MASTER'S THESIS

Thermal Cascade Analysis of a Straight Grate Induration Furnace

Hans Almqvist
2013

Master of Science in Engineering Technology
Mechanical Engineering

Luleå University of Technology
Department of Engineering Sciences and Mathematics

LULEÅ UNIVERSITY OF TECHNOLOGY

MASTERS THESIS

Thermal Cascade Analysis of a Straight Grate Induration Furnace

Hans Almqvist

Division of Energy Engineering

Department of Engineering Sciences and Mathematics

Luleå University of Technology

Luleå, Sweden 2013

Preface

First of all I would like to thank my supervisors during my master thesis, Johan Sandberg (LKAB) and Andrea Toffolo (LTU) for their guidance and help throughout the work.

Thanks to Per-Mikael Grape-Nutti (LKAB) and Christian Fredriksson (LKAB) for help with data identification, Ola Eriksson (LKAB) for his help with simulation software and to Samuel Nordgren (LTU) for his previous work and advice.

I would also like to take this opportunity to thank my girlfriend Emma and my family for their support.

Hans Almqvist
Luleå, June 2013

Abstract

Increasing fuel prices and risk of increased emission fees increase the interest in reducing dependence from fossil fuels by reducing energy consumption in the process industry. This thesis aims to perform a pinch analysis on the straight grate induration furnace at the pelletizing plant Malmberget kulsinterverk 3. Pinch analysis is expected to be able to use as a tool for optimization and evaluation of energy efficiency for different process setups.

By mapping the streams in the furnace, balances of mass and energy are constructed and used to create constraints and reference values for the analysis. Control volume boundaries are introduced where intermediate data of the process are known from measurements, CFD simulations or reasonable approximations. Separate balances are calculated for each control volume which identifies their individual constraints in terms of energy demand or surplus and temperature range while keeping the production process intact. Process constraints based on coupling between energy carriers are identified and separate heat cascades based on heat requirements of the production process can be coupled to include constraints.

Hence, a method of matching the demands of each control volume using heat cascades is instead explored. For each zone heat requirements (including heat losses) are represented by hot and cold streams and matched to an ambient air stream and a combustion process to maintain the lowest temperature difference allowed for heat exchange. The developed methodology can be used in the future for the optimization of the air streams in the pelletizing plants from an energy point of view.

As a result of pellet bed heat transfer simulations the minimum temperature difference of the pellet bed is estimated to be 45ºC, a value that gives a similar oil consumption as in the reference case when all demands of the machine are fulfilled. Results can be improved by increasing the number of control volumes and the details about the calculations. With further development it is believed that this method can be used as an optimization tool for the air streams in the pelletizing plant without affecting pellet production quality.

Table of contents

1 Introduction 1
1.1 Pinch analysis and process integration 1
1.2 Targets 2
1.3. Limitations 2
2 Process overview 3
2.1 Company description 3
2.2 Process description 4
2.2.1 Mass flows 5
3 Theory 7
3.1 Literature study – Previous work 7
3.2 Mass and energy balance 7
3.2.1 Stoichiometric combustion 8
3.2.2 Chemical reactions 9
3.3 Pinch analysis 9
4 Methodology 13
4.1 Modified pinch analysis 13
4.2 Control volumes 13
4.3 Mass balance 14
4.3.1 Stoichiometric calculations 15
4.4 Energy balance 16
4.4.1 Moisture content 16
4.4.2 Chemical energy 17
4.4.3 Grate 17
4.5 Input data 17
4.6 Calculations 17
4.7 Assumptions for the mass and energy balances 18
4.7.1 Air leakage 18
4.7.2 Ash 19
4.7.3 Heat losses 19
4.7.4 Combustion 19
4.7.5 Transportation piping 19
4.7.6 Temperatures 19
4.8 Pinch analysis matching 20
4.9 Bedsim 21
4.10 Assumptions for the matched pinch analysis 22
5 Results 23

5.1 Mass and energy balances 23
5.2 Composite curves and control volume demands 25
5.3 Matched streams 25
6 Discussion 29
7 Conclusion 31
8 Future work 33
9 References 35
Appendix A – Table of contents calculation sheet 37
Appendix B – Stream list 38

Nomenclature

L_f	Air factor	[kg air/kg fuel]
u_0	Amount of oxygen for stoichiometric combustion	[mole/kg fuel]
ρ	Density	[kg/m^3]
g_{0d}	Dry stoichiometric amount of product gas	[Nm^3/kg fuel]
h	Enthalpy	[kJ/kg]
h_f	Enthalpy of formation	[kJ/kg]
CP	Heat capacity flow rate	[kW/K]
$\dot{Q}$	Heat flow	[W]
H_i	Lower heating value	[MJ/kg]
m	Mass	[kg]
$\dot{m}$	Mass flow	[kg/s]
ΔT_{min}	Minimum temperature difference for heat exchange	[°C, K]
M	Molar mass	[g/mol]
F	Moisture content	[kg/kg]
n	Number of moles	[-]
p	Pressure	[Pa]
c_p	Specific heat capacity	[kJ/kgK]
n_{ao}	Stoichiometric amount of air	[Nm^3/kg fuel]
g_0	Stoichiometric amount of product gas	[Nm^3/kg fuel]
T	Temperature	[°C, K]
$\dot{V}$	Volume flow	[Nm^3/s, m^3/s]

Explanations

AF1, AF2	After firing zones one and two in the MK3 straight grate process.
C1, C2	Cooling zones one and two in the MK3 straight grate process. Incoming ambient air in these zones cools the pellet bed for storage and transportation to customers.
CFD	Computational Fluid Dynamics, simulation software.
DDD	Zone in the MK3 straight grate for Down Draught Drying of the pellet bed using recycled air. The change of air drying direction is necessary because of condensation problems and to create more uniform pellet bed properties.
F	Firing zone in the MK3 straight grate process. The zone with highest temperatures due to the fuel combustion with recuperated air from the cooling zone.
GCC	Grand Composite Curve, external heat sources plotted versus the shifted temperature.
MK3	Malmberget Kulsinterverk 3 is a pelletizing plant located in Malmberget, Sweden. This plant uses straight grate technology for the sintering of iron ore pellets.
PH	Pre Heating zone in the MK3 straight grate process. Hot recuperated air from the cooling zone pre heat the pellet bed before the firing zone.
Straight grate	The general principal of a straight grate pelletizing plant is that the pellets are transported on a straight production line through the drying, burning and cooling zones of the plant. A schematic can be viewed in Figure 2.2.1.1.
UDD	Zone in the MK3 straight grate for Up Draught Drying of the pellet bed using recycled air. Air is blown in a up draught direction mainly to reduce the moisture content in the pellets.

1 Introduction

With increasing global energy consumption and as a result increased emissions of carbon dioxide, economically developed countries are required to lead the charge in the battle against global warming through reduced emissions of greenhouse gases. Processing of iron ore and steel production accounts for about five percent of the global carbon emissions. The Swedish mining company LKAB has the most carbon efficient iron ore refining process in the world and is actively working to further reduce emissions in the steel industry by producing more efficient products. As an example LKAB is currently the only iron ore producer that is operating an experimental blast furnace (EBF), and this is an important part of the research process in order to improve blast furnace performance and to develop new products [1]. Involvement in projects aimed at reducing carbon emissions further establish the environmental thinking at LKAB: the ULCOS project aims to reduce carbon emissions by 50 percent in the iron and steel industry in Europe. LKAB also participates in the Japanese project Course 50 where the target is to reduce carbon dioxide emissions by up to 30 percent.

During the past 30 years, LKAB has halved its emissions to air despite iron ore pellet production more than tripled [1]. The majority of the current emissions come from the sintering of raw pellets, which occurs in the combustion zone of the sintering machine. The burners in the combustion zone currently use fossil fuels such as coal and oil. Minimizing the use of these fuels will greatly reduce the emissions and operational costs of the pelletizing plants. These plants are mainly optimized to run for the highest quality end product and production rate, but there is an interest from LKAB to look at the plants from a pure energy perspective and more precisely a pinch analysis. Since this method has never been used to analyze a pelletizing plant at LKAB, it is believed to bring new insights to the development process.

1.1 Pinch analysis and process integration

Much of the optimization work in the industry is traditionally focused on how to improve individual units. However a method to optimize an entire system is needed, this is because the optimization of a single sub process does not always ensure the optimization of the system as a whole. A common name for this kind of method is process integration, some of the used techniques are mathematical programming, exergy analysis and pinch analysis [2]. Process integration is defined as a holistic approach to design and operation that considers the unity of the process [2].

The pinch analysis methods used in this thesis were originally developed by Linnhoff and Flower [3], the method has primarily been used to lower energy consumption [4]. With further development reduced wastewater consumption in the process industry among other things has been achieved [5]. In its early days pinch analysis was quite controversial due to its simplicity, some researchers stated that major improvement opportunities could be overlooked. However, today the pinch analysis method is widely accepted as a development and optimization technology [6].

1.2 Targets

The main targets of this thesis is focused on mapping the streams of energy in a straight grate pelletizing plant (Malmberget kulsinterverk 3, MK3) using the pinch analysis method to determine energy efficiency and to provide a method for energy optimization and evaluation in the future. This is expected to increase the knowledge of how process changes affect energy efficiency. Sub targets for work are listed below.

- Define the energy streams of the current process at MK3.
- Perform a mass and energy balance and set the constraints for pinch analysis.
- Build a pinch analysis model for MK3 that can be adjusted for different process operation settings.
- Analyze the results from the pinch analysis model using current operational settings.

The thesis will include a literature study of the process, pinch analysis in general and previous work done in the field.

1.3. Limitations

The energy analysis will be restricted to the sintering machine, influence of the remaining part of the refining process at Malmberget is only briefly inspected. The reason for this is that the sintering machine is the most energy intense part of the process and should be taken into account first. Extending system boundaries can possibly be a future work topic depending on results. Smaller scale energy systems such as water cooling is not taken into consideration.

Moreover, the thesis will mainly focus on creating a method of energy analysis for the process and will not go into optimizing a heat exchanger network. If the results show that this could be of interest it will be suggested for future work. The properties of the iron ore pellets in the different parts of the machine create many constraints on the analysis. Production quality must always be the first priority, and because of this the many process parameters concerning the pellet bed are locked in and cannot be changed.

2 Process overview

2.1 Company description

Luossavaara-Kiirunavaara AB (LKAB) is a mining company owned by the Swedish government that is world leading in the field of upgraded iron ore production for the manufacturing of steel. The company has seven subsidiary companies and approximately 4100 employees including about 650 employees outside of Sweden. Customers are located in 21 different countries around the world, but most of the iron ore production is sold to steel mills in northern Europe. LKAB accounts for about 90 percent of iron ore product production in the EU and 40 percent of pellet deliveries worldwide [7].

The main part of LKAB's iron ore deposits are located below ground, leading to logistic difficulties in the extraction process. In underground mines, a method known as sub-level caving is used which means that gravity causes the ore to plummet down to preparation locations and is then shipped up to ground level. Thanks to efficient mining techniques and the high iron content in the ore deposits, the underground mines can compete with open-pit mining sites [7].

Approximately 80 percent of LKAB's production consists of iron ore pellets, divided into blast furnace pellets and direct reduction pellets with an iron content of about 67 percent. The remaining part of the production consists of sinter fines which is a fine ore powder that has been lumped together in a sintering process to larger parts before use. Sinter from LKAB in Malmberget is considered the best in the world thanks to the unusually high iron content in the ore [7]. The high iron content in the magnetite ore for pellet production also has major environmental benefits compared to competing pellet products and hematite fines, around 60 percent of the energy demand for the sintering process being supplied from magnetite oxidation. Currently six pelletizing plants on three different sites are operated by LKAB for iron ore processing.

LKAB has a well-developed logistics system which is necessary in order to be competitive on the global market. When processed, the iron ore products are transported by train to the loading ports of Narvik and Luleå. Every day, 15 trains depart with finished iron ore products, about 35 percent of the total freight on the railways in Sweden is carried out by LKAB making them the largest shipping company in Sweden. So far in the 2000s, LKAB has invested more than 4.5 billion SEK in the railroad, new ore cars, locomotives and a new loading port in Narvik. In 2011, LKAB delivered approximately 26 million tonnes of finished product, and in the same year it was also decided that a new large scale investment would be made in new locomotives and wagons. The goal is to achieve a transport capacity of 40 million tons in 2015 [1].

LKAB used 2.2 TWh of electricity in 2011, making the company one of the largest electricity consumers in the country with about 1.5 percent of Sweden's total electricity consumption [1]. In addition, LKAB annually uses around two TWh of coal and oil, and 0.5 TWh of recovered waste heat. Increased environmental focus and higher energy costs encourages LKAB to continue working with energy efficiency and alternate fuels to replace the current fossil.

In 2011, LKAB had a total turnover of over 31 billion SEK, with 14.8 billion SEK in profits, which was the best economic result in the company's history [1].

2.2 Process description

In this section the general process in the straight grate induration furnace will be described. For more information about the refining process in Malmberget see [7].

The incoming pellets to the sintering machine are loaded on the grate consisting of steel wagons and are dried in the up draught drying zone (UDD) and down draught drying zone (DDD) where streams of hot air flows through the pellet bed, see Figure 2.2.1. Changing direction of the drying air is required because of water vapor condensation on the pellets in the colder upper part of the bed in the UDD zone, but it also creates a more uniform drying process. If too much water is condensed on the pellet bed the pellets can disintegrate, this problem being more likely to occur when the pellet bed height is increased, the pellet diameter is reduced or air temperature is increased. If the drying process is too fast a phenomenon called chock drying can occur, making the pellets explode because of the high local steam pressures caused by quick temperature variations [8].

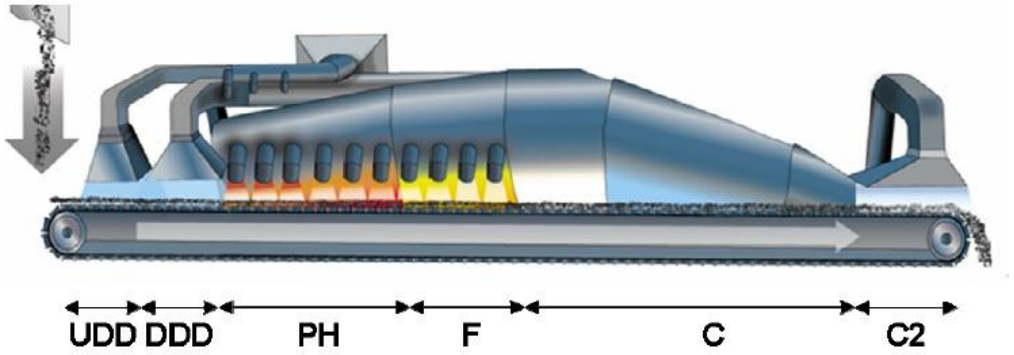

Figure 2.2.1. Straight grate process scheme. Source: [7]

In the pre-heating zone (PH) the pellet bed is heated to around 800 ºC and the remaining moisture content is vaporized. At around 200 ºC the oxidation of the iron ore pellets begins according to the chemical formula

$$4\,Fe_3O_4 + O_2 \rightarrow 6\,Fe_2O_3 + Heat, \qquad (2.2.1)$$

which is the exothermic reaction for magnetite oxidizing to hematite. The released heat corresponds to approximately 60 percent of the heat demand for the sintering process. The rate of oxidation is increased with increasing temperature, however equation 2.2.1 is in equilibrium at 1380 ºC which indicates that the oxidation rate is lowered at very high temperatures. The temperature where the sintering in the burning zone (F) is performed is usually around 1250 ºC [8]. Another interesting chemical reaction from an energy point of view occurring in the furnace is calcination, where instead heat is needed for the reaction to proceed. In this endothermic reaction limestone is dissolved to calcium oxide and carbon dioxide [9] according to

$$CaCO_3 + Heat \rightarrow CaO + CO_2. \quad (2.2.2)$$

Eighteen oil burners increase the air temperature and the magnetite pellets are further oxidized. Not all of the burners are operated continuously and typically the burners in later part of the grate can be shut down to save fuel. In the cooling zones (C) and (C1) ambient air is used to cool the pellets to around 100 ºC for storage and transportation to customers.

2.2.1 Mass flows

Description of the mass flows and the process in general is with respect to the configuration of early 2010, although the sintering machine has since this time been slightly modified. Figure 2.2.1.1 below shows a schematic of the straight grate sintering machine at MK3, the different air flows are shown as arrows and described in this section. A list of these streams can be found in Appendix B.

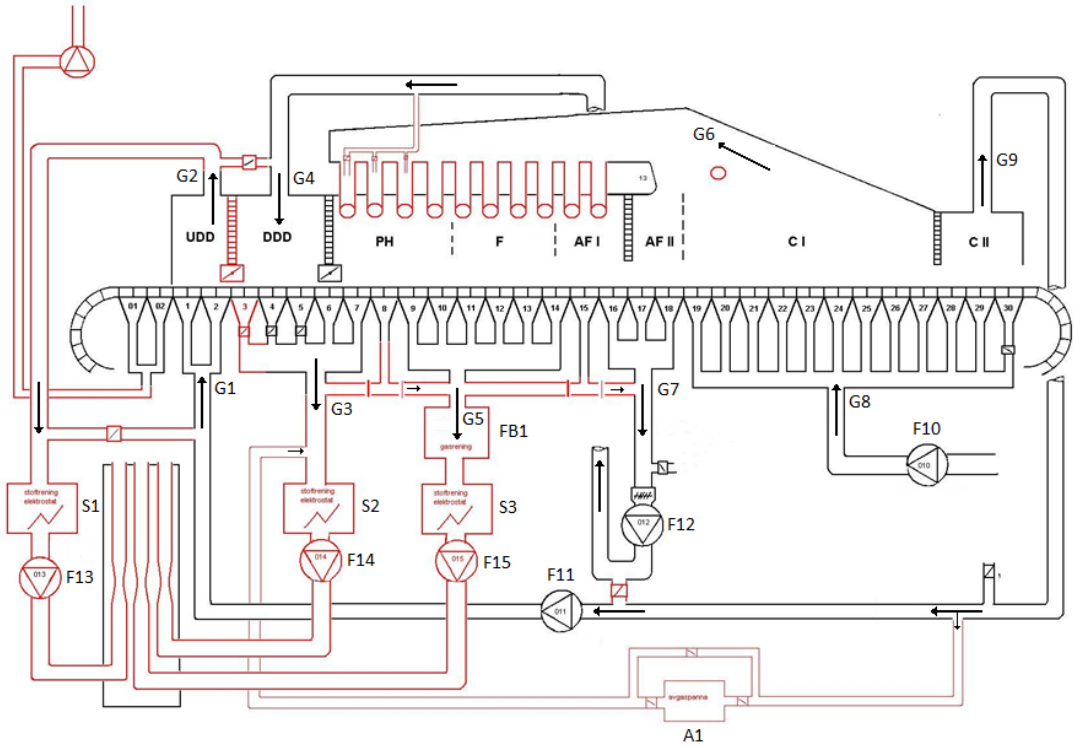

Figure 2.2.1.1. Schematic of the induration machine with air streams and component denotations.

The numbered ducts 01, 02 and 1-30 are wind boxes where gas flow properties are measured, each wind box is 3 meters long and has an area of 10.5 m^2, the grate is in total 90 meters long. In the UDD zone (wind box 1 and 2) air stream G9 is recycled from C2 through the fan F11 and is used for drying, then fan F13 blows the exhaust air G2 through a dust cleaning (S1, electrostatic precipitator). The exhaust air G2 leaves the system through a chimney.

In the DDD zone, hot gas G7 from the after firing zone is blown through the pellet bed. The exhaust G3 from the DDD zone leaves through wind boxes 3-5 and is cleaned from dust (S2) and further blown to the chimney by fan F14.

The pre heating zone (PH) uses a part of the hot air G6 from section C1 for combustion of oil using four of the eighteen oil burners. Twelve burners are located in the firing zone and two in the recuperation duct. The exhaust gas from this section leaves through wind boxes 6-9, which then leaves the system by the help of fan F14 and F15. Much like the PH zone the firing zone (F) uses air from stream G6 for combustion with oil. Wind boxes 10-14 leads the flue gas to the chimney through fan F15 after gas and dust cleaning in FB1 (fluidized bed process) and S3.

Two after firing zones (AF1 and AF2) also use oxygen for combustion from the air of C1, however wind boxes 15-18 take the product gases from this zone to the DDD zone through the help of fan F12.

Cooling zone one (C1, wind boxes 19-27) uses ambient air G8 through fan F10 to cool the pellet bed. The hot air G6 leaving this zone is used for combustion. Zone C2 (wind boxes 28-30) also cools the pellet bed with ambient air but the air G9 leaving this zone is used in the UDD zone for drying driven by fan F11. When there is an excess of the gases from C2 they are used in an economizer (heat exchanger) that boils water. Additionally, there are two ducts for bleed in ambient air to fans F11 and F12 to prevent overheating. Since the process is not sealed, ambient air can leak in and out of the system at the beginning and end of the grate. Leakage between the different wind boxes also occurs due to pressure differences.

3 Theory

The theoretical relationships that are used for calculations in this thesis are presented in the following sub sections. Pinch analysis theory is presented and a literature study of similar papers is included.

3.1 Literature study – Previous work

To get a better view of what has already been done in similar studies, what problems might arise and how to avoid them a brief literature study was carried out. The most interesting papers found for this work are mentioned in this section.

The work done by Samuel Nordgren in his licentiate thesis at Luleå University of Technology is the most similar study that has been found [9]. It uses mathematical programming as a process integration approach to the pelletizing plant MK3. This report presents many suggestions, for instance on how to divide the plant in control volumes and where uncertainties in input data occurs.

Extensive research about the input green pellet temperature to the pelletizing plant has been carried out by Ulf Sjöström, Magnus Lundqvist and Johan Riesbeck in a series of papers from MEFOS and the institute PRISMA (Process Integration in Steel Making) [10]-[13]. The most important information concerning this thesis is that many process data parameters have been calculated using CFD (Computational Fluid Dynamics) and compared to measured values. These studies can possibly provide fairly accurate process data where measurements are currently unreliable or missing.

Many studies at different industries using pinch analysis have been made throughout the years, however a closer look at a master thesis involving a pinch analysis at Billerud pulp and paper mill by Lina Eriksson and Simon Hermansson gives some indication of the work process and how to decide the minimum temperature difference for heat exchange [14].

3.2 Mass and energy balance

For a given control volume it is assumed that no mass is lost and the continuity equation can be applied according to

$$\dot{m} = \rho \cdot \dot{V} \,, \tag{3.2.1}$$

where ρ is density, $\dot{m}$ is the mass flow rate and $\dot{V}$ the volume flow rate [15]. The first law of thermodynamics states that energy cannot be created or destroyed, only transformed, which implies that balances of energy and mass can be used to analyze measured flows. A heat flow can according to the first law of thermodynamics and the definition of enthalpy be written as

$$\dot{Q} = \dot{m} \cdot c_p \cdot \Delta T, \tag{3.2.2}$$

where c_p is the specific heat at constant pressure and ΔT the temperature difference with respect to the reference temperature [15].

3.2.1 Stoichiometric combustion

For a given composition of the fuel used for combustion, the composition of the product gases can be calculated through a mass balance from the ingoing elements. The following relations used in this section are originated from [16]. It is assumed that all fuel elements only react with oxygen and that all elements are fully oxidized. A mass balance for the combustion follows

$$C_x \cdot H_y \cdot O_z \cdot N_r \cdot \mathrm{S}_t + u_0 \cdot \mathrm{O}_2 + u_0 \cdot N_2 \rightarrow \mathrm{a} \cdot CO_2 + \mathrm{b} \cdot H_2O + \mathrm{c} \cdot \mathrm{SO}_2 + \mathrm{d} \cdot N_2, \quad (3.2.1.1)$$

from equation (3.2.1.1) balances for the elements follow

$$u_0 = a + 0.5b + c - z, \quad (3.2.1.2)$$

$$a = x, \quad (3.2.1.3)$$

$$2b = y, \quad (3.2.1.4)$$

$$c = t, \quad (3.2.1.5)$$

$$d = 3.76 \cdot u_0 + 0.5r. \quad (3.2.1.6)$$

At a given weight percentage including moisture the amount of dry substance can be calculated through the moisture content *F* as

$$Dry\ Substance = \frac{wt\%}{1-F}, \quad (3.2.1.7)$$

The number of moles *n* of the different elements is determined as

$$n = \frac{wt\%}{M}, \quad (3.2.1.8)$$

where *M* is the molar mass. The number of moles of oxygen from stoichiometric combustion can now be decided by using equation (3.2.1.8) inserted into equation (3.2.1.2)-(3.2.1.6). The number of moles for complete combustion is obtained as

$$u_0 = \frac{x_c}{M_C} + 0.5\frac{x_H}{M_H} + \frac{x_S}{M_S} - \frac{x_O}{M_O}, \quad (3.2.1.9)$$

to obtain the amount of air per kilogram of fuel it is assumed that 3.76 moles of nitrogen is needed for every mole of oxygen, other species in the air are neglected. The amount of air for complete combustion is then given by

$$n_{ao} = 22.7 \cdot 10^{-3} \cdot (1 + 3{,}76)u_0. \quad (3.2.1.10)$$

Now the theoretical amount of product gases can be calculated. With the assumption that the gases produced from combustion are CO_2, H_2O, SO_2 and N_2 according to

$$g_0 = 22.7 \cdot 10^{-3}\left(\frac{x_c}{M_C} + \frac{x_H}{M_H} + \frac{x_S}{M_S} + \frac{x_N}{M_N} + \frac{F}{M_{H_2O}} + 3.76 \cdot u_0\right) + n_{ao} \cdot \varphi, \quad (3.2.1.11)$$

where φ is the amount of water vapour in the air given in kg/kg. The amount of dry gases is given by

$$g_{0d} = 22.7 \cdot 10^{-3} \left(\frac{x_c}{M_C} + \frac{x_S}{M_S} + \frac{x_N}{M_N} + 3.76 \cdot u_0 \right). \quad (3.2.1.12)$$

and the air factor can be calculated from air and fuel flows as

$$L_f = \frac{m_{air}}{m_{air0}}, \quad (3.2.1.13)$$

m_{air} is the actual air flow and m_{air0} is the theoretical amount of air needed for combustion according to (3.2.1.10). The specific heat of the product gas can be calculated from the now known volume fractions, *y*, and values from thermodynamic tables for specific heat as

$$c_{p,gas} = c_{p(CO_2)} \cdot y_{CO_2} + c_{p(H_2O)} \cdot y_{H_2O} + c_{p(SO_2)} \cdot y_{SO_2} + c_{p(N_2)} \cdot y_{N_2} + c_{p(O_2)} \cdot y_{O_2}. \quad (3.2.1.14)$$

The density is calculated as the sum of the volume fractions multiplied by the molar masses of the components

$$\rho_{gas} = M_{(CO_2)} \cdot y_{CO_2} + M_{(H_2O)} \cdot y_{H_2O} + M_{(SO_2)} \cdot y_{SO_2} + M_{(N_2)} \cdot y_{N_2} + M_{(O_2)} \cdot y_{O_2}. \quad (3.2.1.15)$$

3.2.2 Chemical reactions

As a measure to determine how much of the magnetite in the pellet bed has been oxidized to hematite an oxidation fraction is used. In this work, the oxidation fraction is defined as zero when the iron ore is in its original composition and one when all magnetite is oxidized to hematite. However, the theoretically correct definition is how much oxygen is bound to form iron oxide out of the total possible amount. In other words the formation of iron oxides such as wüstite (FeO) is not considered. Calculation of chemical energy has been carried out using HSC Chemistry [17]. To verify the heat required or released in the exothermic and endothermic reactions the standard enthalpy of formation is used according to

$$\Delta h_m = \sum \Delta h_{f,products} - \sum \Delta h_{f,reactants}, \quad (3.2.2.1)$$

where Δh_f is the standard enthalpy of formation for the different species and Δh_m is the enthalpy change for the reaction.

3.3 Pinch analysis

As mentioned in section "1.1 Pinch analysis and process integration", pinch analysis is a process integration tool that is mainly used to optimize energy consumption in the process industry through heat exchange. Calculations are based on a reasonable target for energy reduction, or a target set by technology restrictions, represented by a minimum temperature difference ΔT_{min} between hot and cold streams where heat exchange is desired [6]. Using this minimum heat exchange temperature it is possible to determine the minimal use of external heating and cooling for the system. With the minimum temperature difference in mind, all hot streams (streams that need cooling) and cold streams (streams that need heating) are defined and plotted in a temperature (ºC) versus heat flow (kW) diagram. The specific heat capacity

for the hot and cold streams are assumed to be constant in their temperature range, streams can be divided for further consideration of varying specific heats [6]. One example of three hot streams plotted in a temperature versus heat flow diagram is shown in Figure 3.3.1 below. The slopes of each stream, *a, b* and *c*, are determined by the heat capacity flowrate which is defined as

$$CP = c_p \cdot \dot{m}. \tag{3.3.1}$$

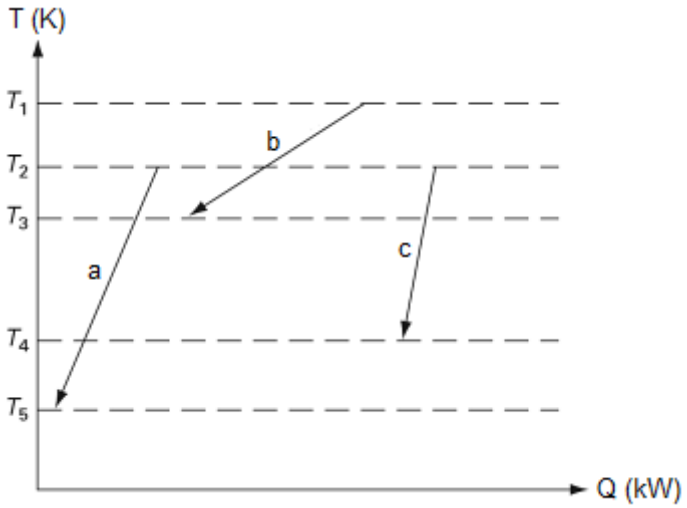

Figure 3.3.1. Hot streams for construction of the hot composite curve. Source: [6]

Merging all hot and cold stream diagrams in the system using the superposition principle composite curves are acquired (a hot composite curve for the streams in Figure 3.3.1 is shown in Figure 3.3.2 below). The superposition principle combines the slope of the curves in each interval, for example the slope and thus the heat available per unit temperature in interval T_2-T_3 is equal to $a+b+c$.

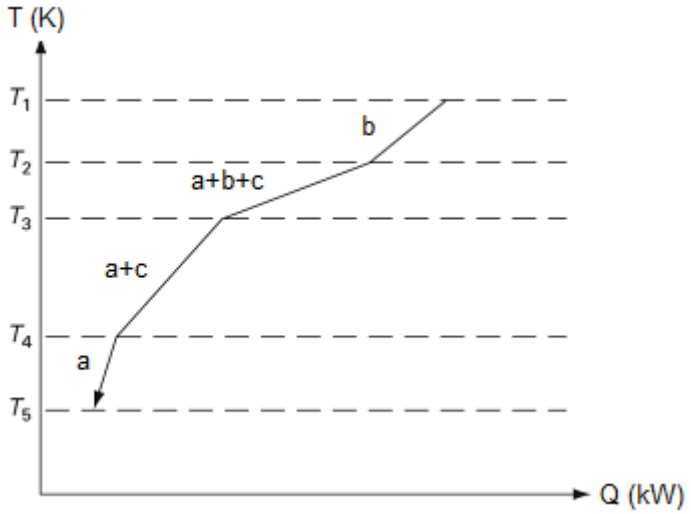

Figure 3.3.2. Hot composite curve from the hot streams in Figure 3.3.1. Source: [6]

The pinch point is defined as the point where the hot and cold composite curves are closest to each other (temperature difference). The pinch point represents a dividing point where the process is divided in two zones. Above the pinch external heating is to some degree needed, below the pinch no external heating is needed but instead external cooling is. Heat exchange across the pinch point will require more external heating/cooling and should be avoided. The overlap of the hot and cold composite curves represents a possible target for heat recovery in the studied process. An example of a composite curve diagram is shown in Figure 3.3.3.

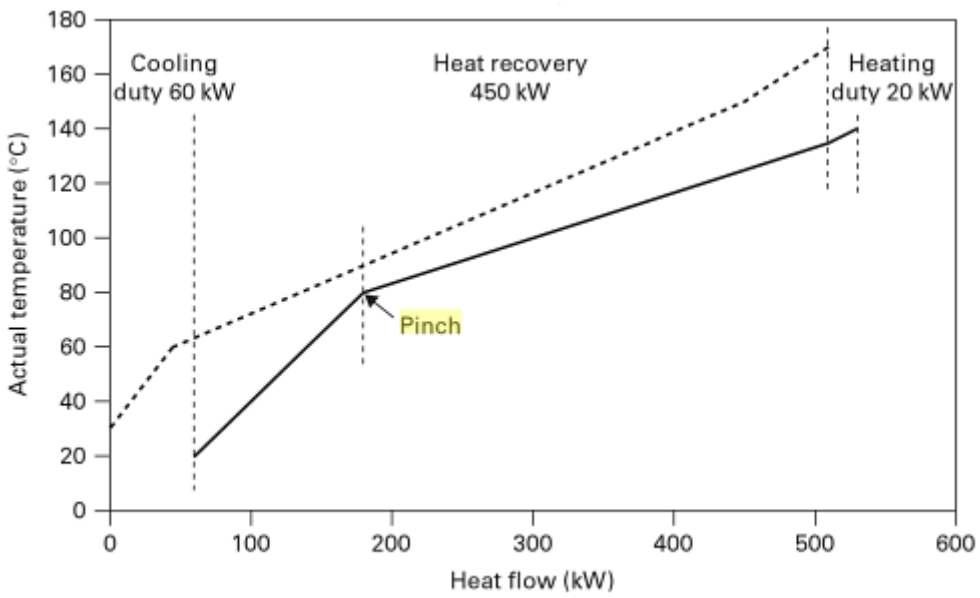

Figure 3.3.3. Composite curve from hot streams (dotted line) and cold streams. Source: [6]

To determine targets for external heating and cooling duties heat cascades are used (commonly known as the problem table method). In this method enthalpy balance intervals are set for the hot and cold streams based on temperatures, allowing for maximum heat exchange within each temperature interval. To ensure that the minimum temperature difference between hot and cold streams is kept, $\frac{\Delta T_{min}}{2}$ is added to the cold streams and subtracted from the hot streams [6]. The grand composite curve (GCC) is a graphical plot of the heat cascade. The GCC represents the difference between the heat available from hot streams and the heat needed for the cold streams at different temperatures [6]. The minimum external heating can be found at the top of the GCC and the cooling demand at the bottom of the curve. Figure 3.3.4 below shows a typical GCC.

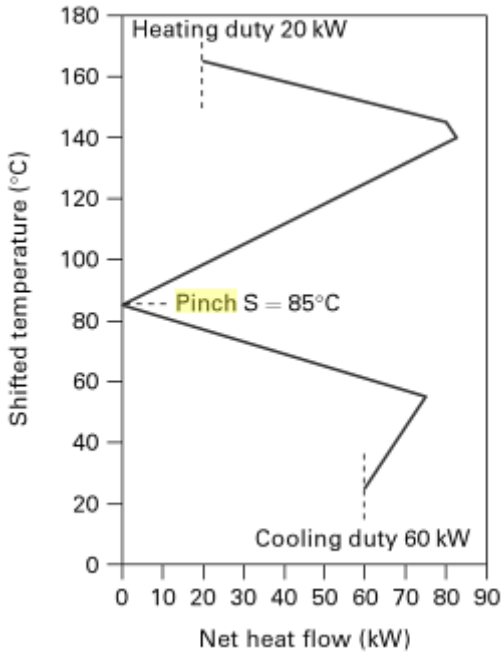

Figure 3.3.4. Typical appearance of a grand composite curve. Source: [6]

By detecting areas in which the heat transfer rules of the pinch analysis are broken suggestions for improvement can be made.

4 Methodology

This section will describe the work process and what tools have been used. Process data used will be presented and the required assumptions will be stated.

For the construction of a pinch analysis model a spread sheet is used for the mass and energy balances as well as for the pinch analysis itself. The model is built with the intention that time intervals and input data easily can be changed.

4.1 Modified pinch analysis

Pinch analysis traditionally assumes that there is complete freedom when connecting streams to each other for heat transfer. For this thesis however this is not true, tight constraints involving the pellet bed properties and the relations between the different gas flows exist in reality. The pinch analysis would for example obviously suggest that heat should be exchanged from the hot stream of pellets in the cooling zone to the cold stream of pellets in the other zones. Heat exchange directly in this way would not be possible. Considering these constraints a slightly different method of pinch analysis is required.

Instead of viewing the entire system at once, the process should be divided in at least six different control volumes, in detail described in section “4.2 Control volumes”. For each of the control volumes mass and energy balances are performed based on a reference case of process operation, composite curves are constructed for each of the control volumes. This reference set will define the basic demand of energy for a set of fixed pellet bed parameters for each of the zones and can be represented by both hot and cold composite curves. With this energy demand or surplus in mind, the thermodynamic relations between the gas streams are unlocked, different approaches concerning properties of the gas flows and how they are connected to each other can now be evaluated manually. This work process is further described in section “4.8 Pinch analysis matching”. For a more precise solution additional control volume are needed because the demands of the zones are lumped together using the superposition theorem described in section “3.3 Pinch analysis”, only one hot or cold stream can be used to supply a demand for a zone. With higher resolution of control volumes a optimization process would likely be needed.

4.2 Control volumes

A prerequisite of performing an energy analysis is to have information from a mass and energy balance, and for this task control volumes are needed to define the boundaries of the considered balance. These control volumes are to be chosen very carefully taking into account which information is needed for the analysis. Because the pellet bed has different targets in properties for different locations on the grate it is necessary to divide it in several smaller control volumes. Boundaries have been chosen in consideration of the separation of the gas streams, where process data is available as well as the control volumes used in [9] and [10]-[13] (the latter can also provide an opportunity for comparison of results). Additionally there is a heating utility from combustion of oil with air. To be able to see the effects of a change on the oil consumption, separate control volumes are needed to represent the combustion. There are product gases from the combustion flowing in two separate zones of the pellet bed which

will both need separate control volumes. The different control volumes are shown in Figure 4.2.1 below, and are in detail described in Table 4.2.1.

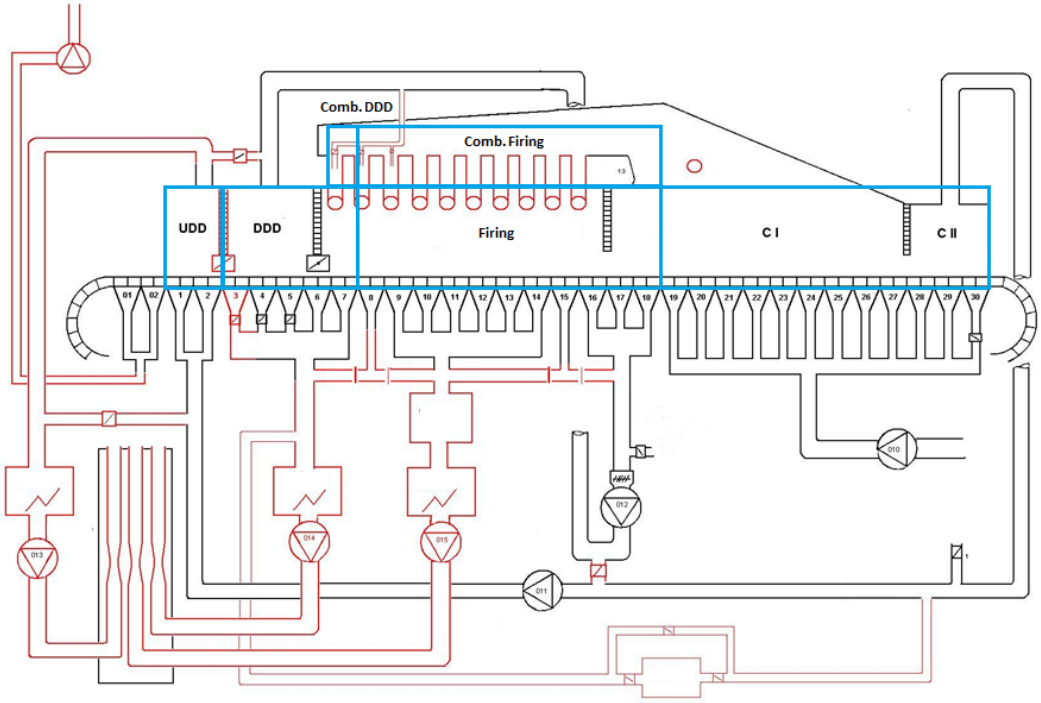

Figure 4.2.1. Schematic of the straight grate process with control volumes marked in blue.

Table 4.2.1. Description of control volumes.

Control volume	Wind boxes	Nr. of wind boxes	Distance from entrance (m)	Area (m^2)	Nr. of burners
UDD	1-2	2	0-6	21	0
DDD	3-7	5	6-21	52.5	0
Combustion DDD	3-7	5	6-21	-	2
Firing	8-18	11	21-54	115.5	0
Combustion Firing	8-18	11	21-54	-	16
Cooling	19-30	12	54-90	126	0

Calculations for the balances was started from the cooling section and moving from right to left in the schematic in Figure 4.2.1.

4.3 Mass balance

To perform a mass and energy balance all streams of mass and energy must be identified. First, mass flows were identified and specified according to Figures 4.3.1 and 4.3.2. A list of the different streams and their origin can be found in Appendix B. Later sections will account for energy transfer in the form of among other things moisture content and oxidation.

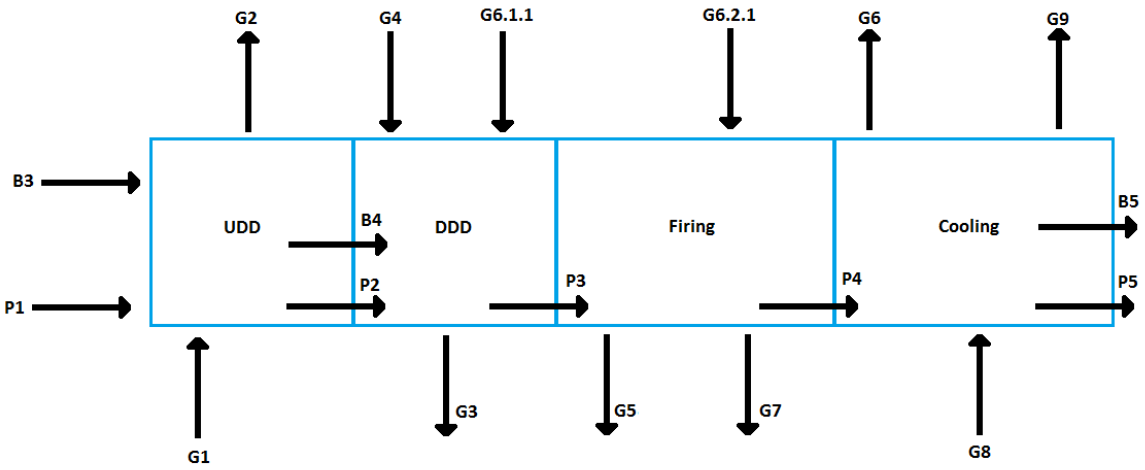

Figure 4.3.1. Mass balances for the different pellet bed control volumes, more information about the streams in Appendix B.

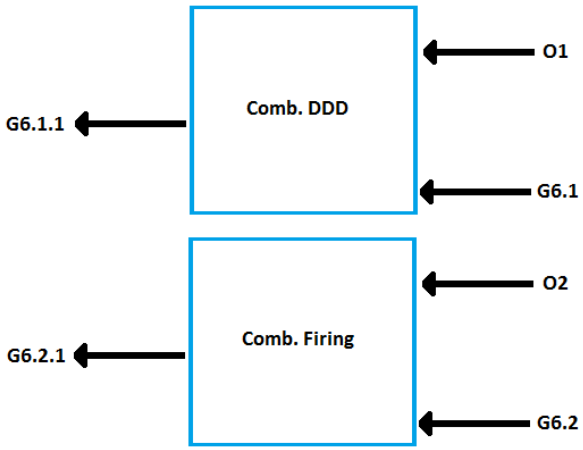

Figure 4.3.2. Mass balances for the two combustion zones, more information about the streams in Appendix B.

Now, mass balances for each of the control volumes are carried out. An example of a mass balance follows for the UDD zone

$$\dot{m}_{P1} + \dot{m}_{B3} + \dot{m}_{G1} = \dot{m}_{P2} + \dot{m}_{G2} + \dot{m}_{B4}. \qquad (4.2.1)$$

The main difficulty concerning the mass flows for this work is specifying the leakage across system boundaries. Assumptions for leakage and mass flow distribution are presented in section “4.7 Assumptions for the mass and energy balances”.

4.3.1 Stoichiometric calculations

As described in section “2.2.1 Mass flows”, oil is combusted in DDD and firing zone, this is however accounted for in the combustion control volumes described in section “4.2 Control volumes”. To determine the composition and amount of the output gases from control volumes “Comb. DDD” and “Comb. Firing” a stoichiometric calculation is required and

performed according to the theories described in section “3.2.1 Stoichiometric combustion” using the input fuel composition.

4.4 Energy balance

To determine unmeasured data and to set reference values for the matched pinch analysis an energy balance is performed using the control volumes described in section “4.2 Control volumes”. The basic concept for the balance with the different energy carriers denoted in Appendix B can be viewed in Figure 4.4.1 below.

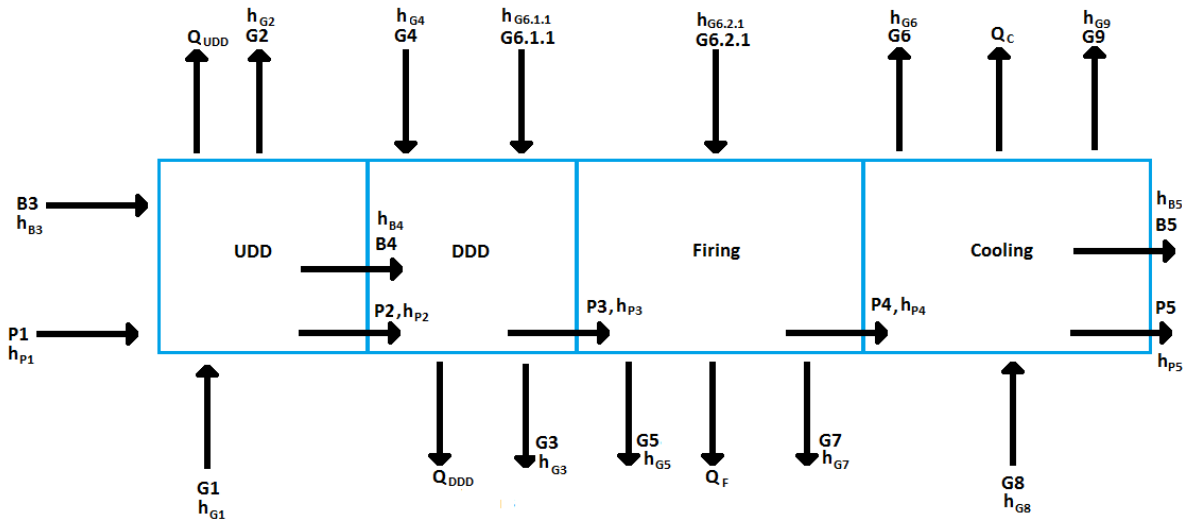

Figure 4.4.1. Energy balance for the control volumes.

The different energy carriers considered in this balance are thermal energy in different streams (pellet bed, gas flows, oil flow), heat losses through the system boundaries, chemical energy from oxidation and calcination, drying of the pellet bed and the combustion of oil. An example of an energy balance for the UDD zone follows

$$\dot{m}_{P1} \cdot h_{P1} + \dot{m}_{B3} \cdot h_{B3} + \dot{m}_{G1} \cdot h_{G1} = \dot{m}_{P2} \cdot h_{P2} + \dot{m}_{G2} \cdot h_{G2} + \dot{m}_{B4} \cdot h_{B4} + Q_{UDD} + Q_{evap,UDD}, \quad (4.4.1)$$

Where $Q_{evap,UDD}$ is the heat required for evaporation of moisture content in this control volume and Q_{UDD} is the heat losses. Moreover, the pellet bed rests on a hearth layer consisting of recycled pellets, this layer and the grate also undergo heat exchange during the process and are included in the balances as well. The following sections will further explain how these different energy carriers are treated.

4.4.1 Moisture content

The moisture content of the pellet bed is given as a weight percentage of the inlet pellet composition. Simulation results give additional values of moisture content at the different control volume boundaries [10]. Using this data the mass of water evaporated in each section is calculated and added to the exhaust air.

4.4.2 Chemical energy

The chemical reactions taking place mainly in the DDD, firing and cooling zone make it necessary to consider chemical energy into the energy balance. Interesting reactions from an energy point of view are oxidation and calcination (which were described in section "2.2 Process description"): these reactions are treated by adding or subtracting thermal energy to the system. The amount of energy from chemical reactions is determined by experimental values and simulations for oxidation fractions, whereas the enthalpy of formation is calculated using HSC Chemistry [17] and confirmed with table values from [14] for 1 bar pressure and 25 ºC using equation (3.2.2.1). Considering the relatively large impact from these reactions this is assumed to be a possible source of error.

4.4.3 Grate

The traveling grate itself undergoes heat transfer during the process and must be taken into account. Temperatures at the different control volume boundaries are estimated to be equal to the air temperature in the wind boxes from personal contact with process engineers. The mass flow of the grate is calculated from the measured grate speed and drawings of the construction.

4.5 Input data

The identification and collection process of input data has been a major part of this work. Most of the data collection has been through the LKAB databases using Aspen Process Explorer and Aspen Tag Browser. Choosing a suitable time interval for the analysis has been of great importance, a 24 hour average value case from 2010-01-17 has been used as reference. This is the same interval considered in [9] and [10]-[13] which will allow for comparison and use of simulation results, according to [9] the process is in stable operation for this time interval and can be assumed to be in a steady state condition. Input data from CFD simulations include pellet bed and hearth layer temperatures, moisture content and oxidation fractions at the different control volume boundaries.

The identification of the different sensors and the correct use of the available information has been very time consuming. Data management has been carried out by importing the information into MS Excel, in which the time and date for all measurements have been coupled to easily be able to change the analysis interval. For some streams doubts were raised about the units for the measurement. This work was however simplified by the fact that Samuel Nordgren's earlier study [6] and personal contacts provided help in terms of identification of the different measurements.

Many of the volume flows have not been measured, for example the flows in fans 10, 11 and 12. For these flows fan diagrams, approximations from mass continuity and leakage assumptions have been made.

4.6 Calculations

Calculation of enthalpies and densities for different streams were executed using HSC Chemistry [17]. This software allowed for quick calculations given stream composition (e.g.

moisture content) and temperature, with the ability to change input data. Without this software massive amounts of thermodynamic tables would have been needed, combined with interpolation functions for automatic updates when input data are changed. All mass and energy balances were performed in MS Excel, and a table of contents for the calculation sheets can be viewed in Appendix A.

4.7 Assumptions for the mass and energy balances

In this section necessary assumptions are explained and the list below consists of some of the assumptions made. For the mass and energy balances many assumptions have been made for the sake of simplicity.

- The moisture content in the ambient air 0.02 Nm^3/Nm^3 and ambient temperature minus 15 °C from weather data at Malmberget [19].
- Slag materials in pellet bed are neglected.
- Other chemical reactions besides magnetite oxidation and calcination are neglected (e.g. the formation of other iron oxides).
- When there are several streams of air exiting the same control volume, it is assumed that they have the same chemical composition.
- For some volume flows the measurements have been made quite far from the selected control volumes, so that the use of these measurements neglects the actual leakage.
- All of the calcination reactions are assumed to occur in the firing zone due to the fact that calcination is triggered by high temperatures.
- The mass flow to and from the economizer has been neglected.

4.7.1 Air leakage

Leakage of air occurs in several locations in the machine. Both the inlet and outlet for the pellet flow is subject to surrounding air which creates unknown leakage flows. The grate is not perfectly sealed which causes air to leak from below the grate through the entire process. The change in direction of the air streams through the bed causes air to leak between wind boxes. Leakage is known to occur between wind box 2-3 and from 19 to 17-18. This leakage is clearly noticeable when observing measurements on the wind box temperatures. For the mass and energy balances this is a major source of error. Assumptions have been made about the locations where major leakages are known to occur and some estimations about the splitting of the air streams have been made mainly considering the flow area. The assumptions regarding the air streams shown in Figure 2.2.1.1 and described in Appendix B are listed below.

- The volume flow of stream G8 is approximated from fan diagrams, knowing that it should be lower than the sum of the flows through fans F13, F14 and F15. The approximated flow for this stream includes leakage in-to the cooling zone.
- The leakage from G8 to G7 is assumed to be a fraction of G8 based on the number of wind boxes.
- The fraction of G8 that goes to G9 is estimated from the number of wind boxes (this assumption also includes the leakage air from outside of the machine).

- The fraction of stream G6 that goes to G6.1 is estimated from the number of downcomers in each control volume.
- The fraction of downcomer air from G6 that is not used for combustion in the firing zone is estimated from the fraction of inactive burners.

4.7.2 Ash

All ash produced in the process is assumed to be carried by the exhaust air in each control volume and finally leaving the system with the exhaust gases. This assumption is reasonable because the ash part of the energy balance is very small. However, in the long run process parameters can be affected by ash coatings. Additionally the ash content in the air flows are not considered when calculating enthalpies and densities.

4.7.3 Heat losses

It is assumed that the difference in the energy balances are due to the heat losses to the surroundings, and this amount of heat is therefore added as a requirement in the pinch analysis to the different zones. In reality this is not true because this difference also represents errors in measurement, unknown leakage and margins of error for the calculation procedures. Another assumption involving the heat losses is that they are constant and equal to those of the reference case when temperatures and mass flows of the gas streams are changed in the matched pinch analysis. This assumption is purely made for sake of simplicity.

4.7.4 Combustion

The control volumes where combustion is taking place are exclusively considered for calculating the resulting temperature and composition of the product gas. In these control volumes complete combustion is assumed as well as no losses are considered. Losses are instead visible in the other control volumes.

4.7.5 Transportation piping

In the calculation model the variation of the transport distance for the different air flows have not been considered. The heat losses from the pipes are assumed constant and equal to values represented in the reference case by measured temperatures. Measurements of some temperatures have been performed some distance from the control volume, in these cases the heat losses from the pipes have been neglected.

4.7.6 Temperatures

Positions where no measurements are made and no CFD results are available approximations are necessary. The temperature of the outgoing traveling grate and hearth layer from the cooling zone is approximated to 25 ºC. Average temperatures for evaporation of water in each zone are set to an average temperature for the pellet bed with the exception that the evaporation temperature in the firing zone is set to 280 ºC. These values are very uncertain, however the latent heat from evaporation is a small contributor to the energy balance. The same average temperatures for the pellet bed are used for the chemical energy calculations regarding the oxidation and calcination reactions, knowing that the oxidation speed is highly dependent on temperature this is possibly a rough assumption.

4.8 Pinch analysis matching

If the demand of energy for a generic control volume of the grate is considered, illustrated by the composite curve in Figure 4.8.1 below, this demand can be matched using only one stream according to Figure 4.8.2. Composite curves were constructed using the software supplied from [6]. The demand of energy in a specific zone is defined by the energy change for the production related streams and can be represented by both hot and cold streams, typically the pellet bed, hearth layer, grate and any necessary chemical reactions. The minimum temperature difference ΔT_{min} defines the separation denoted in Figure 4.8.2, this temperature difference represents the possible rate of heat transfer of the pellet bed. Heat losses for the system, which are assumed constant from the reference case, are represented by an external cooling demand denoted by x.

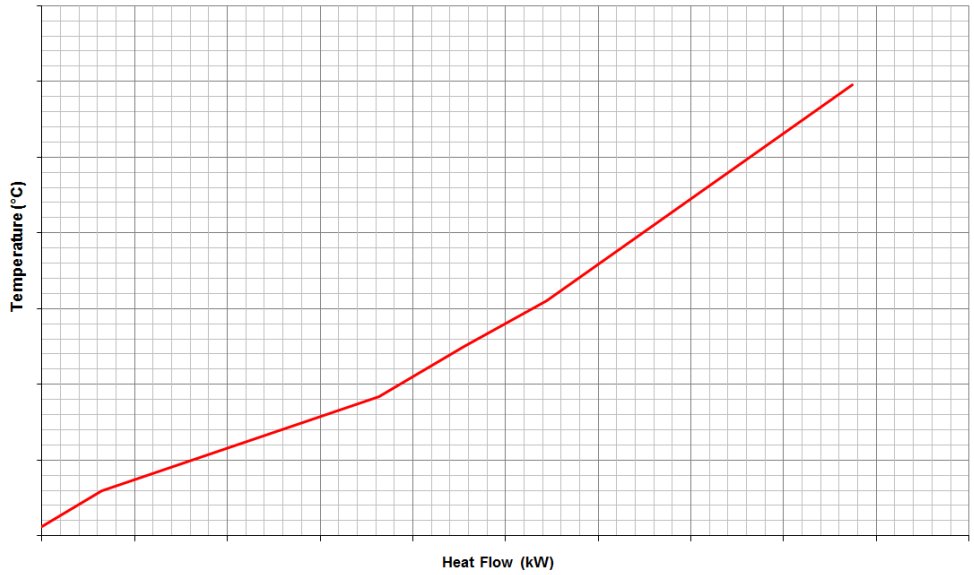

Figure 4.8.1. Demand composite curve, represented as a hot stream.

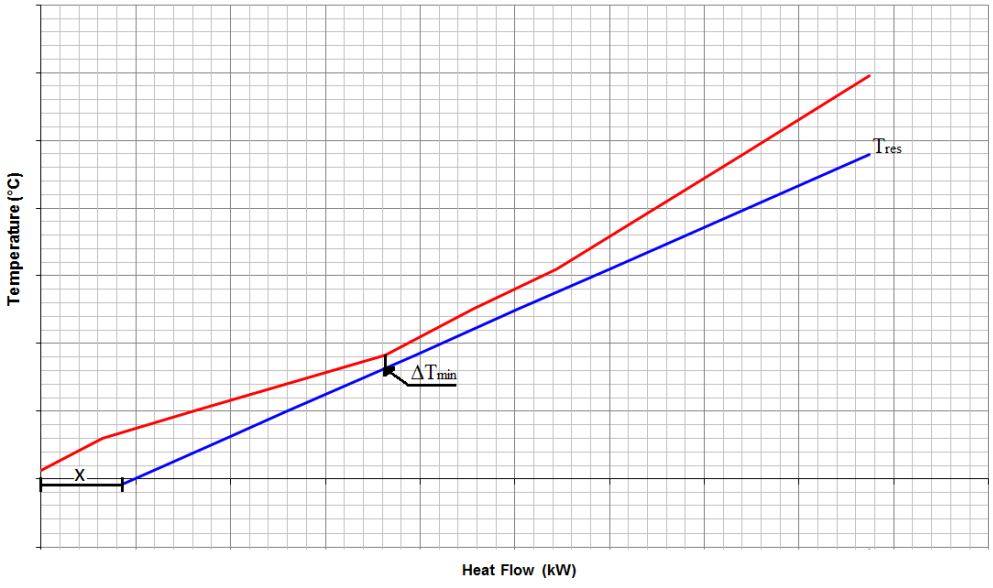

Figure 4.8.2. Matched curve (cold) for demand composite curve (hot).

The resulting mass flow of the stream is calculated from the found resulting temperature T_{res} and the heat flow. The resulting outgoing temperature and mass flow of the stream can now be used in a different control volume to satisfy another demand.

Beginning with the cooling zone a recycle temperature corresponding to stream G6 in Figure 2.2.1.1 is found, so that the fuel consumption can be calculated from the required increase in enthalpy flow to satisfy the demand of the firing zone. The exhaust gases from the firing zone and remaining recycle air from the cooling zone are entered in a heat cascade to ensure that these streams can match the demands of the remaining zones UDD and DDD. A schematic of the stream separation for the heat cascades can be viewed in Figure 4.8.3.

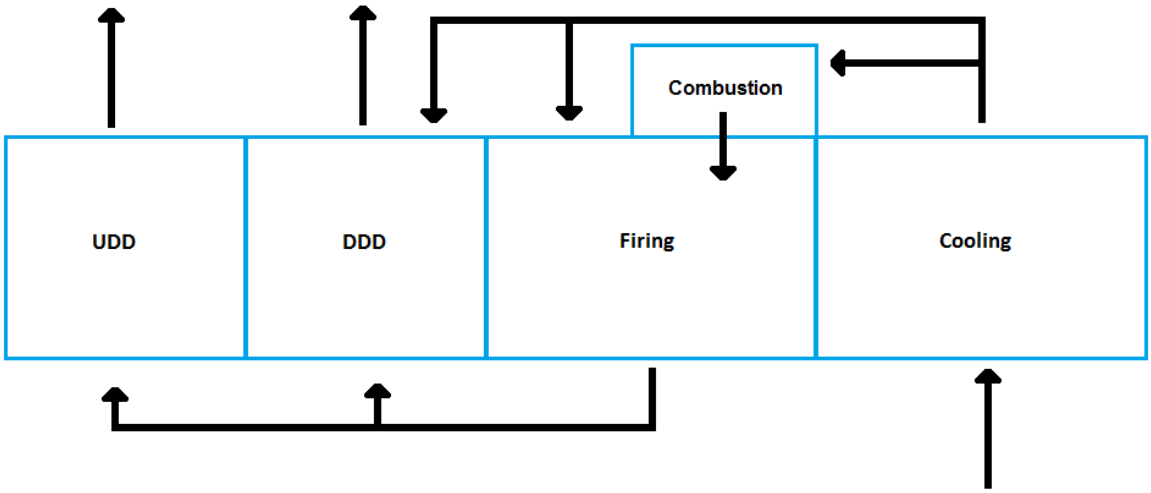

Figure 4.8.3. Stream separation for the heat cascades.

The determination of the minimum temperature difference is vital to the results of this analysis. Using the simulation software for pellet bed heat transfer described in section "4.9 Bedsim", this temperature difference can be estimated through an iterative process using the ingoing air stream temperature and mass flow in a zone to obtain an outgoing average temperature for different values of ΔT_{min}.

The temperature interval in which the heat from vaporization of moisture, oxidation and calcination is released is treated by assumptions based on the reaction rates. These assumptions listed in section "4.10 Assumptions for the matched pinch analysis" affect the location of the pinch point and consequently the slope and resulting temperature of the gas stream.

4.9 Bedsim

For an estimate of the minimum temperature difference for heat exchange the internally developed software Bedsim was used. The program is written in Fortran and simulates the heat exchange through a user defined pellet bed using a one dimensional calculation net. The software uses a shrinking core model for the oxidation and empirical equations for the heat transfer in the pellets. Input data of the pellet bed and air flows are set and a heat balance is calculated with outgoing air stream temperatures as a result. It is possible to create an

indefinite number of control volumes with couples between the different zones for the air streams.

To obtain an estimate for the minimum temperature difference, the cooling zone was simulated. Ingoing air temperature was fixed and the ingoing air flow profile was set constant for the entire zone. Each of the different simulations performed resulted in different values of ΔT_{min} represented by the total ingoing mass flow of air. When the reference outgoing properties of the pellet bed from the cooling zone are achieved, an estimate for ΔT_{min} is found using a separate heat cascade for the simulation streams. It should be noted that no losses or leakage are taken into account in the simulations.

4.10 Assumptions for the matched pinch analysis

A general assumption for the construction of the composite curves is that the specific heat of the different streams are constant and equal to an average calculated over their temperature range. The minimum temperature difference calculated for the cooling zone using Bedsim is assumed to be constant for all of the zones. In the recycle heat cascade for the demands of the UDD and DDD zones a minimum temperature difference of 20°C is used for the heat exchange among air streams.

Estimates for the amount of chemical energy that is supplied or demanded in each temperature interval are needed because the reactions are temperature. These estimates have been made roughly using information from [8] and are listed below.

- Oxidation of hematite starts at 200 °C, the reaction rate is low prior to 500 °C and is at its maximum around 1100 °C [8].
    - Oxidation in the cooling zone is divided in two parts where 90 percent of the energy is released in the higher interval (above 500 °C) and 10 percent in the lower interval.
    - In the firing zone the energy from oxidation is similarly split to a higher and lower interval with 90 and 10 percent distribution.
    - For the DDD zone all the oxidation energy is supplied at a higher temperature interval starting at 200 °C.
- Calcination starts at 850 °C and is evenly distributed above this threshold.
- The evaporation rate of water will vary through different temperature intervals knowing that it is depending on partial pressures, air speed and temperature. For simplicity it assumed that all the water is evaporated evenly in the interval of 70-130 °C. The average temperature in the pellet bed is lower than 70 °C in the UDD zone however the highest temperatures at the bottom of the bed are high enough to vaporize moisture.

5 Results

Obtained results are presented according to the different methods described in section “4. Method”. Due to confidentiality restrictions no numeric values are presented, distributions and trends are instead visible. A general result is the discovery that a traditional pinch analysis method cannot be applied to the sintering machine only due to constraints on the pellet bed properties and relations between the different mass flows.

5.1 Mass and energy balances

The mass balances are mainly a resource for the energy balances, their main purpose being to calculate the composition of the streams and to ensure that mass continuity applies according to equation 3.2.1. Table 5.1.1 below shows the difference between in- and outgoing mass for the balances in each separate control volume. This difference is the error from assumptions, measurements and calculations.

Table 5.1.1. Difference in the mass balances.

Control volume	Difference (% of ingoing)
UDD	1
DDD	-8
Firing	13
Combustion DDD	1
Combustion F	1
Cooling	0

Results from the energy balances for the control volumes UDD, DDD, Firing and Cooling are shown in Table 5.1.2-5.1.5 below. The most important information from these results is how much energy input is needed for each separate control volume. The heat losses are represented as the error in the balance originating from assumptions, measurement errors, calculation errors and the actual heat losses. The energy input from the combustion of oil is not included in these results because it occurs in a separate control volume.

Table 5.1.2. Energy balance for the UDD control volume.

In UDD			Out UDD		
Stream	**Label**	**Percent (%)**	**Stream**	**Label**	**Percent (%)**
Pellet bed	P1	1	Pellet bed	P2	11
Drying air	G1	99	Exhaust air	G2	19
Hearth layer	HL	0	Hearth layer	HL	26
Roster wagons	R1	0	Roster wagons	R2	40
SUM	-	100	Evaporation	-	1
			Heat loss	-	3
			SUM	-	100

Table 5.1.3. Energy balance for the DDD control volume.

In DDD			Out DDD		
Stream	**Label**	**Percent (%)**	**Stream**	**Label**	**Percent (%)**
Pellet bed	P2	4	Pellet bed	P3	40
Drying air	G4	37	Exhaust air	G3	22
Recycled air from C	G6.1.1	31	Hearth layer	HL	1
Hearth layer	HL	9	Roster wagons	R3	9
Roster wagons	R2	14	Evaporation	-	20
Oxidation	-	5	Heat loss	-	8
SUM	-	100	**SUM**	-	100

Table 5.1.4. Energy balance for the firing control volume.

In Firing			Out Firing		
Stream	**Label**	**Percent (%)**	**Stream**	**Label**	**Percent (%)**
Pellet bed	P3	11	Pellet bed	P4	54
Recycled air	G6	11	Exhaust gas	G5	4
Combustion gas	G6.2.1	58	Exhaust to DDD	G7	3
Hearth layer	HL	0	Hearth layer	HL	9
Roster wagons	R3	3	Roster wagons	R4	16
Oxidation	-	17	Evaporation	-	3
SUM	-	100	Calcination	-	1
			Heat loss	-	10
			SUM	-	100

Table 5.1.5. Energy balance for the cooling control volume.

In Cooling			Out Cooling		
Stream	**Label**	**Percent (%)**	**Stream**	**Label**	**Percent (%)**
Pellet bed	P4	67	Pellet bed	P5	4
Ambient air	G8	-6	Recycle air	G6	74
Hearth layer	HL	12	Recycle to UDD	G9	13
Roster wagons	R4	20	Hearth layer	HL	0
Oxidation	-	7	Roster wagons	R5	0
SUM	-	100	Bleed to F	-	-1
			Heat loss	-	10
			SUM	-	100

5.2 Composite curves and control volume demands

Results obtained using the method described in section “4.8 Pinch analysis matching” are presented below. Matched demand curves for the different control volumes using $\Delta T_{min}=40°C$ can be viewed in Figures 5.2.1-5.2.2 below.

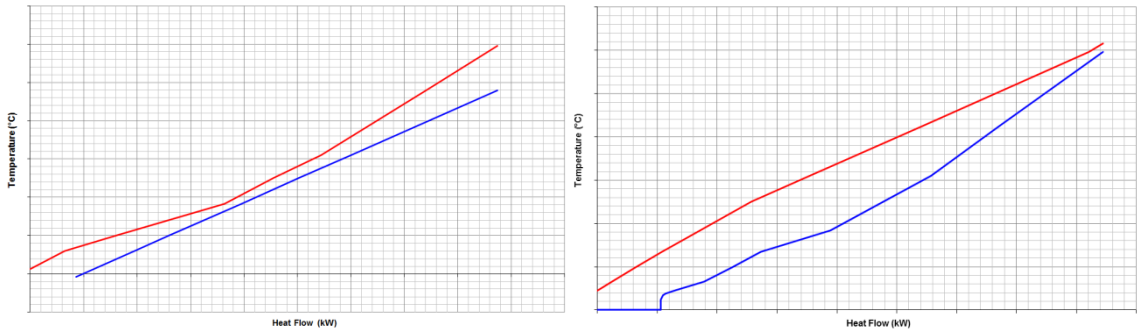

Figure 5.2.1. Matched cold stream for the cooling zone (left) and matched hot stream for the firing zone (right).

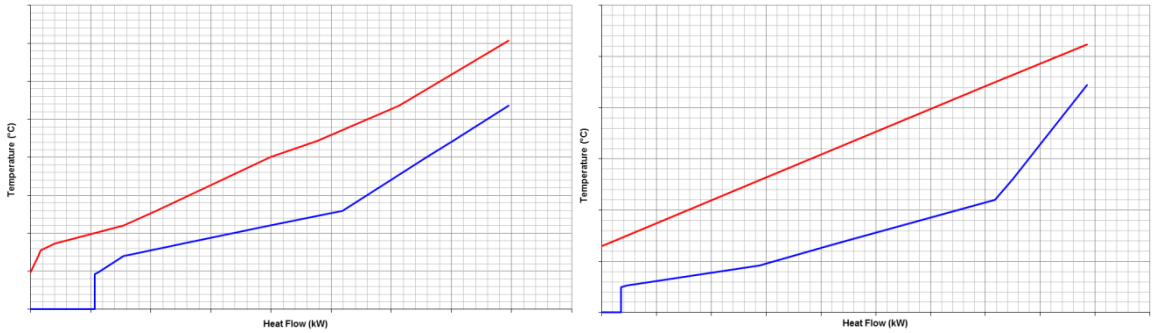

Figure 5.2.2. Matched hot streams for the DDD zone (left) and UDD zone (right).

From these matches the mass flows and temperature intervals of the streams needed for each control volume are determined.

5.3 Matched streams

The current method is only adapted to handle one stream for the firing and cooling zone, whereas in reality the streams are divided. If all of the air used in the firing zone is heated to the highest temperature, more oil than necessary is needed. If the mass flow of recycle air used in the combustion is lowered to match the power needed above the recycle temperature in the firing zone, a minimum oil consumption is found. Figure 5.3.1 below shows the power needed above and below recycle temperature in the firing zone.

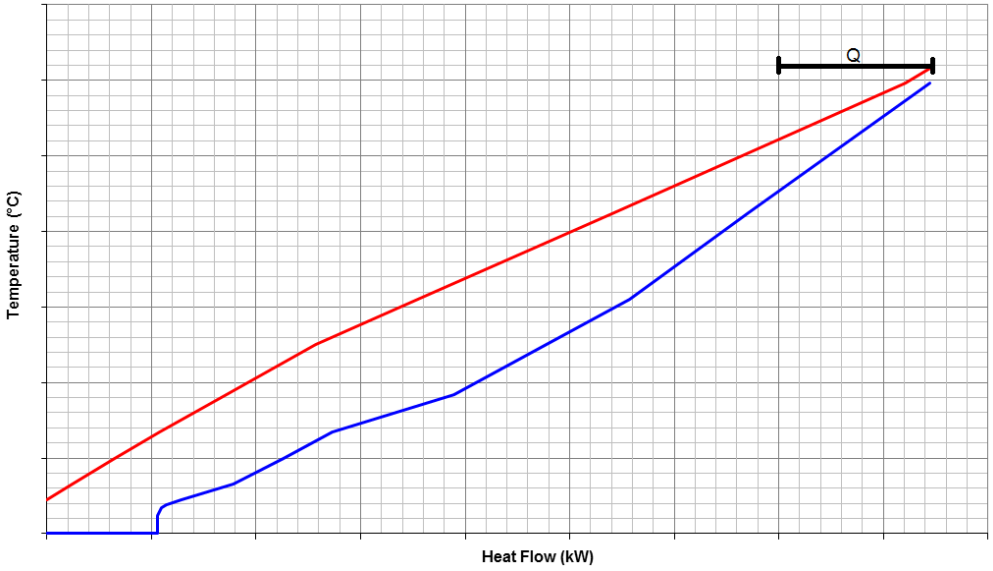

Figure 5.3.1. Amount of power needed in firing zone above the recycle temperature, denoted by *Q*.

Figure 5.3.2 shows how the minimum oil consumption calculated in this way varies with the minimum temperature difference as described by the pellet bed.

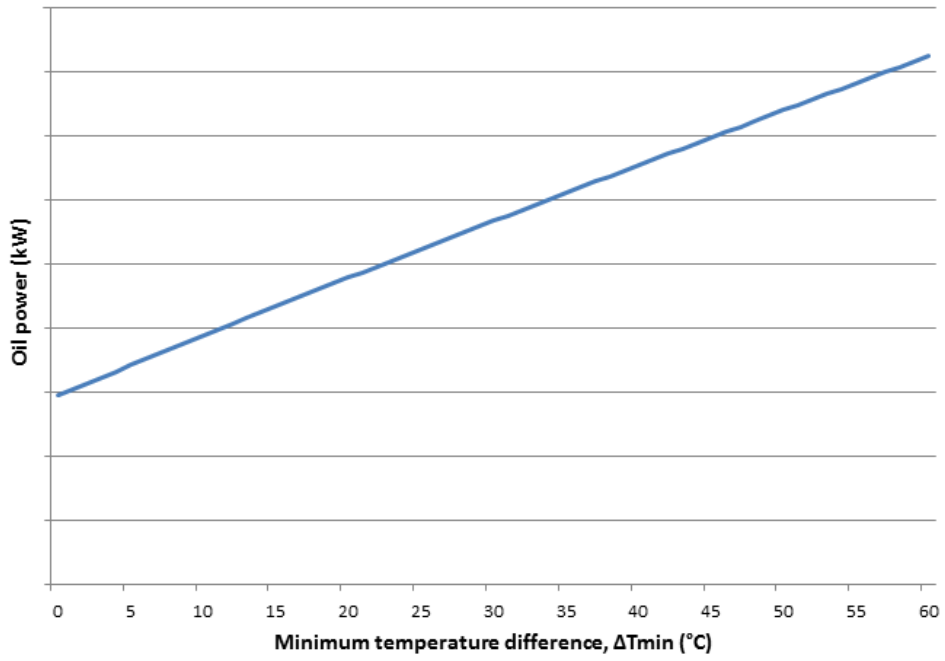

Figure 5.3.2. Relation between minimum oil consumption and the minimum temperature difference.

Results from the method described in section "4.9 Bedsim" suggest a value 45ºC of for the minimum temperature difference in the cooling zone. Recycle streams from the cooling and firing zones are calculated for a minimum oil consumption in the firing zone and listed in a heat cascade (composite curves shown in Figure 5.3.3) to satisfy the streams demanded by the

UDD and DDD zones. The oil consumption for $\Delta T_{min}=45°C$ is similar to that of the reference case.

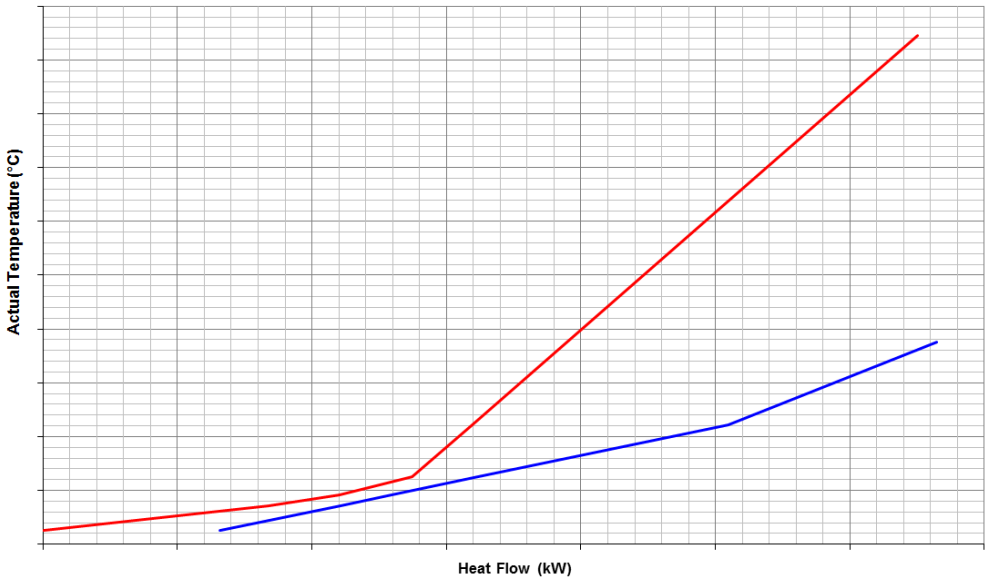

Figure 5.3.3. Composite curves for the recycle heat cascade of the UDD and DDD zones.

6 Discussion

During this master thesis the knowledge needed to perform a classic pinch analysis was gathered but never implemented. Instead a new methodology for energy analysis using the pinch method specifically designed for pelletizing plants was developed and explored. It should be possible to implement the same method used in this thesis on any process industry where energy demands and constraints can be clearly stated for the production process in a similar way.

Many improvements can be made to the mass and energy balances, however this was not the major focus of this thesis. Completing mass and energy balances can be considered a good way of learning and understanding the process. Those presented here are sufficient to explore the developed methodology for pinch analysis matching of streams. A source of error for the mass and energy balances is that a combination of measurements, simulation results and assumptions have been used as input data. Lack of measured data introduces inconsistency errors in the calculations, and for more reliable balances more measurements would be needed especially for air flows. The alternative is to establish balances for theoretical data only, but the value of such an analysis would be questionable.

The temperature data for the hearth layer from CFD results are increasing in the UDD zone and decreasing in the DDD zone. These values could be questioned from a thermodynamic point of view when comparing them to the pellet bed temperatures. Calculated percentage heat losses are relatively stable for the different control volumes, although it should be noted that they are heavily dependent on the assumptions for the air flows. The evaporation temperature used for the firing zone is quite high and should likely be lower, the energy from evaporation in that zone is only 3 percent of the total energy and the significance of this error is relatively small.

Results obtained using this methodology should be handled with care, knowledge of the assumptions made must exist and further development is recommended before any kind of experiments. Improvement of the composite curves include temperature dependent functions for the chemical energy contribution such as oxidation and evaporation. The assumption regarding that the specific heat for the hot and cold demand streams are constant at the average value can also by improved by splitting the streams in different intervals. To be able to create possibilities for optimization of the streams additional control volumes are needed mainly because the streams supplying a demand must be used for all of the demand streams of that interval of the machine. A supply stream can not only be used to heat the pellet bed, for example the traveling grate must also be heated by the same stream from process restrictions. Additional control volumes would require more input data such as properties of the pellet bed.

The constraints from pellet bed properties have been adjusted for from an energy point of view by temperatures and chemical compositions in the different control volume boundaries. It is not considered, for example, that oxidation speed is varying with temperature through the entire control volume and will be dependent on time as well. This would be improved by introducing more control volumes. Additional control volumes would increase the detail of

the outgoing temperatures from their respective zones, for instance the recycle temperature from the cooling zone is highest in the beginning of the zone.

In order to verify the method, calculations should be carried out with the same separation of air streams as in reality, comparison with a real process change would then be possible assuming that enough data is available. The estimated value of ΔT_{min} should be investigated further, since this value was calculated for the cooling zone only and will vary in the different zones.

An optimization process would be aimed at using the least possible amount of air in the combustion process, heating it sufficiently to be able to overcome the minimum temperature difference allowed and the power demand of the firing zone above the temperature where direct recycle is not possible. Meanwhile the demands of the other zones are not to be overlooked, this part of the optimization will increase the possible heat recovery.

7 Conclusion

The goals stated in section “1.2 Targets” to define streams and set up energy balances has been fulfilled, constraints caused by the pellet production have been identified and represented by the composite demand curves. Constraints originating for example from material limitations and work environment have however taken into account. The energy balances create a base for further analysis using process integration tools such as pinch analysis. Uncertainties in the mass and energy balances occur where no measurements are made, assumptions and theoretical values introduce inconsistency to the calculations.

The last two goals concerning the construction of a pinch analysis model to be analyzed using the current process setting has not been achieved. This is because of the traditional pinch analysis method would not allow for the necessary process constraints.

Instead a method for involving these constraints has been explored, results suggest similar oil consumption to the reference case. Further development with this method is needed and suggested in section “8 Future work” before a model to fully represent the plant can be constructed. If there is interest from LKAB to continue working with this method of mapping and matching energy carriers, it could be used in the future to compare the effects on the oil consumption to a reference case from different process changes. It is believed that further development of the method, the assumptions and the details of this work will allow the use of it as an optimization tool for air streams in pelletizing plants.

8 Future work

The amount of recycled air that needs to be heated using combustion with oil can be further investigated if the firing and cooling zone control volumes are split, preferably the firing zone is split into one control volume for each pair of downcomers. An optimization procedure of the stream matching and heat exchange would be a natural follow up to this work, since it should be able to find an optimum solution for the system as described by the control volumes, heat exchange capacity of the pellet bed and energy balances. The modified pinch analysis developed in this work should also be verified by exploring a process change already implemented. Improved calculations about the considered assumptions would increase reliability of the method.

Development of a composite curve and problem table construction software with more user input functions would be of use if this line of work is continued. External heating and cooling demand should be possible input data instead of the slopes (heat capacity flow rate) of the different streams for the matched composite curves. Further development of the Bedsim software with a built in matched pinch analysis optimization tool would be a possible approach since Bedsim can divide and couple the grate using multiple zones. Increased detail in determining the minimum temperature difference is recommended due to its high impact on the results.

The mass and energy balances calculated in this work can be improved in many areas and are the foundation for the results from the pinch analysis. For more precise results further investigation regarding the unmeasured air flows and leakages are the most impactful.

Extending the pinch analysis to other systems adjacent to the pelletizing plant would be another approach to the pinch analysis concept. In this case the sintering machine should be treated as one control volume. However the probability of relevant results in such a scenario needs to be evaluated firstly.

9 References

[1] LKAB annual report 2011. (2012). Sustainability report.

[2] El-Halwagi, M. (2006). *Process Integration, Process Systems Engineering Volume 7.* Elsevier Inc. ISBN: 978-0-12-370532-7.

[3] Linnhoff, B., Flower, J. (1978). *Synthesis of heat exchanger networks: Part I: Systematic generation of energy optimal networks.* AIChE J, 24(4): 633-642.

[4] Linnhoff, B., Turner, J. (1981). *Heat-recovery networks: new insights yield big savings*. Chem Eng, 56-70, November 2.

[5] Wang, Y., Smith, R. (1994). *Wastewater minimisation*. Chem Eng Sci, 49: 981.

[6] Kemp, I. (2007). *Pinch Analysis and Process Integration: A User Guide on Process Integration for the Efficient Use of Energy*. Butterworth-Heinemann. ISBN: 978-0-75-068260-2.

[7] LKAB, About us, http://www.lkab.com/en/About-us/Overview/, Date: 2013-02-05.

[8] Internal report, LKAB.

[9] Nordgren, S. (2010). *Energy Analysis of Pelletising in a Straight Grate Induration Furnace,* Licentiate thesis. Division of Energy Engineering, Department of Applied Physics and Mechanical Engineering, Luleå University of Technology. ISSN: 1402-1757.

[10] Sjöström, U., Lundqvist, M. (2010). *Inverkan av Råkuletemperatur på Temperatur, Torkning och Oxidation – Tillämpning av CFD-Modell på Pelletsproduktion i MK3.* Swerea MEFOS.

[11] Sjöström, U. (2011). *Inverkan av Råkuletemperatur på Temperatur, Torkning och Oxidation – Tillämpning av CFD-Modell på Pelletsproduktion i MK3, Del 2.* Swerea MEFOS.

[12] Sjöström, U. (2011). *Inverkan av Råkuletemperatur och Bäddporositet på Temperatur, Torkning och Oxidation – Tillämpning av CFD-Modell på Pelletsproduktion i MK3, Del 3.* Swerea MEFOS.

[13] Sjöström, U., Riesbeck, J. (2012). *Tillämpning av CFD-Modell på Pelletsproduktion i MK3 – Slutrapport från PRISMA Etapp 1 och 2.* Swerea MEFOS.

[14] Eriksson, L., Hermansson, S. (2010). *Pinch Analysis of Billerud Karlsborg, a Partly Integrated Pulp and Paper Mill*, Master's thesis. Department of Energy and Environment, Division of Heat and Power Technology, Chalmers University of Technology.

[15] Sonntag, R., Borgnakke, C. (2009). *Fundamentals of Thermodynamics -7th edition*. John Wiley & Sons, Inc. ISBN: 978-0-470-17157-8.

[16] Kjellström, B., Lindberg, J., Keikkala, G. (2003). *Combustion and Gasification in Theory and Practice*, Compendium. Department of Applied Physics and Mechanical Engineering, Division of Energy Engineering, Luleå University of Technology.

[17] HSC Chemistry. Simulation and modeling software, version 6.1. Outotec Research Oy, Pori Finland.

[18] Perry, R., Green, D. (1998). *Perry's chemical engineers' handbook, Seventh Edition.* McGraw-Hill Book Co. ISBN: 0-07-115982-7.

[19] Weather measurement data sheet. Swedish Meteorological and Hydrological Institute.

Appendix A – Table of contents calculation sheet

Contents

1. Input
1.1 Input data
1.2 Stream list

2. Stream list pinch
2.1 Stream list
2.2 Matched demands
2.3 Resulting streams
2.4 Resulting streams with min. oil

3. Mass calculation
3.1 In UDD
3.2 Out UDD
3.3 In DDD
3.4 Out DDD
3.5 In Firing
3.6 Out Firing
3.7 In Comb. DDD
3.8 Out Comb. DDD
3.9 In Comb. Firing
3.10 Out Comb. Firing
3.11 In Cooling
3.12 Out Cooling

4. Energy balances
4.1 Energy Balance Up Draught Drying
4.2 Energy Balance Down Draught Drying
4.3 Energy Balance Firing zone
4.4 Energy Balance for Combustion before DDD zone
4.5 Energy Balance for Combustion before Firing zone
4.6 Energy Balance Cooling zone

5. Stoichiometric calculation
5.1 Calculation
5.2 Fuel properties

6. Compositions
6.1 Dry ambient air
6.2 Moist ambient air
6.3 Composition of P1
6.4 Composition of P2
6.5 Composition of P3
6.6 Composition of P4
6.7 Composition of P5
6.8 Composition of Hearth layer
6.9 Composition of G6, G9, G1
6.10 Composition of G2

7. Summarized results
7.1 Energy balances
7.1.1 UDD
7.1.2 DDD
7.1.3 Firing
7.1.4 Cooling
7.1.5 Combustion control volumes
7.2 Mass balances
7.3 Oxidation and oil

8. Pinch oil consumption calculation

9. Data

Appendix B – Stream list

Stream description	Label	Type
Drying gas to UDD	G1	Drying gas
Exhaust from UDD	G2	Exhaust gas
Exhaust from DDD	G3	Exhaust gas
Drying gas to DDD	G4	Drying gas
Exhaust from firing	G5	Exhaust gas
Recycle from C1	G6	Hot gas
Combustion air to Comb. DDD	G6.1	Hot gas
Combustion air to Comb. Firing	G6.2	Hot gas
Product gas from Comb. DDD	G6.1.1	Product gas
Product gas from Comb. Firing	G6.2.1	Product gas
Exhaust from firing	G7	Recycled gas
Ambient air intake	G8	Ambient air
Recycle from C2	G9	Hot gas
Pellet bed to UDD	P1	Pellet bed
Pellet bed to DDD	P2	Pellet bed
Pellet bed to firing	P3	Pellet bed
Pellet bed to cooling	P4	Pellet bed
Pellet bed out	P5	Pellet bed
Fuel flow to DDD/PH	O1	Fuel flow
Fuel flow to Firing	O2	Fuel flow
Bleed to Fan 11	B1	Bleed air
Bleed to Fan 12	B2	Bleed air
Bleed to UDD	B3	Bleed air
Bleed from UDD to DDD	B4	Bleed air
Bleed from C2 out	B5	Bleed air
Roster to UDD	R1	Roster wagons
Roster to DDD	R2	Roster wagons
Roster to firing	R3	Roster wagons
Roster to cooling	R4	Roster wagons
Roster out	R5	Roster wagons
Hearth layer	HL	Hearth layer