\right]$	Total gas use in a year $\left[\frac{MWh}{yr}\right]$
Line A	291446	3559
Line B	296058	3615
Total	587504	7174

Table 5. The gas data for the Heaton II furnace lines.

6.2.3 Flue gas measurements

The flue gas measurements gave the following results:

$$\textit{Flue gas temperature: } T_{flue\ gas} = 430°C$$

$$\textit{Air to fuel ratio: } \lambda = 1.1$$

$$\textit{Oxygen concentration: } C_{O_2} = 2\ \%$$

$$\textit{Carbon monoxide concentration: } C_{CO} = 0\ ppm$$

With lambda known the flow relation of flue gas to natural gas is now known.

$$12.61 \frac{Nm^3_{wet\ flue\ gas}}{Nm^3_{Natural\ gas}}$$

The heating power in the flue gas if it is cooled to ambient temperature was found to be

$$Q = 139\ kW$$

With the previously stated 8424 hours of operation each year this leads to an energy loss of

$$1172 \frac{MWh}{yr}$$

6.2.4 Atmospheric gas measurements

The composition and flow of the endogas was obtained as displayed in Table 6

$Carbon\ monoxide\ content\ CO$	$20\ \%_{vol}$
$Hydrogen\ content\ H_2$	$40\ \%_{vol}$
$Nitrogen\ content\ N_2$	$40\ \%_{vol}$
$Endo\ gas\ flow$	$2 * 20 \frac{m^3}{h} = \frac{40m^3}{h}$

Table 6. The atmospheric gas composition

Using the formula provided in section 5.2.5 the calculated natural gas use to provide this volume will then be

$$62009 \frac{m^3}{yr} \text{ or } 757 \frac{MWh}{yr}$$

With the composition of the endogas known it is possible to calculate the amount of nitrogen used to dilute it, this was using the equations in section 5.2.5.

$$54.11 \frac{m^3_{N_2}}{h}$$

According to the assumptions the total amount of atmospheric gas that was injected into the furnace was about $220 \frac{m^3_{Atmospheric\ gas}}{h}$ including the diluted endogas.

The atmospheric gas simply passes through the furnace and hence the energy required to heat it is the same as the energy lost when the gas leaves the furnace

$$Q = 70\ kW$$

Which adds up to

$$591 \frac{MWh}{yr}$$

6.2.5 Surface Losses

There are two types of surface losses, radiation and convection losses.

6.2.5.1 Radiation loss

Figure 21 shows a picture from the thermal imaging camera.

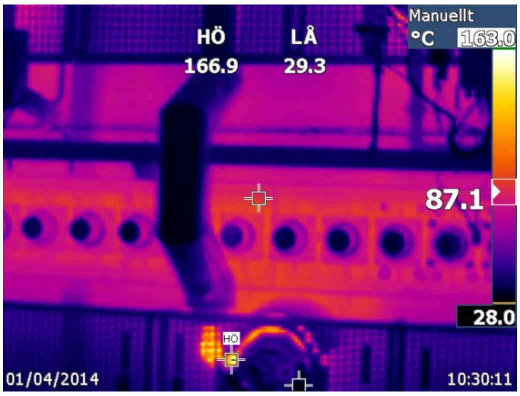

Figure 21. A picture of the furnace skin with the thermal imaging camera

The total average temperature of the furnaces are 77.6 °C. From blueprints the surface are of the furnace was found to be $263\, m^2$ which for both of the furnaces ads up to $526\, m^2$.

$$Q = 220kW$$

Which adds up to

$$1851 \frac{MWh}{yr}.$$

6.2.5.2 Convection losses

Using the equations presented in section 5.2.3.2 and the measured surface temperatures

	Convection loss [kW]
Line A	56
Line B	57
Total	112

This adds up to: 947 MWh/yr.

6.2.6 Production data

In Table 7 a summary of the result of the production data is available.

General information		
Time period for the logging	2013-10-01 to 2014-04-07	That corresponds to 4518 h
Number of charges heat treated	12108 charges	
Carrier weigh	50 kg	
Maximum charge weight	830 kg	
Maximum capacity both lines	2000 kg/h	
Normal operation capacity both lines	1200 kg/h	
Normal yearly operating capacity	10000000 kg/yr	
Total material flow without carrier weight	$556\, kg_{steel}/h$	
Total weight produced in a year	$4680279 \frac{kg_{steel}}{year}$	
	Line A	**Line B**
Utilization concerning time	67.62%	67.89%
Flow utilization with carrier	62%	64%
Flow utilization without carrier	49%	46%
Weight utilization with carrier	29%	34%
Weight utilization without carrier	23%	28%

Table 7. Summary of the production data.

Using a program that was provided to calculate the energy needed to raise the temperature of one kilogram of steel of grade 146S from 25 °C to 864 °C. The amount required is $662 \frac{kJ}{kg}$. This gives the following results for the energy that goes into the steel, see Table 8.

Energy into product	861 MWh/yr
Energy into carrier	208 MWh/yr
Total energy into charges	1069 MWh/yr

Table 8. The amount of energy that is required to heat components and carriers.

To show the flexibility of the furnace Figure 22 shows the series length, or number of articles, in a batch for the respective furnaces. In this context a batch refers to an unbroken chain of charges that carries the same article number.

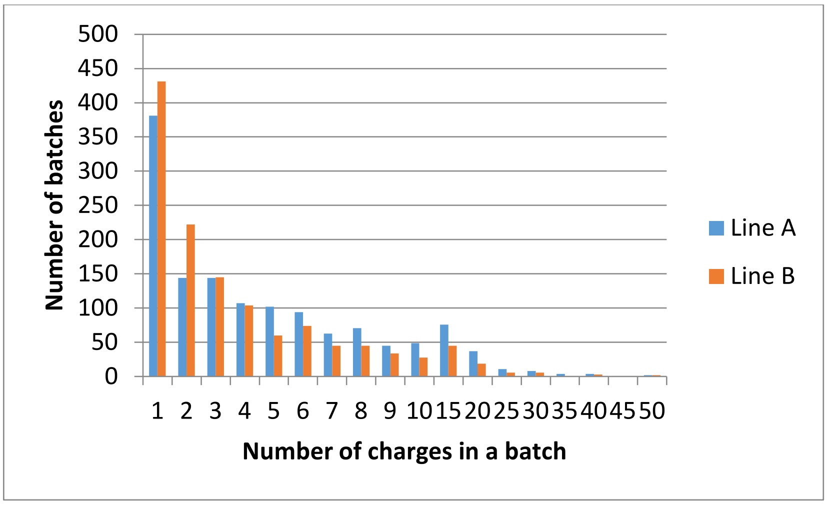

Figure 22. The number of charges in a batch and the frequency of respective batch.

6.2.7 Key performance figures

With a total energy input over an operating year being 7174 MWh of natural gas the distribution of the energy balance of the furnace is given in Figure 23.

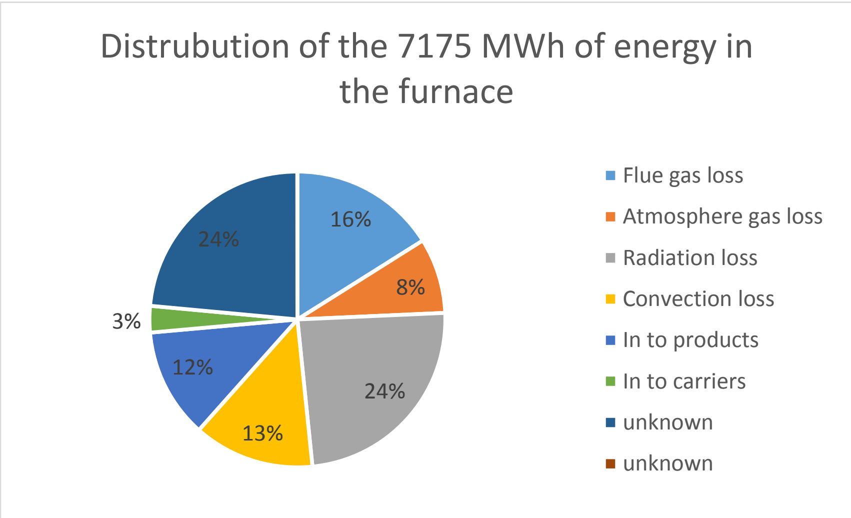

Figure 23. The distribution of the energy content of the natural gas used to power the furnace.

Another important figure is how much energy is required to heat treat one kilogram of steel in this facility, this is called the key performance indicator or KPI. The figures to this are provided in Table 9 below.

	Energy use	Key Performance Indicator	CO_2 emissions with SKF electric mix	CO_2 emissions with EU-27 electric mix
Electricity use	$8444218\ kWh_{el}$	$1.80 \frac{kWh_{el}}{kg_{steel}}$	$0.01 \frac{kg_{CO_2}}{kg_{steel}}$	$0.83 \frac{kg_{CO_2}}{kg_{steel}}$
Natural gas use burner	$7174545\ kWh_{gas}$	$1.53 \frac{kWh_{NG}}{kg_{steel}}$	$0.3154 \frac{kg_{CO_2}}{kg_{steel}}$	$0.3154 \frac{kg_{CO_2}}{kg_{steel}}$

Natural gas use endo	$757255\ kWh_{gas}$	$0.16\frac{kWh_{NG}}{kg_{steel}}$	$0.033\frac{kg_{CO_2}}{kg_{steel}}$	$0.033\frac{kg_{CO_2}}{kg_{steel}}$
Total	$15618762\ kWh_{tot}$	$3.50\frac{kWh}{kg_{steel}}$	$0.36\frac{kg_{CO_2}}{kg_{steel}}$	$1.179\frac{kg_{CO_2}}{kg_{steel}}$

Table 9. The performance figures for different energy carriers and the corresponding CO_2 emissions.

6.2.8 D-furnace

The total yearly production weight of the D furnace was found to be

$$11613062\ kg/yr.$$

The flow utilization of the D-furnace was found to be

$$93\% - 95\%$$

The time utilization of the D furnace is

$$61\%$$

Comparing only the natural gas use of both lines in the D-furnace with both lines in Heaton II the result is displayed in Table 10.

Heaton II burner natural gas use	$1.53\frac{kWh_{NG}}{kg_{steel}}$
D-Furnace burner natural gas use	$0.99\frac{kWh_{NG}}{kg_{steel}}$

Table 10. A comparison of the performance figures for the D-furnace facility compared to the Heaton II facility.

7 Analysis

In this section earlier research and theory is applied in analyzing the results of the empiric measurements and interesting statements from the interviews. This is a comparison of what the theory and research says on the topic of energy conservation in heat treatment and what is actually the case.

Electricity measurements

As could be seen from Figure 20 there are three individual components that uses a lot of electricity for heating, these three are pre wash, transformation and post wash. This matches what Heling (Heling, 2014) found in her work about the energy usage that the electricity usage of the washes have the biggest impact. Since SKF is using green electricity the carbon dioxide emissions from the electricity consumption could be drastically reduced. Just as Källen (Källen, 2012)) and Ångström (Ångström, 2009) concluded in their reports the washes are well suited to heat recovery since most of the electricity used in them is used for heating. As stated in the interviews some crude efforts on heat recovery in the wash have been attempted but not optimized in accordance with heat transfer theories provided by (Incropera, Dewitt, Bergman, & Lavine, 2007).

Flue gas measurements

The measured exhaust temperature of the flue gases was $430\ ℃$ and this correlates well with the stated performance of a recuperative burner which is claimed to be able to raise the combustion air temperature to about half of the furnace temperature and also release the exhaust gases at a similar temperature (Flox, u.d.). However in the interviews with the people who have worked with and also designed the furnace it was claimed that the exhaust temperature would be somewhere about $300\ ℃$. In some cases it was thought to be as low or lower than $250\ ℃$. As has been emphasized in interviews, by Mullinger and Jenkins (Mullinger & Jenkins, 2013) and Seifert and Nathan (Seifert & Nathan, 2010) the use of a burner in an efficient way is of big importance for the energy performance of a furnace. As could be seen from the measuring of the flue gases, air to fuel ratio correlates well with the lambda value that is recommended to ensure complete combustion with limited amount of excess air, that is $\lambda = 1{,}1$ $(\text{Thunman}, 2013)$. However the burners are not of the most efficient model, the regenerative model where temperatures of the pre heated combustion air could reach as high as $90\ \%$ of the furnace temperature (Arvidsson, 2014) are not installed and hence there is potential for improvement. There is no further heat recovery equipment installed in the flue gas stack system and according to (Incropera, Dewitt, Bergman, & Lavine, 2007) this is possible since the temperature difference between the flue gases and the ambient is above $400\ ℃$. Källen (Källen, 2012), Ångström (Ångström, 2009) and Mullinger and Jenkins (Mullinger & Jenkins, 2013) all emphasis the importance of recovering the flue gases in order to give a heat treating facility as good energy performance as possible.

Surface losses

The surface losses of both the furnaces amount to $332\ kW$ of heat energy being released from the surface of the furnaces and the furnace skin temperature was found to be about $77\ ℃$. With a total surface area of $526\ m^2$ the heat flux per unit area will be $631\frac{W}{m^2}$. Both temperature and surface heat flux is higher than the numbers suggested by Andersson et al. (Andersson, o.a., 2012) who claims that it should be somewhere around $200\frac{W}{m^2}$ and a surface temperature of about $40\ ^\circ C$. Whoever the measured values are matching the values stated during interviews. Interviewees also brought this difference up as a problem since it is not always clear under what condition these values should be measured. It was pointed out that in some cases manufacturers could use methods like double hulled furnaces and chimney effects to drastically reduce surface temperature or refer to furnaces with impractically thick insulation and hence lower surface temperatures.

Production data

Sala et.al (A, P, J, & A, 1994), Lawer (Lawler, 2012) and Seifert and Nathan (Seifert & Nathan, 2010) al emphasis the importance of good utilization in a furnace, but similar to what was found in interviews it is no statements of how to define the way a furnace should be utilized. In the work of Sala et.al (A, P, J, & A, 1994) the weight of the charges are bought ups as important factors. In the results above three kinds of utilization has been presented. From interviews it is pointed out that the most correct way to judge the utilization of a furnace is to look at the actual flow versus the designed maximum production flow. However in this case the difference between the utilization based on production flow and the utilization based on charge weight is significant. The importance of having a well filled furnace was also brought up in the study performed by Davis and Nilsson (Davis & Nilsson, 2012) where it is discussed that there might be advantageous to use a furnace for a through hardening process on many small rings since the energy impact on each ring could be reduced. In the interviews it was also found that the up time, or the time utilization of the furnace is of big importance. This due to that fact that even though there is a stop in the production the furnace is kept on according to the interviewees. However the temperature is lowered to reduce the energy consumption and this is in line with what is said in Incropera et.al (Incropera, Dewitt, Bergman, & Lavine, 2007). The importance of good utilization could also be supported by the fact that the results from the D-furnace facility indicate that better utilization has an effect on the energy use per component.

Figure 22 indicates that the variation in the types of products that flow through the furnace is large. The number of series that only is one charge long is clearly the most common scenario. This type of operation is not optimal for a continuous furnace according to Andersson et.al (Andersson, o.a., 2012). For this type of shorter series Andersson et.al (Andersson, o.a., 2012) recommend a batch type furnace. It was found in the interviews that the operation of the furnace used to be more aimed to longer series but demands from management on increased flexibility lead to an operation mode more governed by costumer demands rather than energy efficiency. To quote one of the interviewees: “Flexibility is a guide word, energy management is not”. This is however contradictory to what was brought forward in most interviews where the importance of energy conservation and environment was brought forward as a very important topic in the company.

Performance figures

In figure 27 the distribution of the ingoing energy to the furnace is displayed. In accordance with what has been expressed in the interviews surface losses of the skin is a big part of total energy loss of the furnace, a total of 34 % of the energy content of the fuel is lost through the surface skin as waste heat. This will also support the statements in interviews that one effective way of improving the energy performance of the furnaces is to improve insulation. Close to a quarter of the energy is lost with the flue gases and atmospheric gases leaving the furnace. This is similar to what Källen (Källen, 2012), Ångström (Ångström, 2009) and Mullinger and Jenkins (Mullinger & Jenkins, 2013) and could and emphasizes the importance of a heat recovery system even more. In one interview it was brought forward that efforts have been spent on optimizing the carriers in the furnace by making them slimmer and lighter. From the results it is clear that only $3\,\%$ of the energy that goes into the furnace is lost in heating the carriers. This is clearly not the area where time should be spent in improving the energy efficiency of the facility.

Only $12\,\%$ of energy is used to heat the actual components that are to be heat treated. This value is far from the efficiency that Andersson et.al (Andersson, o.a., 2012) stated of $50 - 70\,\%$. It is however correlating with the results from the interviews where interviewees stated typical furnace efficiency of about $10 - 15\,\%$.

8 Discussion

In this section the results from the measurements and interviews are discussed and questioned; also the choice of method will be discussed and evaluated. This thesis aimed to clarify the situation within heat treatment at SKF, provide recommendation and information about important factors to consider when trying to optimize the energy performance of a furnace facility and to give recommendations on improvement and their consequences.

Sources of errors and discussion of the choice of method

The method in this thesis was to tackle the questions at issue with two approaches; by interviewing people involved in heat treatment and by taking measures of the actual facility. This hade both upsides and downsides. Since almost all of the interviewees where employees at SKF, it is unavoidable that the outcome of the interviews would be more or less biased in SKF's favor. Even though the interviewer was an external part this has of course effected the answers but perhaps not as much as if the interviewer himself was an employee at SKF. It could not be denied that the interviewer himself was tainted by the opinions expressed during the interviews. However despite the risk of getting biased answers the interviews provided an invaluable source of information about the two furnace facilities studied. It gave clear direct answers to what is and can be problematic when building a furnace facility. Especially since the Heaton facilities are new, people who were involved in the designing and building of the furnaces could tell first hand of the difficulties and pitfalls in designing a new furnace facility.

The choice of doing measurements of two of the facilities was a very good approach in theory and it turned out to be quite successful in practice. However it was very time consuming and since SKF is a very big organization it turned out to be very difficult at times to get hold of the right equipment and a technician who knew where to measure to get the desired data. Also since it is an industry with equipment that could be unsafe and hence a lot of rules and regulations had to be followed which in some cases led to restricted access. The consequences of this was that if a measurement turned out to be faulty or additional data needed to be collected, the next window of opportunity to do so could in some cases be weeks away. This made the process of gathering data very prolonged and unfortunately, to save time, a sort of make do attitude was applied. This could be part of the reason for some sources of errors in the measurements.

The data about the electricity use was not up to date. It is a possibility that the situation have changed since this data was collected and therefore it might not be accurate. Furthermore there was no definition of the categories; running, 100% loaded and installed capacity and the interpretation of this information could be wrong.

Data on the gas consumption of the furnace was collected during one week of normal operation. Despite the absence of anomalies during the measurements, one week could not be considered as a representative sample due to the large variations in product type and flow. Neither was the measurements correlated to data from the production at the time.

The assumption was made that the gas composition was that of typical Danish natural gas. It is not certain that this was representative for the gas used at the time.

Much of the information obtained from the flue gases was calculated from the usage of natural gas and hence have the same uncertainties as the natural gas data. Values for heat capacity and density of the flue gas were taken from literature for an arbitrary hydrocarbon gaseous fuel and might not be completely accurate for this application.

Equipment for measuring the flow of atmospheric gas was limited and because of this the data was calculated from momentary flow of natural gas to the endogas generator. The amount of additional nitrogen used in the process was obtained through the interviews. This leads to uncertainties in the calculations of the atmospheric gas use.

Due to incorrect settings of the infra-red camera the surface temperature is incorrect and hence leads to errors in the sub ceding calculations.

Questioning and discussion of the current situation and the decisions that been made and the results of the interview

The choice of Key Performance Indicator (KPI) was partly based on that during interviews it was mentioned that there was no KPI clearly defined for heat treatment and this was a problem. The decision to use $\frac{kWh}{kg_{steel}}$ was based on that it is the best compromise regarding differences in geometry, size and definitions of what is considered "useful" energy in heat treatment. It was found during interviews that in some cases the unit $\frac{kWh_{valueadding\ energy}}{kg_{steel}}$ is used. Other interviewees reacted to this and said that this is border lining something called green washing and should be avoided. As can be seen from the pie chart in Figure 23 the part of the energy that goes into the components are only 12 % of the energy actually needed in the furnace. By using the $\frac{kWh}{kg_{steel}}$ a fair picture of how much energy is needed to treat a kilogram of steel is shown.

During the interviews examples where given of different kinds of energy saving efforts. None of them is according to me very ambitious and as could be seen from the pie chart a lot of energy is wasted. What was brought up the most was that heat recovery was installed in the general ventilation system and also from more point sources like the quenches and transformation baths. This is not in any way a bad solution since much of the energy that is being lost from the furnace ends up in the surrounding indoor environment end could hence be recovered in the ventilation system. However this could be seen as a lost opportunity since installing a heat recovery system in the ventilation system is in no way unique for a heat treating facility, this type of recovery could be used in all facilities like residential housing, offices and other types of industries. What is more unique with a heat treating facility is that, if done properly, the heat that is available for collection is of much higher quality then say for an office building. This makes the alternatives for where the wasted energy could be used so many more. As was found in the interviews, efforts had been made in trying to heat one of the prewashes in Heaton IV but the heat exchanger was very crude and the system is not yet fully operational. With the flue gas temperature of $430\ ℃$ and the atmospheric gas losses at furnace temperature ($850 + ℃$) the heat is of high enough quality to produce steam that could be used in other processes or as been discussed, for district heating. Unfortunately this idea was not realized due to the fact that the district heating producers in the city of Gothenburg feared that there operations would be more or less sub-optimized. This might very well be the case but it could be a good lesson to learn that when a larger heat treating facility is being planned it would be advantageous to involve the municipality at an early stage to be able to integrate district heating plans at an early stage of the build.

As always in industry money is a big driver and as said in the interviews demands on payback times tend to hold back the progression of energy efficiency in heat treatment. But also other factors are brought up such as the relation with the furnace manufacturers. Despite demands on low surface temperature and, as could be seen from the results, a need for low surface losses is of big importance, manufacturers (according to people in SKF) are very hesitant towards changes on their products. Putting higher demands on manufacturers to improve insulation should, from an energy perspective, be one of the main topics for the manufacturers. More insulation will make the dynamics of the furnace worse. This will impinge on the demands for flexibility that is today but the tendencies observed in this study shows that flexibility and energy efficiency in a furnace facility is not compatible. Another drawback that was lifted with having a flexible furnace operation is that the frequent changing of the temperature will wear the refractory quicker due to thermal stress. For today industries seems to have choose from one or the other.

In the interviews people were confronted with why the transformation baths had not been considered for heat exchanging. Some claimed the reason for this was that the temperatures of the waste heat was too low, this has proven false by the measurements and data collection of the facility. Others claimed that this was avoided due to the risk of explosive boiling if the heat exchanger fluid is mixed with the hot salt in the event of a leakage. This would be a mistake to rule out the transformation bath as a possible use for the waste heat because of this risk. In the distillation process of crude oil highly flammable liquids passes through tubing over open flamed furnaces to be heated (Petroleum refining processes, 2013). From this it could be said that heat exchanging media that, if mixed, is highly explosive is indeed thinkable and hence it would be suggested to reintroduce the option of heat exchanging the transformation baths with a water or steam based system.

As Davis and Nilsson (Davis & Nilsson, 2012) concluded in their report the use of induction heat treatment in certain applications could reduce energy usage considerably. This, in combination with information about the possibility of using induction together with furnace technology in a form of a hybrid heat treatment, sound like a good idea. Especially if the furnace part of this process could be improved in the ways described above.

Based on the above discussion and analysis a couple of improvement suggestions will be presented. In appendix 6 there is a table of 23 different options for energy improvements for this furnace facility, only a couple of these will be discussed in detail. The options that will be discussed are (see Table 11):

1. Only adding a heat exchanger to recover the hot atmospheric gases and use the energy to pre heat the atmospheric gases going into the furnace based on a $\Delta T_{min} = 10K$
2. Choosing a regenerative burner, this uses more combustion air preheat and therefore only has an exhaust temperature of about $300\ ℃$ (Flox, u.d.). This is to be combined with a lowering of the surface temperature of 20 K.

3. The third option is to combine the two options above and adding an extra heat exchanger to recover the energy in the flue gases and use them in the post wash. It should be mentioned that this is the most effective option of them all.

Option	**Description**	**NG use** $\left[\frac{MWh}{yr}\right]$	**El. use** $\left[\frac{MWh}{yr}\right]$	**KPI** $\left[\frac{kWh}{kg_{steel}}\right]$	**Furnace KPI** $\left[\frac{kWh}{kg_{steel}}\right]$	CO_2 **SKF mix** $\left[\frac{kgCO_2}{kg_{steel}}\right]$	CO_2 **EU27 mix** $\left[\frac{kgCO_2}{kg_{steel}}\right]$
Current		**7174**	**8444**	**3,50**	**1,53**	**0,36**	**1,18**
#1	Pre heat atmospheric gases with outgoing atmospheric gases using a delta T_min=10K	6479	8444	3,3504	1,3844	0,3272	1,1481
#14	Change to regenerative burner an lower surface temperature with 20K	5298	8444	3,0981	1,1321	0,2752	1,0962
#23	Change to regenerative burner, use hot outgoing atmospheric gases to preheat ingoing atmospheric gases using $\Delta T_{min} = 10K$, lower surface temperature with $20K$ and heat exchange flue gases with the post wash	4657	8112	2,8905	0,9952	0,2467	1,0355

Table 11. The three options that was looked at in more detail.

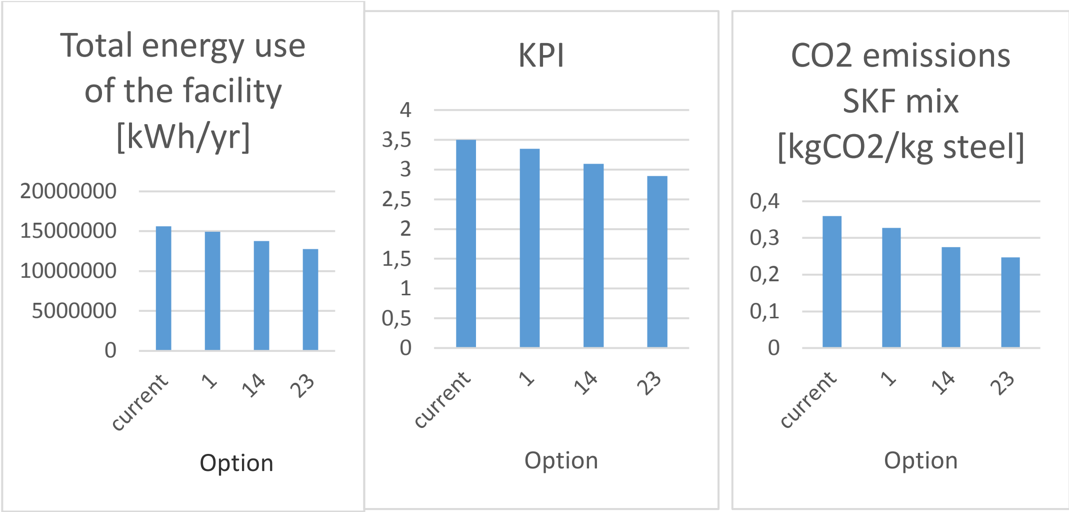

Figure 24. The performance figures for the three options.

As can be seen from both Table 11 and Figure 24 the energy usage, KPI and carbon dioxide emissions drop with each option. It is also clear that the measures needed to be taken to accomplish these reductions get more and more extensive and hence also more expensive. Note that all the suggested modifications are purely based on improving the hardware i.e. machinery of the facility. No suggestions on the effect on improved operations i.e. increased throughput have been made. This is due to the issue with no data collected that could correlate fuel use to production flow. Figure 25 shows the savings of each individual improvement.

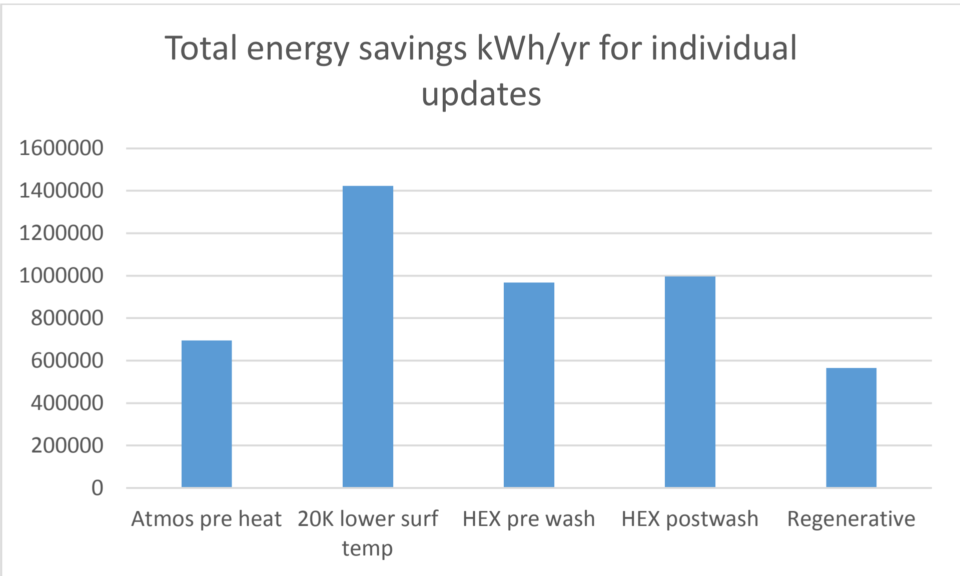

Figure 25. The effects of only one single measure

As can be seen in Figure 25 the lowering of the furnaces surface temperature of 20 K is the most effective single measure that could be performed. Unfortunately for SKF this is a measure that is dependent on the furnace manufacturer’s willingness to change. Other interesting observations are that the energy that could be used in the washes is significantly reduced when switching from recuperative to regenerative burners. This is due to that not only the temperature drop of the flue gas but with the increased pre heat of the combustion air the fuel consumption of the burners is reduced and hence also the flow of flue gases is reduced and this also contributes to reduced energy content of the flue gases (see equation (4)) (Incropera, Dewitt, Bergman, & Lavine, 2007).

The reason for why the post wash is more favorable to heat exchange with from an energy perspective then the pre wash is that the temperature in the post wash is 10 °C colder than the pre wash and hence more energy could be recovered from the flue gases in the post wash. However the difference between them is very small and the pre wash is located much closer to the exhaust pipes of the burners which would make the need for transporting the gas smaller and hence will reduce loses from pipes and ultimate make the system cheaper since less material is required.

Another problem with using regenerative burners that was brought up during interviews was that they are too large for a heat treating furnace of this size and this gives rise to a problem where not enough burners can be installed in the furnace and this leads to problems with controlling the temperature distribution in the furnace.

As mentioned before the most effective choice of improvements from an environmental point of view is option 23. It will reduce natural gas consumption with 2516 MWh/yr (35 %) and the electricity consumption with 331 MWh/yr (4 %). The distribution of the natural gas used in the furnace is displayed in Figure 26.

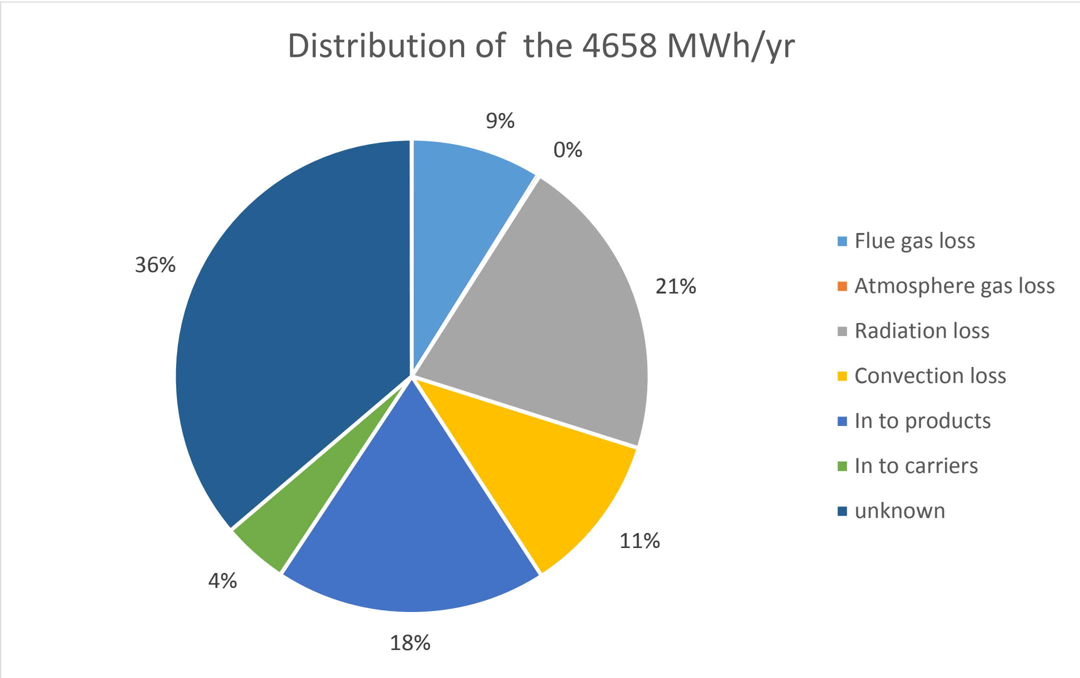

Figure 26. The energy distribution in the furnace with option 23

It could be seen that the efficiency of the furnace will now be 18% and flue gas and atmospheric gas losses have been reduced. The part that is unknown has grown, this is due to the fact that the unknown part could not be related to any aspect of the furnaces and hence will remain the same in both cases. Surface losses are still the biggest losses but since the overall fuel use of the furnaces has dropped dramatically the suggestion is still an improvement. The KPI is now 2,89 compared to the previous 3,50. What is interesting is that the KPI for the furnace is now 0,99 instead of the 1,53 of the original setup. This is as low as the furnace KPI for the D-furnace facility and this is despite no improvements to the process flow and utilization has been made. If such changes where to be implemented the KPI's could be lowered even more. An increased product flow will probably raise the fuel consumption of the furnace. However looking at Table 3 the use of "green electricity" has a big effect on the carbon dioxide emissions and in retrospect the best solution, when green electricity is available, is to use an electrically powered furnace.

9 Conclusions

Here the conclusions of the study are presented.

From the interviews and the measurements of the furnace the following conclusions could be established:

- Before to start looking for improvement options in a furnace facility it is very important to have a clear picture of the current situation.
- It is important to have high furnace utilization factor. This goes hand in hand with keeping the furnace temperature even since changing temperature takes time and will result in additional energy usage. Temperatures fluctuations wears on the refractory. Keeping the temperature more constant will spare the refractory.
- The heating of the furnace is important. Modern burners are a good way to incorporate heat recovery in the facility without the need of bulky heat exchangers. Changing from recuperative to regenerative burner is, however, not the first step that should be taken.
- Recovery of the waste heat is very important for an energy efficient furnace. Flue gas and atmospheric gas temperatures are usually high and this energy could be utilized in many different process steps, for example to heat washes.
- The washing stages are most suitable for a heat exchanging effort since there are no hazardous flows involved but transformation baths should not be ruled out just because it is difficult.
- The biggest source of losses in furnace is the surface losses and this is also the area where efforts should be made first since this is where it will have the biggest effect. Unfortunately this is perhaps also the most difficult place to make improvements since the furnace could be hard to retrofit and this will leave the plant owners in the hands of manufacturers who tend to be hesitant towards these types of changes.

For the Heaton II facility the recommendation for optimizing the energy performance will be option number 23 in Table 11 (or appendix 6). That is to switch to regenerative burners, drop the surface temperature with 20 K, use the outgoing atmospheric gases to preheat the ingoing atmospheric gases and finally heat exchange the flue gases with the post wash. This will decrease the gas use from7174 MWh/yr to 4658 MWh/yr , and the electricity use will decrease from XX to 8112 MWh/yr, the new KPI will be 2,89 and finally the carbon dioxide emissions with the SKF “green” electricity mix will be $0{,}2467\,\frac{kg_{CO_2}}{kg_{steel}}$compared to the previous $0{,}36\,\frac{kg_{CO_2}}{kg_{steel}}$.

10 Recommendations

To continue this work it would be recommended to correlate the natural gas use with the flow of products. This would probably also help to reduce the portion of energy that was unaccounted for in the energy balance.

As this work demonstrates the possibilities to improve the energy efficiency of the heat treating facility is big and it would be recommendable to delve even deeper into the details that are unknown and perhaps even try to implement some of the improvements.

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12 Appendixes

12.1 Appendix 1

Values for typical Danish natural gas. (GasAkademin, 2006)

Typical danish natural gas stats		
Gaskomponent		
Metan CH_4	88,97%	Volym-%
Etan C_2H_6	6,14%	Volym-%
Propan C_3H_8	2,51%	Volym-%
Butan C_4H_{10}	0,95%	Volym-%
Pentan C_5H_{12}	0,18%	Volym-%
Hexan C_6H_{14}	0,05%	Volym-%
Kvävgas N_2	0,29%	Volym-%
Syrgas O_2	0,00%	Volym-%
Koldioxid CO_2	0,91%	Volym-%
Kolmonoxid CO	0,00%	Volym-%
Vätgas H_2	0,00%	Volym-%
Vatten H_2O	0,00%	Volym-%
Svavelväte H_2S	0,00%	Volym-%
SUMMA	**100%**	**Volym-%**
Lambda vid förbränning	1,1	(-)
Gasblandningen		
Densitet	0,827	kg/Nm^3
Relativ densitet	0,640	(-)
Undre värmevärde	39,76	MJ/Nm^3
Undre värmevärde	11,05	kWh/Nm^3
Övre värmevärde	43,96	MJ/Nm^3
Övre värmevärde	12,21	kWh/Nm^3
Undre wobbeindex	49,72	MJ/Nm^3
Undre wobbeindex	13,81	kWh/Nm^3
Övre wobbeindex	54,97	MJ/Nm^3
Övre wobbeindex	15,27	kWh/Nm^3
Undre explosionsgräns i luft	4,2	(volym-%)
Övre explosionsgräns i luft	15,9	(volym-%)

Stökiometriskt syrebehov	2,212	(m^3/m^3)
Stökiometriskt luftbehov, torr luft	10,557	(m^3/m^3)
Verkligt syrebehov	2,433	(m^3/m^3)
Verkligt luftbehov, torr luft	11,613	(m^3/m^3)
Avgasvolym vid stökiometrisk förbränning i torr luft		
Koldioxid CO_2	1,150	(m^3/m^3)
Vatten H_2O	2,062	(m^3/m^3)
Kvävgas N_2	8,252	(m^3/m^3)
Argon Ar	0,095	(m^3/m^3)
Svaveldioxid SO_2	0,000	(m^3/m^3)
SUMMA TORR LUFT	**9,497**	**(m^3/m^3)**
SUMMA VÅT LUFT	**11,560**	**(m^3/m^3)**
Verklig avgasvolym vid förbränning i torr luft		
Koldioxid CO_2	1,150	(m^3/m^3)
Vatten H_2O	2,062	(m^3/m^3)
Kvävgas N_2	9,077	(m^3/m^3)
Argon Ar	0,105	(m^3/m^3)
Syrgas O_2	0,221	(m^3/m^3)
Svaveldioxid SO_2	0,000	(m^3/m^3)
SUMMA TORR LUFT	**10,553**	**(m^3/m^3)**
SUMMA VÅT LUFT	**12,615**	**(m^3/m^3)**
Bränslerelaterade emissioner		
Koldioxid CO_2	57,16	g/MJ Bränsle
Svaveldioxid SO_2	0,19	mg/MJ Bränsle

12.2 Appendix 2

t	P	c_p	$\mu *10^6$	$\nu *10^6$
[^{O} C]	[kg/m^3]	[kJ/kgK]	[Pas]	[m^2/s]
0	1.295	1.042	15.8	12.2
100	0.95	1.068	20.4	21.54
200	0.748	1.097	24.5	32.8
300	0.617	1.122	28.2	45.81
400	0.525	1.151	31.7	60.38
500	0.457	1.185	34.8	76.3

600	0.405	1.214	37.9	93.61
700	0.363	1.239	40.7	112.1
800	0.33	1.264	43.4	131.8
900	0.301	1.29	45.9	152.5
1000	0.275	1.306	48.4	174.3
1100	0.257	1.323	50.7	197.1
1200	0.24	1.34	53	221

12.3 Appendix 3

dist. from entrance [m]	Temperatures line A				Temperatures line B			
	Left		Right		Left		Right	
	C	K	C	K	C	K	C	K
1	46	319,15	55	328,15	57	330,15	58	331,15
2	62	335,15	55	328,15	54	327,15	73	346,15
3	68	341,15	74	347,15	80	353,15	79	352,15
4	77	350,15	75	348,15	76	349,15	95	368,15
5	84	357,15	79	352,15	80	353,15	78	351,15
6	76	349,15	82	355,15	77	350,15	83	356,15
7	82	355,15	82	355,15	79	352,15	85	358,15
8	85	358,15	79	352,15	79	352,15	86	359,15
9	84	357,15	77	350,15	82	355,15	80	353,15
10	84	357,15	82	355,15	82	355,15	85	358,15
11	86	359,15	80	353,15	75	348,15	81	354,15
12	82	355,15	80	353,15	80	353,15	76	349,15
13	84	357,15	80	353,15	79	352,15	78	351,15
14	75	348,15	77	350,15	76	349,15	76	349,15
15	87	360,15	73	346,15	78	351,15	82	355,15
16	82	355,15	73	346,15	78	351,15	75	348,15
17	86	359,15	79	352,15	84	357,15	79	352,15
18	75	348,15	88	361,15	87	360,15	77	350,15
19	82	355,15	79	352,15	76	349,15	77	350,15
Average individual	78,26316	351,4132	76,26315789	349,4131579	76,78947368	349,9395	79,10526	352,2553
Average furnace	77,26315789		350,4131579		77,94736842		351,0973684	
Average total				77,60526316	350,7552632			

12.4 Appendix 4

- **General**
  - What are your thoughts about SKF’s efforts on saving energy in general?
    - Do you think they are effective?
    - If you alone had the power to change what is being done in terms of energy saving efforts, what would you do?
- **Heat treatment**
  - How much focus have been put on the heat treatment in terms of energy savings. Do you think it is too much, enough, or too little?
  - What has been done so far in terms of saving energy in the heat treatment step of the production.
    - Has there been any kind of mapping of the energy consumption in the heat treatment process?
    - How many details are available on the performance of the equipment
      - Is the combustion complete for example? Are flue-gas mass-flows, and temperature data available
      - What does the supplier say about the performance of the equipment? Is it met? If not, why?
    - Is there any form of heat recovery being conducted at the moment?
      - Where, how much and what is the recovered heat used for?
  - What are the plans for the future in terms of saving energy in the heat treatment process?
  - What kinds of furnaces are typically used in SKF, and what is considered to be the advantages of these types of furnaces, both from an energy perspective and a metallurgical perspective.
    - The types will refer to if they are electrically or gas fired. Induction hardening or some other type of heat treatment equipment.
    - How is the outlook for prioritizing bigger gains in energy efficiency over a smaller gains in product or production performance.
  - Generally, how do SKF look at prioritizing energy efficiency over product and production performance.
  - What could be done with for example utilization factors and time temperature curves optimized for both energy and heat treatment purposes?
    - Are the furnaces bottle necks?
    - Could they be turned off when not in use?

12.5 Appendix 5

Pre-wash	Furnace	Quench	Transformation bath	Post-wash	Componenets for both lines
Electrical heating	Electric heating	Electrical heating	Electrical heating	Electrical heating	Electrical heating
Running 70 kW	Running 0 kW	Running 10 kW	Running 80 kW	Running 70 kW	Running 117 kW
Loaded 100% 70 kW	Loaded 100% 0 kW	Loaded 100% 50 kW	Loaded 100% 800 kW	Loaded 100% 70 kW	Loaded 100% 117 kW
Intsalled 75 kw	Installed 0 kW	Intsalled 815 kW	Intsalled 800 kW	Intsalled 75 kW	Installed 910 kW
Drying fan					Salt pumping electric
Running 15 kW					Running 26 kW
Loaded 100% 15 kW					Loaded 100% 39 kW
Intsalled 15 kW					Installed 49 kW
Auxiliary equipment	Auxiliary equipment	Auxiliary equipment	Auxiliary equipment	Auxiliary equipment	Auxiliary equipment
Running 15 kW	Running 47 kW	Running 46 kW	Running 26 kW	Running 25 kW	Running 51,4 kW
Loaded 100% 15 kW	Loaded 100% 63 kW	Loaded 100% 47 kW	Loaded 100% 146 kW	Loaded 100% 25 kW	Loaded 100% 51,4 kW
Intsalled 19 kW	Intsalled 108 kW	Intsalled 64 kW	Intsalled 155 kW	Intsalled 35 kW	Installed 65,5 kW

12.6 Appendix 6

	Fuel use [kWh/yr]	Electricity use [kWh/yr]	KPI [kWh/kg_steel]	Furnace KPI [kWh/kg_steel]	CO2 emissions SKF mix [kgCO2/kgSteel]	CO2 emissions EU27 mix [kgCO2/kgSteel]
Current situation	**7174545**	**8444218**	**3,50**	**1,53**	**0,36**	**1,18**
Improvement suggestions						
Keeping recueparative burner						
Pre heat atmospheric gases with outgoing atmospgeric gases using a delta T_min=10K	6479326,212	8444218	3,3504	1,3844	0,3272	1,1481
Lower surface temperature 20K	5751113,044	8444218	3,1948	1,2288	0,2951	1,1161
Pre heating of atmospheric gases with delta T_min=10K and lower surface temperature with 20K	5055894,406	8444218	3,0463	1,0803	0,2646	1,0855
Heat exchange flue gas with **pre wash**	7174545	7476938,477	3,2923	1,5329	0,3567	1,0836
Pre heat atmospheric gases with delta T_min=10K and heat exchanging with **pre wash** (delta T_min=10K)	6479326,212	7570668,531	3,1638	1,3844	0,3262	1,0622
Lower surface temperature 20K and heat exchanging with **pre wash** (delta T_min=10K)	5751113,044	7668846,939	3,0291	1,2288	0,2943	1,0399
Pre heating of atmospheric gases with delta T_min=10K and lower surface temperature with 20K and heat exchanging with **pre wash** (delta T_min=10K)	5055894,406	7762576,993	2,9006	1,0803	0,2639	1,0185
Heat exchange flue gas with **post wash**	7174544,851	7448489	3,2862	1,5329	0,3567	1,0808
Pre heat atmospheric gases with delta T_min=10K and heat exchanging with **post wash** (delta T_min=10K)	6479326,212	7544975,911	3,1583	1,3844	0,3262	1,0597
Lower surface temperature 20K and heat exchanging with **post wash** (delta T_min=10K)	5751113,044	7646041,92	3,0243	1,2288	0,2943	1,0376
Pre heating of atmospheric gases with delta T_min=10K and lower surface temperature with 20K and heat exchanging with **post wash** (delta T_min=10K)	5055894,406	7742528,74	2,8963	1,0803	0,2638	1,0165
Cahnge to regenerative burner	6609866,898	8444218	3,3783	1,4123	0,3329	1,1538
Pre heat atmospheric gases with delta T_min=10K	5914277,65	8444218	3,2297	1,2637	0,3023	1,1232
Lower surface temperature 20K	5298467,361	8444218	3,0981	1,1321	0,2752	1,0962
Pre heating of atmospheric gases with delta T_min=10K and lower surface temperature with 20K	4657966,428	8444218	2,9612	0,9952	0,2471	1,0680
Heat exchange flue gas with **pre wash**	6609866,898	7995564,299	3,2824	1,4123	0,3324	1,1097
Pre heat atmospheric gases with delta T_min=10K and heat exchanging with **pre wash** (delta T_min=10K)	5914277,65	8042778,323	3,1439	1,2637	0,3019	1,0838
Lower surface temperature 20K and heat exchanging with **pre wash** (delta T_min=10K)	5298467,361	8084577,246	3,0213	1,1321	0,2749	1,0608
Pre heating of atmospheric gases with delta T_min=10K and lower surface temperature with 20K and heat exchanging with **pre wash** (delta T_min=10K)	4657966,428	8128052,079	2,8937	0,9952	0,2468	1,0369
Heat exchange flue gas with **post wash**	6609866,898	8023662,167	3,2884	1,4123	0,3325	1,1125
Pre heat atmospheric gases with delta T_min=10K and heat exchanging with **post wash** (delta T_min=10K)	5914277,65	8023662,167	3,1398	1,2637	0,3019	1,0819
Lower surface temperature 20K and heat exchanging with **post wash** (delta T_min=10K)	5298467,361	8067451,515	3,0176	1,1321	0,2748	1,0591
Pre heating of atmospheric gases with delta T_min=10K and lower surface temperature with 20K and heat exchanging with **post wash** (delta T_min=10K)	4657966,428	8112996,578	2,8905	0,9952	0,2467	1,0355

12.7 Appendix 7

The outcome of the interviews will be presented in subcategories to give a clear picture of the opinions on the energy situation concerning different routes in the heat treatment process.

12.7.1 The general opinions on heat treatment and energy

The general opinion is that there is and has been very little focus on the matter of energy and environment in the heat treatment process, The only exception is for the Heaton projects, where quite a lot of attention was put on the subject of energy conservation when it was planned and built. Energy recovery systems and attention to energy use were taken in consideration to the biggest extent possible throughout the project.

However in the past ten years more focus have started to be put on the energy aspects of heat treatment. During this time several billion SEK have been invested into heat treatment and a lot of the knowledge acquired is carried on in order to improve both the process and the components from an energy perspective. Similar to the Heaton project, attention to energy and environment is taken more and more into consideration but the economic aspects are still predominant. Since the new ISO 50001 has started to be implemented within SKF, energy usage has become even more of a priority and it is an influence when purchasing new equipment.

Heat treatment in general is probably the most energy consuming process that SKF possesses in its factories, unfortunately most of this energy is simply cooled away. This represents a lot of energy. Improvements in this sector could probably have a big effect on the total Carbon dioxide emissions from SKF. Some furnaces that are in operation today are more than thirty years old. Despite the age of some equipment and the huge amount of energy that heat treatment as a process step is using there is very little that has been measured from this process so far. There is not even a clear definition of how the energy usage should be stated, if it should be in $\frac{kWh}{kg_{steel}}, \frac{kWh}{componenet}, \frac{kWh_{value\ adding}}{kg_{steel}}$ or something else. If there is any data that is measured there it is usually stated in a way that says that you have a whole block of heat treatment that requires this much energy input but you didn’t know more specifically where this energy goes.

It was expressed that all previous energy mappings needs to get an update. Despite this some point out that the energy demand in the manufacturing industry is small compared to for example the pulp and paper industry and other big process industry. The efforts on energy efficiency should first and foremost be focused on these industries. SKF as a manufacturing industry don’t even have to pay carbon tax as of today since they are not considered as a big polluter.

12.7.2 Current energy situation

The most common way to recover energy is to do it in the ventilation system. This is used to a large extent in the Heaton facility. Here the heat is recovered and used to heat the building in which the furnaces are placed. Some of the excess heat is transported to the nearby E-factory where it is also used for simple indoor air heating.

In general it is found that most of the heat recovery systems used both on a local and a global scale are installed in the heating and ventilation part of the heat treatment facility. All of the new factories are built with a brand new heat recovery system in the heating and ventilation system but nothing or very little has been done in old factories. One big issue with this is that it is unclear whether the energy recovery installations in Heaton II are profitable or not. For example there is a heat recovery system connected to the ventilation of the quench baths on Heaton II but this heat is very intermittent and it is unclear whether this is an effective measure or not.

Other measures that have been taken are to use as efficient burners as possible. On the new Heaton furnaces the second best option of burners are used, the recuperative burner. The air intakes for the burners have been placed very close to the ceiling where the temperature is higher leading to less pre heat of the combustion air. Burners also have plenty of flue gas recirculation in order to be more efficient. In some of the old furnaces the burners have been replaced with modern more efficient ones.

Plenty of other small measures have been done, for example it is possible to close the salt baths with lids in both Heaton II and IV. In Heaton II it has to be done with the gantry crane since the accumulation of salt makes it difficult to use mechanical lids. However in Heaton IV the lids are mechanical. The salt baths have also been fitted with very simple fiber insulation underneath in order to minimize the heat losses. During stops in production the furnace and the salt bath is lowered in temperature in order to save energy and in some cases when production volumes really drops some furnaces are switched off. In older furnaces the refractory has been replaced and some fiber insulation has been added around the holes in the skin where the rollers are mounted in order to reduce the heat losses.

12.7.3 Thoughts on improving the energy efficiency of the hardware

There have been some thoughts on using the flue gases that currently are wasted to heat the salt baths. The problem is that hot salt does not mix well with neither steam, water or oil. The only way that has been deemed possible is to use the flue gases to put a blanket of warm air around the entire salt bath area. This would require this area to be tightly sealed which is difficult. Others seem to be doubtful that the temperature that is needed to heat the salt baths, which is about 200-250°C, is available.

Continuing on the heat recovery topic there are plenty of thoughts concerning the use of flue gases to heat the washing stations. This is to some extent already done but the system is crude, it is a simple pipe that has been drawn through the wash baths. There is no proper heat exchanger so there is still a lot of potential left in heating the washes. But on a global scale it is important to remember that not all furnaces and washes are heated with gas so the possibility to use flue gas to heat them is limited to a small number of gas fired facilities. Another option that has been discussed regarding the flue gases is to use them to heat the E-factory but this will require a fluid base system and then there is a risk of big losses. Some express that at the moment there is no need for additional heat recovery systems, what is important at the moment is to get everything working properly.

What is really emphasized is that the best is to not have any losses in the first place, better insulation is the key according to many and definitely preferred before heat recovery. Some believe that fiber insulation is the best way to go when insulating the furnaces. The ideal situation would be to add an extra eight to ten centimeters of fiber insulation on top of the furnace skin, hence reducing the surface temperature and energy losses whilst avoiding chimney effects. Others claim that the best way to go is to increase the thickness of the refractory. The standard that is used today, about 280-

350 mm of wall thickness and since radiation losses from the surface is one of the biggest losses for a furnace it is of great importance that the surface temperature is lowered and thicker walls is said to be a solution for this. The suggestion is to increase the wall thickness up to about 500 mm. The effects of this will be that the furnace gets slower dynamics. It will take longer to heat up but it will also be less sensitive to load variations. The drawbacks are that it will take more time for the furnace to heat up or cool down. This doesn't necessarily mean that the flexibility will drop. Forced air cooling could still be used to ensure that temperatures drop within reasonable times. That air is then wasted heat since it will be let out into the ambient atmosphere. Others claim that it is not economically feasible to insulate the furnace further. Yet another problem is that it is very impractical with extremely thick walls.

The problem with heat recovery is that it requires additional systems and the cost of these systems could be quite large. It is also important to keep in mind that the cost of the system is quite independent of the size of the furnace. It costs about the same no matter if the furnace is big or small. Usually smaller furnaces don't have the amount of waste heat needed for heat recovery to be possible. The furnaces that are installed in Gothenburg are unusually large. Another issue with the potential for heat recovery is that very little has been measured which makes it difficult to determine if there is any potential for heat recovery.

There have been some suggestions to make cold air from the waste heat via heat pumps to use in the air-conditioning systems in factories that are located in more tropical climates.

It was said that some effort have been put into making the carriers, where the charges are put, lighter and slimmer.

12.7.4 Thoughts on improving the process to make it more energy efficient

One of the most important factor when it comes to energy efficiency in heat treatment is the utilization of the furnace; the furnace should be run as much as possible and be as loaded as possible all the time to have high efficiency, the more idling that occurs the bigger the energy losses. It is very difficult to shut down the furnace. This is because it is expensive and it will block production. The furnace is called a joint operation and is outside the channel, which will mean that if it stops, several production lines will stop. To cool down a large furnace will take between 3 to 4 days, sometimes even a week. It takes about the same time for it to heat up again and once it reached operating temperature a number of checks have to be performed before production could start. Ultimately this means that if the decision is made to turn off a furnace it will be down for about three weeks. This is why it is kept running the whole time, twenty-four-seven. Not only does a stop takes time, it also causes a lot of thermal stresses in the refractory which ultimately will shorten the life time of the furnace and hence increase maintenance cost. In order to keep the utilization as high as possible, the load on the furnace even and avoid stops in production buffers are required both before and after the furnace. The goal is to keep the furnaces as loaded as possible.

The key to keep utilization high and the load even is to be proactive and try to predict changes in product flow but unfortunately running the furnace empty from time to time is unfortunately unavoidable. The guide word in SKF is productivity, not energy management so all the production flows are run in such a way that the production is as smooth and efficient as possible. This leads to a lot of temperature variations since different components have different recipes. Some claim that these small temperature changes are completely unnecessary. Others refer to the heat treatment experts and says that they are extremely important. The degree of utilization is said to be high within SKF. If business drops and it becomes possible to shut down one facility this is of course done.

At the moment the process is not run in a matter that makes it as energy efficient as possible. It is run in such a way that it could follow customer orders as good as possible. This leads to a lot of temperature changes and this in turn increases the energy losses. It could take as long as 14000 seconds, or about 4 hours, to change the temperature in the furnace and about the same for the transformation baths. The logistics system for how the furnaces are operated have changed, previously the customer demand was visualized for the operators and it was up to the operators to decide in what order products where to be put inside the furnace. This made it possible to minimize the temperature variations in the furnace and hence reduce energy use. Today the process run in a way that the parts enters the furnace in the same order as they arrive to the facility. This is more productive but from an energy perspective it is worse. Ultimately this leads to a very flexible facility where a lot of different parts could be heat treated. The components could vary from about 0.1 kg up to about 680 kg

12.7.5 New technologies

The overall opinion when it comes to new technologies on the market that could have a big impact on the energy use in heat treatment is that induction is the strongest candidate. Suggestions like microwave technology, laser and vacuum have been brought up but these technologies will be in the far future. However there are other opinions that say that induction is all advantageous for a limited amount of highly specialized parts. Because of this limitation it the opinion is that it can’t be seen as a revolutionizing technology. Others claim that induction is interesting, not from an energy point of view but for the properties that could be achieved. Some claims have it that induction will have an efficiency of 70-90% others claim that it will be around 50-60%, if you count it strictly from the electricity drawn from the wall. This is compared to the claimed efficiency of a furnace of about 10%. Others settle on saying that induction is just slightly more efficient for certain applications.

It is said that induction is better for high production volume of small components. If greater hardening depths are sought you risk melting the surface of the component. It is this which is the technical difficulty in induction. The advantage with induction equipment is that it uses very little energy while idling. On the contrary then, when it is running it uses energy in peaks and the power companies charges SKF extra on peak electricity so this is a drawback.

Energy usage is linked to process time and induction could help reduce the process time and hence reduce the energy usage. This has led to the research into if induction and classic furnace heat treatment could be used in combination in some form of hybrid heat treatment.

One project team has looked at induction hardening versus furnace hardening on a case hardening process and what proved to be important from this study was how well you could fill the furnace. That is it looked to be more advantageous to use a furnace if you have a large number of small parts and use the induction if there is a smaller number of big parts.

Vacuum furnace technology is also interesting since the bainite process that SKF uses has been a discussion in the EU concerning its environmental impact. This have not had an impact on the manufacturing industry yet but other bainite industries have started to move away from the conventional techniques and move toward vacuum technology so eventually it will probably reach the manufacturing industry.

12.7.6 The relation between furnace manufacturer and SKF

The key issue that is brought up is to make the furnace manufacturer meet the demands on the surface temperature. If demands are not stated very explicitly they tend to interpret them quite freely. For example if a certain surface temperature is required it is usually met. But this could be made through chimney effects. That is that an extra skin is placed outside the furnace original skin with an air gap in-between. This could give rise to convection and a strong cooling effect on the surface. In this manner the goal of a low surface temperature is received but the underlying reason is to reduce energy cost and unfortunately this solution will cause the furnace to use more energy. Due to this it is of outmost importance that SKF as a costumer stays involved in the entire design process. What this ultimately comes down to is the question of extra insulation and this is something that the costumers have to push the manufacturers to keep developing.

One backside of the customer pushing the manufacturer to build better furnaces is that the manufactures tend to be very cautious when it comes to venture to far from their comfort zone. In these cases, it is the costumer who will have to be willing to take the risk since the manufacturer won't leave guaranties on techniques they have proved successful over longer periods of time. Thicker walls are brought up as an example of this. An interviewee speculated in whether the manufacturers don't want to redo their calculations. Another one says that in the end there is always a customer and that changes have to be proven over longer periods of time and this makes the industry very conservative against drastic changes. If you have used one technique for 100 years you are not willing to make any drastic changes. Everything is moving very slowly.

Another issue is that SKF put very high demands on their furnaces and this is something that the manufacturers are not used to. This leads to situations where manufactures claim they can meet targets and accept an order but in the end they could not deliver what was demanded. Some interviewees even claim that that the manufacturers barely look at the requirements, they say yes to the order no matter what.

Others point out the fact that SKF is not building their own furnace but buys a more or less finished product and energy and environment have not been the manufacturer's biggest priority. There are discussions to try to push the manufacturers to consider the energy and environment more. Some manufacturers have started to use energy declarations like the one you get on the fridge. The difficulty with this is that the equipment SKF buys is not mass-produced which makes it difficult to put in a lab and see how it behaves.

12.7.7 Choice of furnace

There are three factors that determine what type of furnace is used, the energy price, investment cost and finally the cost of connecting to the infrastructure. When choosing gas for certain facilities it was mostly the carbon dioxide emissions that were taken into consideration. Today the situation has changed slightly and the green electricity that SKF buys (in some countries) might put things into a different perspective. Another very important factor that determines the choice of fuel is of course the availability of it. It is good to keep in mind when talking about this matter that over 70 % of all the furnaces in SKF are electrically heated. It is basically only Scandinavia, Germany and Russia that have extensive gas networks. In general electricity is considered to be of “to high quality” to be used for heating. The higher the required temperature the better it is to use gas fired furnaces. The lack of natural gas networks in certain parts of the world leads to higher emissions of carbon dioxide.

12.7.8 Economic and strategic aspects

It turns out that it is a unanimous opinion that it is very difficult to get an investment approved that concerns energy efficiency. The typical payback period for an energy investment in SKF lands on somewhere between five to seven years. If SKF is to consider an investment profitable the payback period should be somewhere around one to two years. If there is energy investments to be made, it is usually easier to get the investment for them in connection with a bigger investment in some other equipment. You kind of have to “sneak” it in there. Fortunately the wind is slowly turning concerning this matter and it has started to lighten up concerning energy investments. In general it is difficult to replace something for the sake of replacing it and this applies particularly to heat treatment.

Some of the interviewees would like to be able to speculate in energy prices. Since there is speculations in pricing and demand in other sectors it should also be allowed to speculate in something where the price is almost certainly about to rise.

When it comes to the strategic point however to invest in making the products better or invest more in making the heat treatment better opinions are raised about that SKF is a premium bearing company and that the product performance is very important. It is easier to get the investment that makes the product better than the energy investment. Some opinions where raised where people expressed that SKF makes too good products. They don’t have to be super good it is sufficient if they are good enough. Others say that the product performance is satisfactory and it should not be lowered or raised but it is worth striving for less energy use and hence lower production costs. To quote an interviewee, “sometimes they go for efficiency, sometimes they go for product performance”.

12.7.9 Opinions on the district heating plans

There is a lot of skepticism towards the possibility to use waste heat for district heating. It requires a continuous process which is kind of what it is on SKF but the simplest way to move heat is with air to the building right next door. To move longer distances a fluid system needs to be involved and then it becomes complicated. There is also the need for a lot of safety systems to avoid overheating the district heating water. It is also important to keep in mind that most of the waste heat have too low temperature. It is essentially only the flue gases that are believed to have a temperature of about 300 °C that could be used for this application. One problem with for example the quench system is that it is to intermittent to be able to be used for district heating.

Let us not forget that there are other players on the market as well and Gothenburg Energy is not too keen on SKF selling district heating since this will sub-optimize their operations. Never the less both D- and E-furnaces are prepared for district heating possibilities.

12.7.10 Other opinions

One issue that was brought up is the positioning of the furnace in the factory. They tend to be placed deep inside the factory since this is beneficial from a logistical point of view. This is unfortunately very bad from a working environment point of view. Furnaces are noisy, release pollutants and makes for uncomfortable indoor climate. Preferably the furnaces should be placed in a separate building but the logistical part have priority.

When it comes to energy management in furnaces there are four key factors that determine its performance:

- Measure everything
- Utilization factors
- How it is heated
- Maintenance

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