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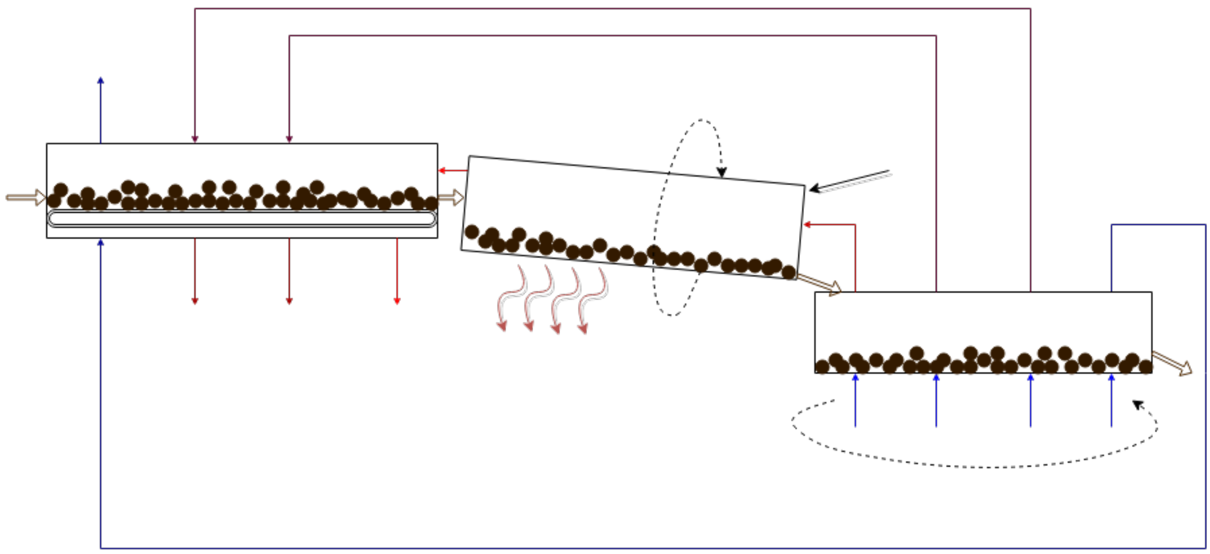

Modelling of heat recovery in LKAB's grate-kiln process

Master's thesis in Sustainable Energy Systems

HANNA ANDERSSON & SIMON PEDERSEN

Department of Energy and Environment
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2015

Master's thesis 2015

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Cover: Schematic of the LKAB grate-kiln process.

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Abstract

This master thesis uses process modelling to investigate energy efficiency measures in the grate-kiln process for iron ore production; specifically, how waste heat contained in flue gas could be recirculated in order to achieve a decrease in specific fuel consumption. Consequently, fossil carbon emissions would be reduced as the grate-kiln units are fired with coal or oil.

The implementation of flue gas recirculation is simulated with a process model in EBSILON Professional 10.0. Process concepts which make use of available waste heat are developed and their impact on fuel usage, pellet temperature profiles and the magnetite oxidation process is evaluated. Aside from partial flue gas recirculation, a heat recovery concept is investigated. Both concepts are applied to decrease the fuel consumption by increasing the temperature and oxidation on the grate and to recover heat at a high temperature. To minimize the effect of recirculation and heat recovery on the pellet heat treatment process, concepts that use intercooling before the grate are also evaluated.

The implementation of heat recovery affects the performance of the pellet cooler. The cooler's operation is studied in detail with a cooler model developed in MATLAB. The cooler model is evaluated, and a sensitivity analysis is made to determine which parameters have a crucial impact on the pellet cooling.

The results indicate that waste heat utilization can reduce the fuel consumption by up to 30 % if a heat exchanger is used. It was revealed that increased temperature into the cooler's hottest section elevates the temperature levels on the grate, which lowers the fuel usage. Direct flue gas recirculation lowers the oxygen content in the air passing the kiln and grate, which has a negative impact on the oxidation process and the overall heat balance.

The cooler model showed that to maintain adequate pellet cooling, the mass flow through cooler zones C3 and C4 should be increased by 70 %, or the area of the C3 and C4 sections should be increased by 40 % when heat recovery is used. The direct flue gas recirculation concepts requires a 40 % and 25 % increase for the two measures, respectively.

The thesis recommends three process designs, based on indirect heat recovery from the flue gases.

Keywords: Iron ore pellets, Grate-kiln process, Flue gas recirculation, Waste heat.

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1
Introduction

The global demand for steel has increased steadily throughout the last century and is continuing to rise [1]. The production and refining of iron ore is of great importance to the steelmaking industry and is at the same time a large energy consumer. Iron ore is typically refined into fines or pellets. LKAB is the main iron ore producer in Sweden and focuses on pellets. According to LKAB's sustainability report of 2013 a ton of produced pellets requires 183 kWh of energy input, of which the pelletizing plants require the major part [2]. The high energy intensity of iron ore production is linked with emissions of fossil carbon, since coal or oil is used in the dominating pelletizing processes [3].

There are two main pelletizing processes, the travelling (or straight) grate process and the grate-kiln process. In the travelling grate process, ore pellets move on a continuous grate through different zones for drying, oxidation, sintering and cooling. The grate-kiln process uses a shorter grate and a rotary kiln in order to achieve a more homogenous heat treatment of the pellets. Hematite ($\alpha-Fe2O3$) ores are often subjected to the straight grate process while for magnetite (Fe_3O_4) ores the grate-kiln process is most commonly employed [4]. This thesis only considers the grate-kiln process. Because of the oxidation taking place in the magnetite-rich ore, less than half of the energy required in the production needs to be supplied externally. The kiln is heated by coal or oil [3], and with growing concerns regarding global warming a reduction of carbon emissions and an increase in the energy efficiency of the process is required.

This thesis evaluates the utilization of waste heat contained in flue gases in the pelletizing plant to decrease fuel consumption in the process, which in turn would result in reduced CO_2 emissions. Specifically, LKAB's KK2 grate-kiln unit is studied.

1.1 Overview of iron ore production at LKAB

Luossavaara-Kiirunavaara AB (LKAB) is a state-owned company in the north of Sweden that extracts iron ore from mines in Kiruna, Malmberget and Svappavaara, which after processing is sold for use in the steel industry. The most important product is iron ore pellets. Ore is mined at a depth of approximately 1000 m below sea level and consists mainly of magnetite ore [5]. The ore is crushed into smaller fractions and sent to a sorting plant where it is further reduced in size and undergoes magnetic separation and sieving [6]. The ore is then passed through concentrating plants where further separation is made. Water and additives are mixed with the crushed ore, and reverse flotation is employed to remove unwanted phosphorus. A slurry concentrated in magnetite is obtained where more additives such as olivine, quartzite and limestone are added before it is sent to the pelletizing plants. The slurry is here dried to a water content of 8.5 to 10 %. Magnetite balls with a diameter of about 10 mm are then formed in rolling drums. The ore, now called green pellets, is then ready to undergo thermal treatment in the coal- or oil-fired grate-kiln process shown schematically in Figure 1.1. Drying, oxidation and sintering are of prime importance to form the pellet product and take place in various parts of the grate-kiln unit.

The pellets must be heated to dry out the remaining water and to increase their mechanical strength [7]. The quality of the finished product depends on the residence time, particle size, additives and temperature profile throughout the heat treatment [8]. Since oxidation plays a significant role in converting the raw pellets into the finished product, the oxygen content in the surrounding gas is also of great importance. The grate-kiln process is explained in greater detail in the theory section.

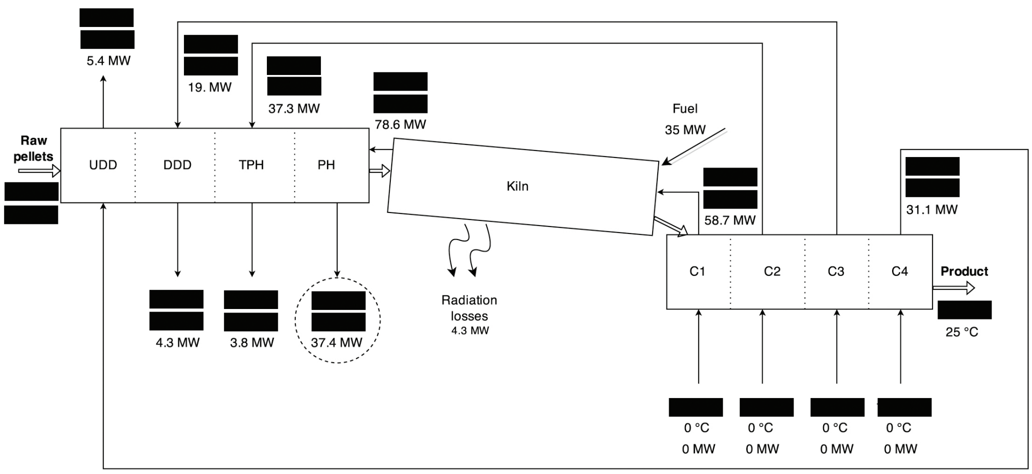


Figure 1.1: Overview of the grate-kiln process as used in LKAB's KK2 pelletizing plant with energy balance. The grate, consisting of drying and preheating zones, prepares the pellets for heat treatment in the rotary kiln. The coal- or oil-fired kiln delivers high thermal input in the form of radiation which sinters the pellets and adds mechanical strength. To cool the pellets fresh air is blown through an annular cooler, which recovers the heat from the fired pellets and supplies it to the grate. $T_{ref} = 273\,\text{K}$. Note that a single large stream, marked by a dashed circle, contains the majority of all useful heat. Mass flow discrepancies can be explained by cold inleakage streams not shown in this picture. [5]

The temperature levels present in the later sections of the grate are very high, and consequently the off-gas from these zones contains considerable amounts of high-exergy heat. Presently this heat is converted to low-grade district heating before the flue gas is led cleaning and then to stacks. If this heat could be used productively, either to decrease the specific fuel consumption or to produce another valuable product such as electricity, then the specific energy intensity of the pellet production could be decreased. Based on the work by Haaf [5] an energy balance showed that there are some 37 MW available at approximately 450 °C ($T_{ref} = 0$ °C). A more complete overview of the heat contained in various air streams can be seen in Figure 1.1 where the waste stream with the most exergy is marked with a dashed circle.

1.2 Aim and scope

This master thesis is focused on the possibility of utilizing the waste heat contained in the flue gas exiting the grate's last and hottest zone (”PH”) by feeding it directly (partial recirculation) or indirectly (air preheating) to the cooler's first stage. The consequences of flue gas recirculation in terms of product-influencing parameters like degree of oxidation and experienced temperature and O_2 profiles by the pellets throughout the process will be investigated using process simulations.

Recirculation of flue gases will furthermore require analysis of the cooler's operational parameters to avoid energy losses in the form of a warmer pellet product stream. There may also be practical limitations to the pellet temperature, e.g. on the equipment used for their transport. The cooler will be subject to detailed bed modelling to give a better understanding of how alterations to streams and conditions will affect the cooler performance.

More specifically, the project aims to evaluate:

- What fuel savings can be achieved through flue gas recirculation to, or preheating of air in, cooler section one?
- What kind of impact does this waste heat utilization have on the temperature and oxygen profiles experienced by the pellets?
- How should the cooler's operational parameters be changed to cool the product sufficiently when these other modifications are made?

2

Theory

This chapter provides the theoretical background to this thesis. First an outline of the grate-kiln process is laid forth, followed by a description of magnetite oxidation. The NTU method for heat exchanger calculations is finally presented, as it is used in the modelling of the cooler.

2.1 The grate-kiln process

The treatment of iron ore into a pellet product contains many steps, and the grate-kiln is the last unit before the pellets exit as a finished product. The process can be divided into three parts: a grate furnace, a rotary kiln and an annular cooler. In the grate, which is the largest part of the grate-kiln unit with a length of 53 m and a width of 4.5 m in the case of KK2, the magnetite balls (called green pellets) are dried and preheated by using hot air from the cooler. The grate is divided in four zones and is illustrated in Figure 2.1. In the first two zones, wet green pellets are first dried by up draft drying (UDD), where hot air is blown in from below the pellet bed, and then by down draft drying (DDD). After the drying zones, the pellets are transported through the tempered preheat zone (TPH) and the preheat zone (PH). These two zones serve to increase the temperature of the pellets prior to the kiln, and here the main part of the oxidation to hematite takes place [9]. Oxidation of the pellets releases a large amount of heat – this is the main heat source in the process [5].

The heated pellet bed then enters the rotary kiln, shown schematically in Figure 2.2. In order to obtain a sufficiently high process temperature in the kiln, heavy fuel oil or pulverized coal are used as fuel in a single burner located at the lower end. During normal operation coal is used with oil used for start-up [4]. A long flame is required in the kiln to avoid heat peaks and to create a homogeneous temperature profile of the pellets; radiation from the flame to the pellets plays a major role in the kiln's heat transfer [5]. The high pellet temperature achieved in the kiln enables sintering which is needed to give strength to the pellets. To make sintering possible a pellet temperature around 1200 to 1300 °C is required in the kiln.

In the cooler, the temperature of the now sintered and oxidized pellets is decreased from some 1300 to below 100 °C by a flow of ambient air before they exit as a finished product [6]. KK2's cooler is designed as a rotating ring as displayed in Figure 2.3

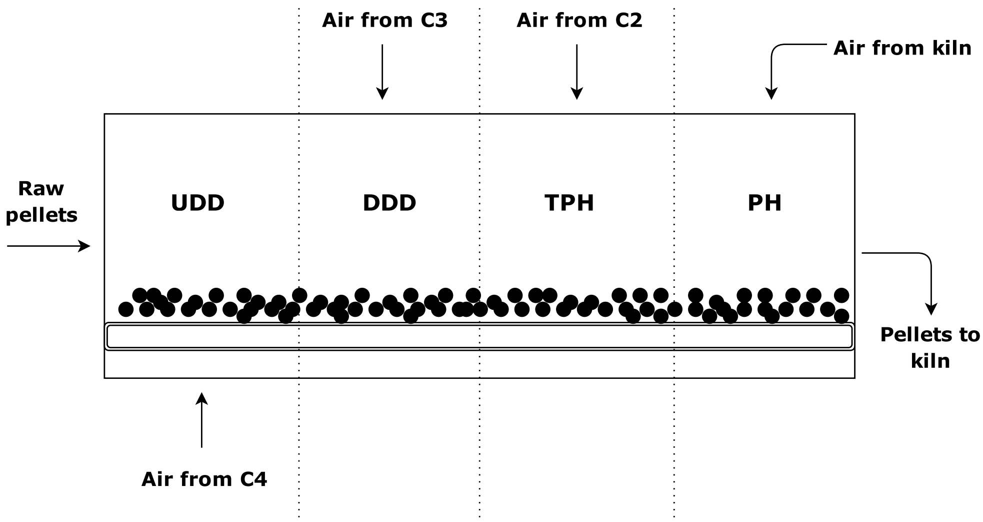
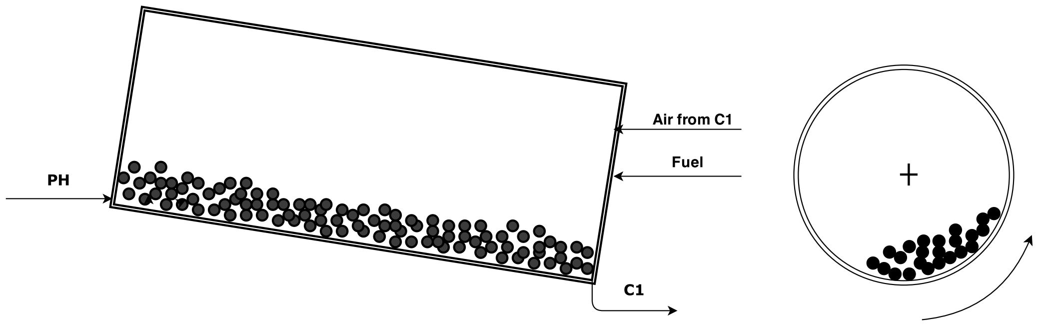


Figure 2.1: Schematic of the KK2 grate with its zones.



(a) Side view

(b) Cross-section

Figure 2.2: Schematic drawing of the rotary kiln.

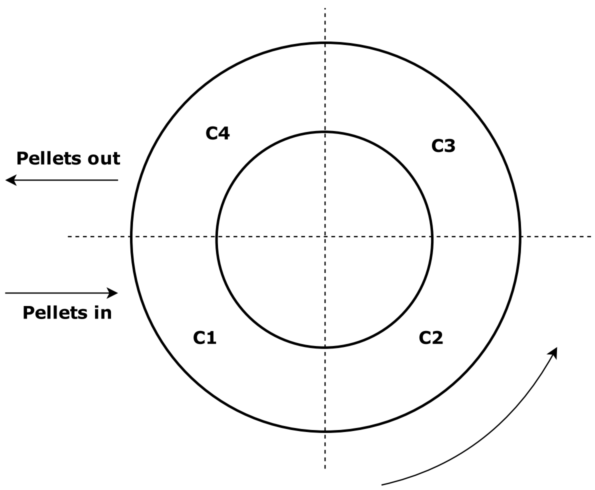


Figure 2.3: Sketch of the cooler and its different sections as seen from above.

with an average diameter of 16 m and a width of 3 m [5]. Cold air (about 0 °C) is passed through the pellet bed and, once heated, onto the kiln and grate. The cooler has four zones, henceforth referred to as C1 through C4, each providing hot air for the kiln and grate zones TPH, DDD and UDD respectively. The grate's PH zone is supplied from the kiln.

2.1.1 Oxidation of pellets

Magnetite has been important for the world steel industry for the last 50 years and will likely continue to be for the foreseeable future [10]. The oxidation of magnetite is a reaction of great importance for the production of iron ore pellets due to its exothermic property, which reduces the fuel input required for their heat treatment. Conversion between magnetite and hematite takes place in three regimes as the temperature is increasing. The first oxidation regime is found below 400 °C, and here oxidation only occurs on the surface of a particle. In the second oxidation regime, ending somewhere between 900 °C and 1100 °C, magnetite is completely oxidized to hematite [11]. The third regime is when dissociation of hematite back to magnetite starts. According to Forsmo, dissociation begins at 1457 °C in O_2 and at 1392 °C in air. The dissociation could start at lower temperatures if basic additives are present [9]. It is therefore important that pellets obtain a high temperature during their heat treatment without overheating.

For the pelletizing process, more than two thirds of the total energy needed for sintering at the LKAB pelletizing plants comes from the oxidation reaction [9]. Since magnetite oxidation is highly temperature sensitive, the oxidation is limited in the rotary kiln as the reaction rate drops above 1100 °C [6]. Even some dissociation of hematite back to magnetite can occur. When the pellets enter the cooler the oxidation rate increases again as their temperature drops, but with continuously decreasing temperature the reaction rate quickly reaches zero [6].

It is important to have a constant level of oxidation in magnetite pellets to maintain a stable process. Variations in the degree of oxidation in pellets leaving the PH zone lead to fluctuations in the amount of oxidation taking place in the cooler, and therefore in the temperature of the recirculated air [9] which may lead to process control issues.

2.2 Heat exchanger rating with NTU method

Normally, the amount of heat q transferred in a counterflow heat exchanger with an area A and an overall heat transfer coefficient U can be expressed as

$$q = UA\Delta T_{lm} \tag{2.1}$$

where ΔT_{lm} is the logarithmic mean temperature difference [12]:

$$\Delta T_{lm} = \frac{(T_{h,1} - T_{c,1}) - (T_{h,2} - T_{c,2})}{\ln \frac{(T_{h,1} - T_{c,1})}{(T_{h,2} - T_{c,2})}} \tag{2.2}$$

This obviously requires all four temperatures $T_{h,1}, T_{h,2}, T_{c,1}, T_{c,2}$ to be known as well as the area and U number for q to be calculated. Often the case is that neither the outlet temperatures nor q are known, and the desire is to find these three simultaneously without iteration. In this case the so-called NTU method, named after the dimensionless number NTU ("number of transfer units"), may be employed [12].

By defining the *heat capacity rate* for stream i, C_i, as

$$C_i = \dot{m}_i c_{p,i} \tag{2.3}$$

and assigning C_{min} and C_{max} so that they take the smaller and larger of the two streams' heat capacity rates

$$C_{min} = \begin{cases} C_h & \text{if } C_h < C_c \\ C_c & \text{if } C_h > C_c \end{cases}, \quad C_{max} = \begin{cases} C_c & \text{if } C_h < C_c \\ C_h & \text{if } C_h > C_c \end{cases} \tag{2.4}$$

then the maximum possible heat transfer over an infinite area would be

$$q = C_{min}(T_{h,in} - T_{c,in}) \tag{2.5}$$

because the minimum stream undergoes the largest temperature change and will reach $T_{max,in}$ before the maximum stream reaches $T_{min,in}$.

If we now define ε as the rate between actual experienced heat transfer and the maximum as defined above, then the actual heat transfer can be expressed as

$$q = \varepsilon C_{min}(T_{in,pellets} - T_{in,gas}) \tag{2.6}$$

and correlations for ε can be established on the form [12]:

$$\varepsilon = f\left(NTU, \frac{C_{min}}{C_{max}}\right) \tag{2.7}$$

The variable (NTU) in the equation above is defined as

$$(NTU) = \frac{UA}{C_{min}} \tag{2.8}$$

and outlet temperatures $T_{h,out}$ and $T_{c,out}$ can thus be found only by knowing UA if a suitable correlation for ε can be obtained.

3

Methodology and model description

In this project, heat recovery and flue gas recirculation in the grate-kiln unit is studied using two models on different aggregation levels. A process simulation model of the entire grate-kiln determines the effects of recirculation on pellet quality and fuel usage. A detailed cooler model analyzes how cooler design with hotter-than-ambient air would affect the pellet cooling and resulting gas streams, and how the cooler and its streams could be modified to keep a constant product temperature in the light of other process modifications.

3.1 Grate-kiln process model

The grate-kiln process model is based on the work by Haaf [5]. A short description of the most important features are given here, while details on the implementation can be found in his report [5]. The model is based on LKAB's grate-kiln plant KK2 in Kiruna and built in EBSILON Professional 10.0, which is a software frequently used for heat and mass balance calculations in power plants or other large thermal systems. The model considers drying, oxidation and calcination of the pellets and the heat recycling from the cooler, but does not account for any electricity demand from pumps, fans and other motors. Figure 3.1 shows an overview of the process model and its structure.

Cold, wet pellets are fed to the grate where the pellet bed is divided into three layers with 20, 60, and 20 % of the total mass, respectively. The four grate zones (UDD, DDD, TPH and PH) are divided into three sections each, giving a 3x3-pattern of calculation macros for every zone. Each macro calculates heat transfer, drying, oxidation and/or calcination. Oxidation and calcination are handled by a custom script, increasing the fractional oxidation and calcination of the pellets and reducing the oxygen content of air as well as releasing some heat to the pellets [5].

After passing the grate the pellets are fed to the kiln, build up by three sequential single-layer macros. Due to rotation of the kiln, the temperature profile of the pellet is assumed to be homogeneous. 50 % of the air from C1 is passed through a combustion chamber where heat is added in the form of a simple coal fuel. The rest of the air bypasses the combustion and is instead blended with the heated flue gas in a linear fashion. In the kiln, convective heat transfer between flue gas and pellets is limited. Radiative heat is instead added to the pellets directly from the combustion chamber, and some radiative heat losses are considered. Radiation is assumed to be equally distributed along the kiln [5]. A control circuit keeps the pellet temperature out of the kiln constant at 1225 °C by varying the amount of fuel added.

The cooler is divided into three distinct layers reminiscent of the grate. The cooler has layers consisting of 6.66, 86.68 and 6.66 % of the total pellet mass respectively. In the first two cooler zones (C1 and C2) the temperature is still high enough for the magnetite to undergo oxidation. In C3 and C4 there is only heat transfer between the air and pellets. In the cooler there is no calcination.

Since oxidation is the main heat source in the process and it is strongly influenced by pellet temperature, this parameter has a large influence on the results. The pellet c_p value is fixed to 0.88 kJ /kgK in the model [5].

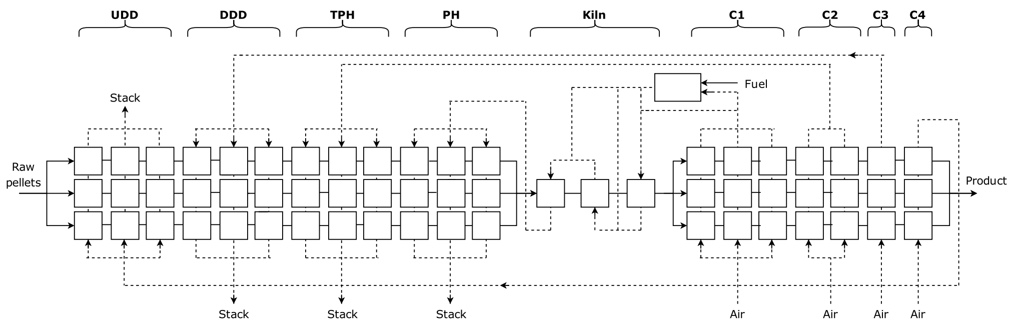


Figure 3.1: Schematic of the KK2 EBSILON process model. Each square represents a calculation of drying, heat transfer, oxidation and/or calcination. Dashed lines show the general pattern of gas streams, excluding mixing and inleakage.

3.2 Cooler modelling

The cooler model describes the performance of the pellet cooler in detail, with focus on heat transfer and the overall energy balance of the cooler. Pressure drop over the bed is also included. The model uses sequential solving of a calculation grid, with each cell containing heat transfer, oxidation and pressure drop functions. Figure 3.2 illustrates the grid with inputs and outputs.

To model the physics in the bed in terms of heat transfer, pressure drop, and oxidation, a number of correlations are used. As these typically take into account not only the studied geometry but also fluid and solid properties, relations for such parameters are also included. The model considers the temperature dependence of fluid properties, but for the pellets only static values are used due to poor availability of correlated data. The equations used and their sources are explained below.

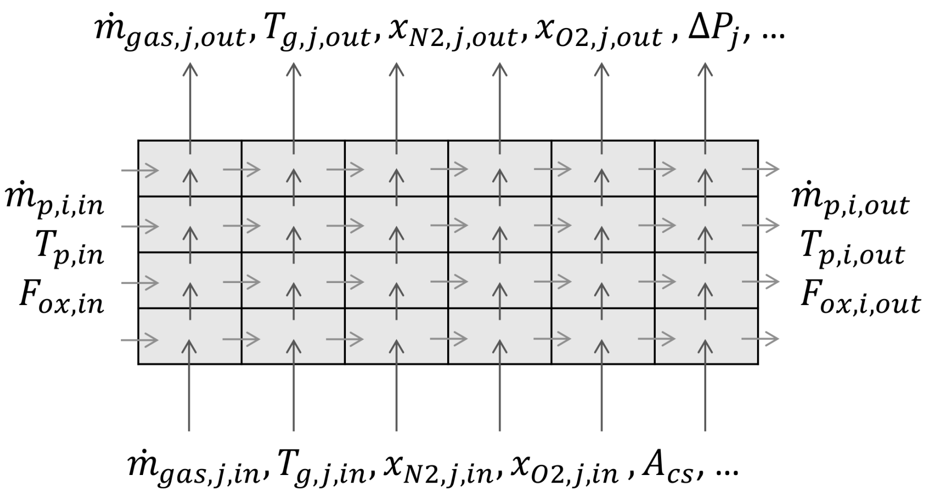


Figure 3.2: Illustration of the cooler model's solver with inputs and outputs. The grid is solved column-wise from the bottom up until results are obtained.

Fluid data

Density is determined by the ideal gas law as a function of temperature and composition:

$$\rho_f = \frac{m}{V} = \frac{n\langle M\rangle}{V} = \frac{P\langle M\rangle}{RT} \tag{3.1}$$

Sutherland's formula is used with the following parameters for dynamic viscosity [13]:

$$\mu = 1.716 \cdot 10^{-5} \left(\frac{T}{273.15}\right)^{3/2} \frac{273.15 + 110.4}{T + 110.4} \quad [\text{Pa} \cdot \text{s}] \tag{3.2}$$

A relation for thermal conductivity on the following form was fitted to data from thermophysical tables [12]:

$$k_f = 16.6 + 42\frac{T}{1000} + 8.68\left(\frac{T}{1000}\right)^2 \quad [\text{mW/m} \cdot \text{K}] \tag{3.3}$$

Air heat capacity is calculated using NASA polynomials for the composite species and then summing [14].

$$c_{p,f} = R \cdot \sum_i c_{p,i} = R \cdot \sum_i a_{0,i} + a_{1,i}T + a_{2,i}T^2 + a_{3,i}T^3 + a_{4,i}T^4 \tag{3.4}$$

Pellet bed properties

The pellets are considered as uniform spherical particles with constant material properties. Pellet diameter, thermal conductivity, heat capacity and specific surface area is of importance to the heat and/or momentum transfer in the bed. A constant thermal conductivity of $k_p = 0.40\,\text{W}\ /\text{m}^2\ \text{K}$ as used by Ljung [15] is implemented along with a heat capacity of $c_{p,p} = 0.88\,\text{kJ}\ /\text{kg K}$ in accordance with Haaf's work [5]. Pellets consist only of hematite and their mass is unaffected by oxidation.

The specific surface area of the pellets in the bed is the area available for heat transfer. By considering the spherical geometry of the pellets Equation 3.5 can be derived for this property, where ϵ is the bed voidage or porosity for which Sandberg [16] provided a value of $\epsilon = 0.38$ for the cooler. Pellet-to-pellet contact area is not considered; the whole surface is in contact with gas.

$$a_{sp} = \frac{6(1-\epsilon)}{D_p} \tag{3.5}$$

Lastly the pellet diameter must be defined as it is a factor in many correlations for heat and momentum transfer. Green pellets are rolled to a diameter of $10 - 14$ mm but in the model only a uniform pellet size, determined by the current source data, is considered.

Heat and momentum transfer

The cooler is modelled as a horizontally moving porous bed of uniformly distributed pellets throughout which gas is permeating in the vertical direction. Lateral gas mixing is not considered. As only the inlet temperatures to each calculation cell are known, the NTU method is utilized. By calculating the effectiveness factor ε for a fixed bed heat exchanger without fluid mixing according to Incroperera et al. [12], here represented as equation 3.6, the amount of heat exchanged can be determined explicitly in spite of unknown outlet temperatures.

$$\varepsilon = 1 - \exp\left[\frac{C_{max}}{C_{min}}(NTU)^{0.22}\left(e^{\left[-\frac{C_{min}}{C_{max}}(NTU)^{0.78}\right]} - 1\right)\right] \tag{3.6}$$

To find the overall heat transfer coefficient U the film heat transfer coefficient in the bed is required, and the following correlation (eq. 3.7) for the Nusselt number was used [17].

$$Nu = 2 + 1.1\ Re^{0.6}Pr^{1/3} \tag{3.7}$$

U was related to the individual resistances (convection to the pellets and conduction inside) in the following manner:

$$U = \left[\frac{D_p}{k_f Nu} + \frac{D_p}{2k_p}\right]^{-1} \tag{3.8}$$

Pressure drop over the bed per unit height H is calculated with the Ergun equation, with u being the superficial velocity, ϵ the bed voidage and ρ the fluid density [18]:

$$\frac{\Delta P}{H} = 150\frac{\mu u(1-\epsilon)^2}{D_p^2\epsilon^3} + 1.75\frac{\rho u^2(1-\epsilon)}{D_p\epsilon^3} \tag{3.9}$$

Oxidation

Oxidation in the cooler model is implemented analogously to the process model [5]. The degree of oxidation is mapped proportionally to oxygen fraction, the temperature in degrees Celsius and the residence time. For this reason a time constant is included in the model's boundary conditions, corresponding to a constant rotational speed of the cooler.

$$F_{ox} = t^{1/4} \cdot \left[f_1(x_{\mathrm{O_2}})T^2 + f_2(x_{\mathrm{O_2}})T + f_3(x_{\mathrm{O_2}}) \right] \tag{3.10}$$

The heat released from a change in fractional oxidation ΔF_{ox} corresponds to this change multiplied by the total amount of heat released when going from $F_{ox} = 0$ to 1, which in turn depends on the initial magnetite content of the pellets and the heat of reaction:

$$\dot{Q}_{ox,max} = \dot{m}_{pellets} \cdot x_{\mathrm{Fe_3O_4}} \cdot \Delta H_{ox} / M_{\mathrm{Fe_3O_4}} \tag{3.11}$$

3.2.1 Boundary conditions

The air is 78.61 % N_2, 20.88 % O_2, 0.03 % CO_2 and 0.48 % water vapor. Fresh air is added at temperatures near 0 °C, similar to the yearly average air temperature in Kiruna [19]. Pellets are admitted at temperatures between 1200 and 1300 °C and distributed evenly along the height of the bed. The residence time is constant, and set to 40 minutes for the whole passage through C1-4.

There is a rather large insecurity in the boundary conditions of the process. The key parameters (air flows and temperatures) vary widely between sources, as does many material properties such as the pellet size distribution. A base case was therefore established from the Bedsim data provided by Sandberg [16], and the sensitivity to changes in these parameters tested which is explained further in the next chapter. Bedsim is an internal tool used by LKAB for modelling the grate-kiln unit's pellet bed. Other data sources include Haaf's process model [5] and process control software screen dumps from KK2. Bedsim boundary conditions were predominantly used when cooler performance was evaluated.

3.2.2 Sensitivity analysis

To investigate whether the new model could provide useful results it was tested with a number of varying input parameters in a boundary condition sensitivity analysis.

The cross-sectional area of the cooler bed when seen from above determines, together with the air flow, the velocity with which the gas passes the pellet bed. The velocity is part of the Reynolds number which determines both the heat transfer coefficient and the pressure drop. It is therefore reasonable to assume that these two parameters have a large influence on the temperature profiles of both pellets and gas throughout the cooler. Furthermore, the mass flow of air through the bed not only affects the velocity of the air for a given cross-section, but it is also of importance for the thermal inertia ($\dot{m}c_p$) of the gas stream. The temperature of ambient air as well as pellet admission temperature were therefore also of interest.

The sensitivity against bed voidage and pellet diameter are also evaluated, as is the correlation for the overall heat transfer coefficient U. A summary of all parameters subjected to sensitivity analysis can be found in Table 3.1.

Table 3.1: Parameters subjected to sensitivity analysis in the cooler model.

Parameter	
$T_{pellets}$	from kiln
T_{air}	fresh air
ϵ	bed voidage
D_p	pellet diameter
$A_{cs,tot}$	total cross-sectional area
$\dot{m}_{tot}$	total air mass flow
U	overall heat transfer coefficient

3.3 Case study of process concepts

Two process concepts were considered in the thesis. The first is a partial recirculation of hot gas from the PH zone to cooler zone 1 (C1). The second is to instead use PH flue gases to preheat the C1 air in a heat exchanger, refered to as the air preheater. Within each case a sensitivity analysis was performed to investigate the impact of the main design parameter, i.e. flue gas recirculation ratio or minimum temperature difference for heat exchange. Two additional concepts based on the first two but using intercoolers between the cooler and the grate are then evaluated.

3.3.1 Flue gas recirculation

By directly connecting the hot stream leaving PH with the cold air entering C1 via mechanisms allowing the regulation of mixing ratio, the effects of direct flue gas recirculation (FGR) were investigated. The connection of streams is presented in Figure 3.3. The variable recirculation ratio was used as the primary design parameter for this concept, and a recirculation ratio of 35 % is considered the standard case throughout the rest of this work.

3.3.2 Air preheating

If the PH flue gases are led in their entirety to C1 but a heat exchanger is used instead of direct mixing, an air preheater (APH) is simulated as shown in Figure 3.4. As it makes little practical sense to only use part of the stream for this, fuel consumption and product temperature is instead plotted against the heat exchanger's minimum driving force as this is a key parameter in the investment of a heat exchanger. 50 K minimum temperature difference is arbitrarily considered the standard case throughout this text. The amount of waste heat added to C1 when using 35 % direct recirculation corresponds approximately to a heat exchanger with 250 K minimum temperature difference.

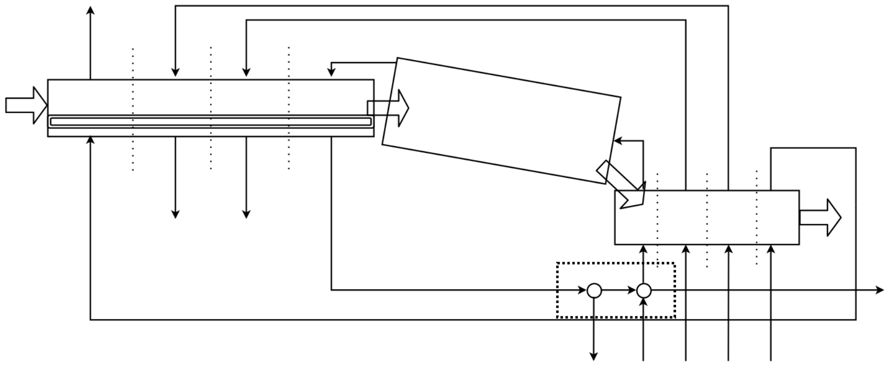


Figure 3.3: Illustration of direct recirculation of flue gas from PH to C1.

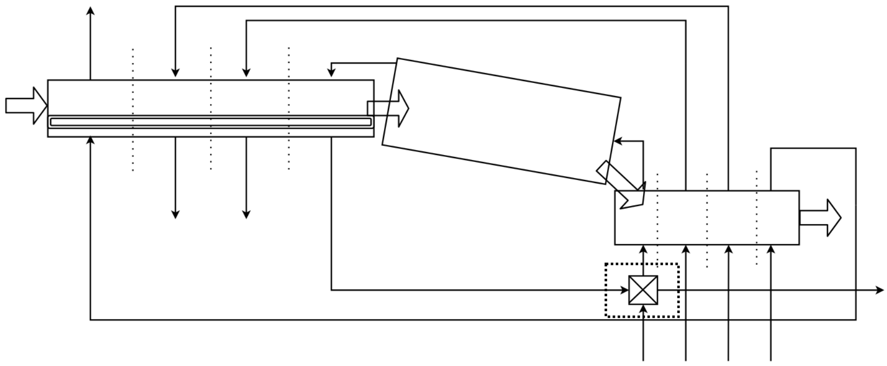


Figure 3.4: The use of a heat exchanger (marked by a dashed box) to preheat the air fed to C1.

3.3.3 C2-TPH Intercooling

In an attempt to utilize PH's waste heat without impacting the grate to any large extent, the two existing cases were supplemented with an "intercooler" between the C2 and TPH zones. This modification served to reduce the temperature of the air stream entering TPH to its normal level, extracting heat to a water stream in the process. The high-temperature heat leaving C2 could in practice be used in a heat recovery steam generator system to drive electricity production. The minimum temperature difference of the intercooler is set to 50 K in both cases.

3.3.4 Double intercooling

Addition of a second intercooler in the C3-DDD channel enables the extraction of more high-temperature heat from the air. Like the C2-TPH intercooling concept, a fixed gas inlet temperature to the grate is maintained.

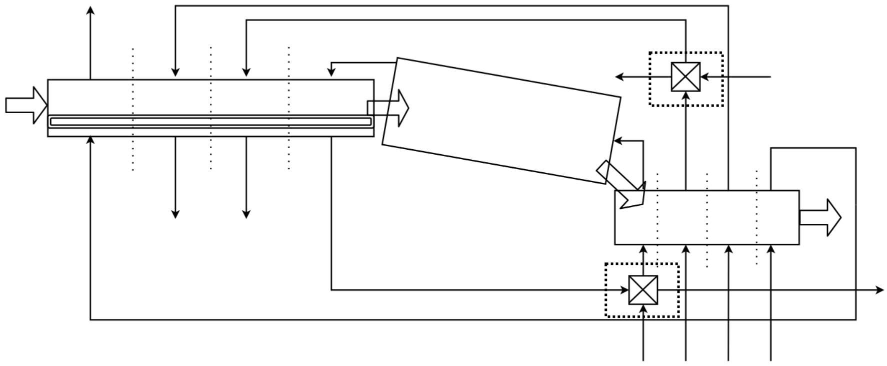


Figure 3.5: Use of air preheater with intercooler (marked by dashed boxes) between C2 and TPH zones to lessen the impact on the grate's temperature profile.

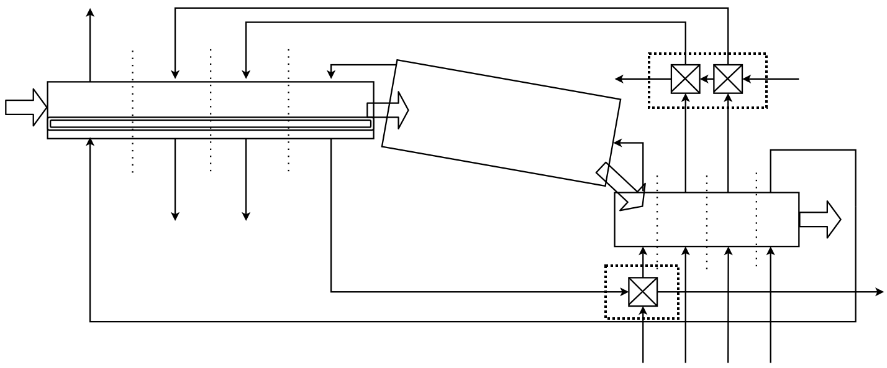


Figure 3.6: Use of air preheater with double intercoolers (marked by dashed boxes) in the C2-TPH and C3-DDD channels to extract heat at two temperature levels.

3.4 Cooler modification concepts

An increase in coolant temperature will inevitably lead to a loss of cooling power for a given gas flow, so for each of the cases described above the product temperature will rise. For each of the studied process concepts, a number of different cooler adjustments to push the product temperature down to its nominal value were tried out. These were investigated using the cooler model developed in the project. The evaluated adjustments are as follows:

- Increased air mass flow in C3 and C4.
- Increased area in C3 and C4 with constant mass flux, leading to longer residence time and more air mass flow.

The first of these can be expected to give a significant increase in pressure drop over the bed, while the second poses practical problems due to the cooler's annular design. The parameter in focus for each case was adjusted until the average product temperature was within 1 °C of that of the unmodified case.

4

Model evaluation

In the following chapter the cooler model is evaluated against data from various LKAB sources in order to assess its viability for use in process improvement. Furthermore, sensitivity analyses are performed to gain understanding of which parameters are the most important to model accuracy and pellet cooling.

4.1 Model output comparison

An overview of model output is shown in Table 4.1.

Table 4.1: Cooler model output.

Parameter			Model result
T_{out}	prod.	°C	90.3
F_{ox}	prod.	%	99.6
T_{out}	C1	°C	1252
	C2	°C	861
	C3	°C	523
	C4	°C	278
Δp	C1	kPa	4.96
	C2	kPa	3.89
	C3	kPa	4.22
	C4	kPa	4.03

The heat removed in the cooler comes from two sources: thermal energy stored in the pellets and heat released from oxidation. Oxidation is controlled by the oxygen content in the air and the temperature of the material and releases an amount of heat approximately determined by the degree of oxidation (F_{ox}) entering the cooler. The largest part of the thermal energy absorbed by the air is however provided by the heat already contained in the pellets, determined by their temperature of admission. An energy balance showed that in Bedsim the oxidation heat amounts to approximately 20 % of the total heat, while in the process model oxidation only gives off some 14 MW in the cooler. Because the oxidation calculations in the cooler model are based on the same oxidation model as used by Haaf, the amount of heat released is the same.

Figure 4.1 shows a contour plot of the cooler's pellet bed temperature. The isotherms in this figure illustrates that heat transfer in the cooler is evenly distributed over the zones.

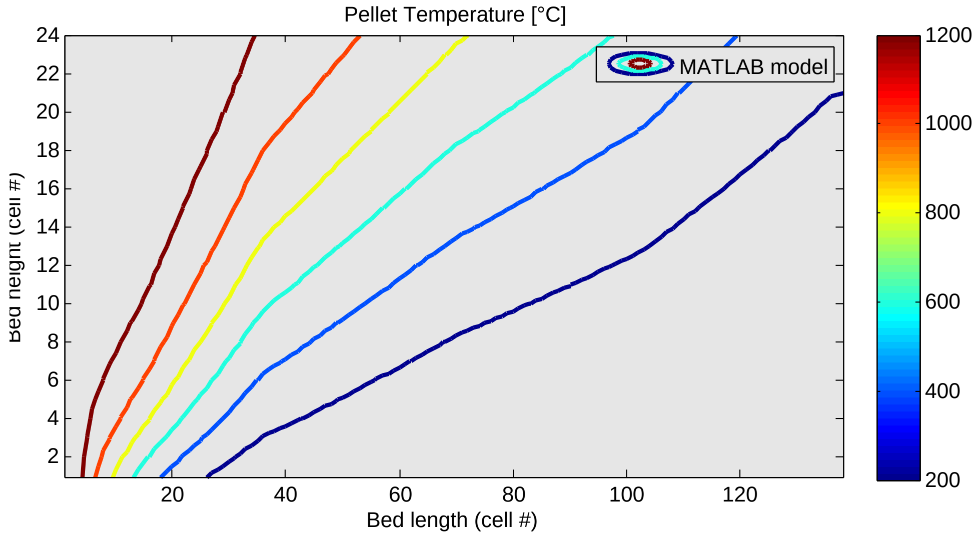


Figure 4.1: Pellet bed isotherms of the cooler model.

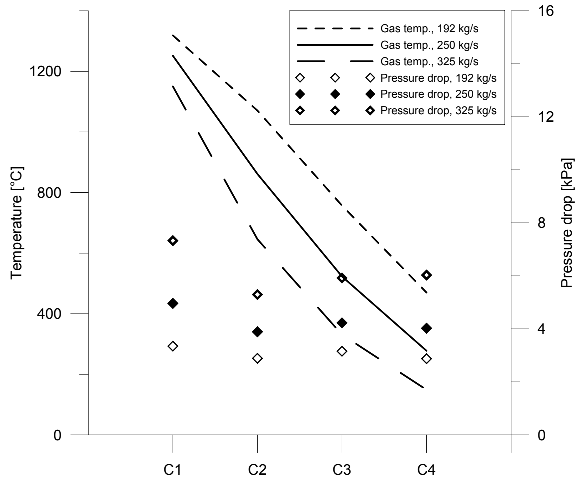
4.1.1 Boundary condition sensitivity analysis

Figure 4.2a shows a plot of gas outlet temperatures in each section varying with the air mass flow, while Figure 4.2b plots the same against the bed voidage for comparison. Figure 4.2c shows the rather small impact of the insecurity in heat transfer coefficient, particularly for the latter zones.

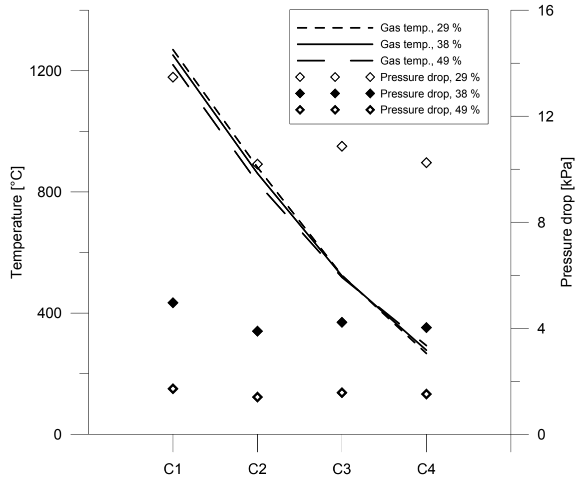
It was shown that the velocity, adjusted by changing the cross-sectional area while keeping mass flow constant, only has a negligible effect on the cooler's performance in the model. The thermal inertia of the gas stream can thus be concluded to be the phenomenon of most importance with respect to the flow. The ambient air temperature does not significantly affect this property when kept within reasonable limits, as any difference in inlet temperature is negligible in comparison to the temperature difference between gas inlet and outlet. The pellet admission temperature does affect the results quite strongly, but is relatively well-specified in the boundary conditions (1225-1300 °C, too small of a difference to be of importance).

Bed porosity and pellet diameter appeared to give negligible effects on heat transfer in the regions investigated. They do however influence the pressure drop strongly.

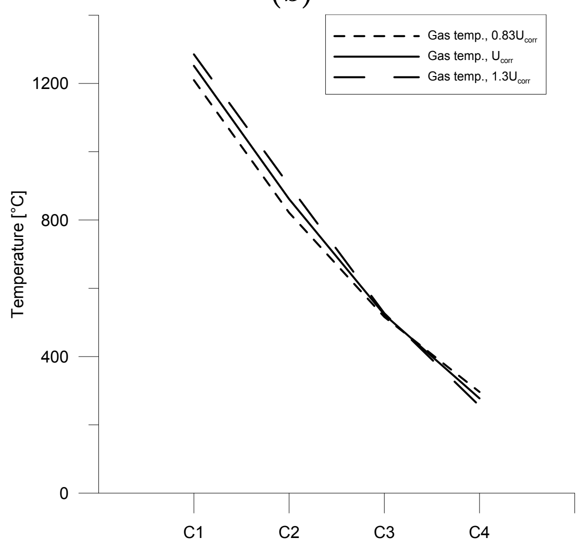
The overall heat transfer coefficient U is determined for each cell through a packed bed correlation (equation 3.7). A multiplying factor was applied to the calculated U and varied over a range from 83 % to 130 % of this value to assess the influence of any insecurity in the correlation, and it appears that the heat transfer coefficient plays a relatively small role in determining the gas outlet temperature.



(a)



(b)



(c)

Figure 4.2: Sensitivity analysis of various parameters' impact on the final average gas temperature leaving C1-4 and the pressure drop over each section. 4.2a) Air mass flow through a constant cross-sectional area. 4.2b) Bed voidage ϵ with constant pellet diameter. 4.2c) Overall heat transfer coefficient U. U_{corr} is the U value as determined by the correlation.

5

Case study – results and discussion

This chapter discusses the proposed process concepts. Rresults are presented with respect to energy savings and other findings. A discussion on why and how these savings are achieved follows. Finally the consequences of each modification on product temperature and the cooler performance are discussed.

5.1 Process modification

The results obtained from simulation of each process concept in both models will be described in each respective section below along with a discussion of the results.

5.1.1 Flue gas recirculation

Figure 5.1 shows how fuel consumption in the modelled process is affected by the recirculation ratio as well as how efficiently the waste heat is utilized in the form of the ratio between reduction in fuel consumption and the amount of heat added. The 35 % case gives a decrease in fuel consumption of 1.8 MW or 5.2 %, with a product temperature increase of 40 °C according to the cooler model. The fractional oxidation of the product is decreased from 99.3 % to 99.1 % when direct recirculation is applied.

By using flue gas recirculation, the temperature into the cooler increases, but the oxygen content of the C1 air decreases. As this air is then passed through the kiln and into the PH zone where oxidation takes place, the lower oxygen content is thought to be the main drawback with direct recirculation. A heat balance over the process was established to evaluate how the heat and oxidation distribution changes with this process modification, the results of which is shown in Figure 5.4.

Recirculation increases the overall temperature levels in the streams leaving the cooler leading to an earlier temperature increase of the pellets in the grate. The higher temperature in the TPH zone increases the fractional oxidation change over this section, but in the PH zone the amount of oxidation decreases. This is thought to arise from the lack of oxygen after the kiln.

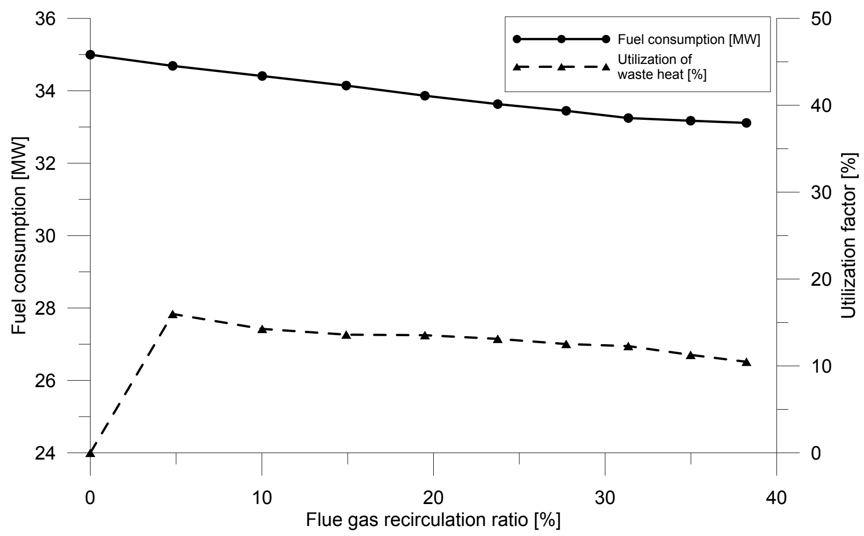


Figure 5.1: Fuel consumption and utilization factor (ratio between saved fuel and added waste heat) as function of flue gas recirculation ratio in the direct FGR case.

The energy balance over the kiln shows that the reduction for 35 % recirculation was 1.8 MW of fuel input, and the main contribution to the fuel saving is that the inlet pellet temperature to the kiln is increased. It was found that the temperature of the ingoing pellets increases both due to higher air temperatures in the grate and due to an increase of oxidation heat released by the pellets in TPH.

5.1.2 Air preheating

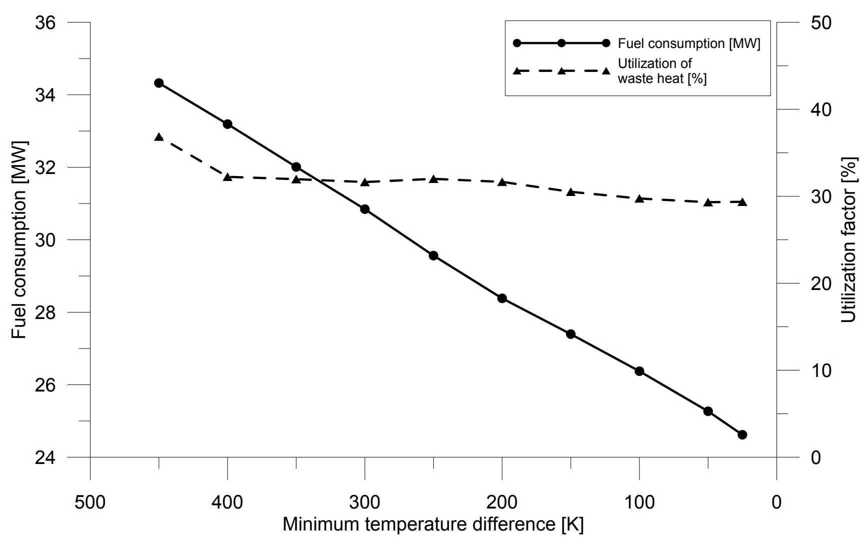


Figure 5.2: Fuel consumption and utilization factor (ratio between saved fuel and added waste heat) as function of minimum temperature difference for heat exchange in the air preheater case.

With 50 K minimum driving force the air entering C1 can be preheated to a maximum of 575 °C which leads to a fuel saving of 9.8 MW or 29 %. Without modifications to the cooler, the average product temperature increases by 67 °C. The average fractional oxidation is > 99.9 % at the end of the cooler. An energy balance over the kiln showed that the increased temperature of the ingoing pellet stream gives the largest contribution to the reduction in fuel consumption.

By using an air preheater to heat the ingoing air to C1 with flue gas, the air temperature increases without the reduction in oxygen content associated with direct recirculation. One can therefore expect to reap the benefits of the latter case without the negative influence on oxidation.

5.1.3 C2-TPH Intercooling

The two main concepts were both expanded upon with an intercooler between C2 and TPH. When limiting the ingoing stream to TPH to its normal temperature in the air preheater case, air is leaving C2 at 867 °C. A heat recovery of up to 9.94 MW was possible to achieve in the intercooler as shown in Figure 5.3. The fuel consumption in the kiln also decreases with 4.8 MW in comparison with the standard case due to the slightly higher temperature leaving C1 when air preheating is used. This reduction thus corresponds to about half of what can be achieved with the basic air preheater concept, but with the added benefit of allowing a substantial heat extraction.

The same intercooling modification was applied to the recirculation (35 %) case. Here 6.27 MW could be extracted in the intercooler to bring the stream down to normal temperature. Unlike the intercooler with air preheater this setup *increases* the fuel consumption of the process by 1.63 MW, presumably due to the reduced oxygen content in PH and the kiln. With decreased recirculation ratio a linear behaviour in the amount of heat extracted can be observed.

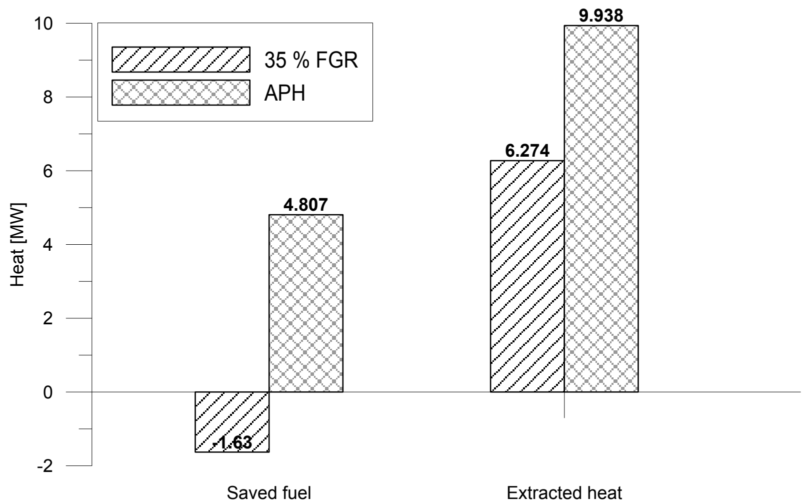


Figure 5.3: The amount of fuel saved and heat extracted in the intercooler when the C2 off-gas is brought down to 700 °C before entering TPH. Note that intercooling in the 35 % recirculation case increases the fuel consumption.

5.1.4 Double Intercooling

The double intercooler concept was only tested for the air preheater design. This concept allowed a secondary extraction of up to 5.9 MW at an intermediate temperature when coupled with 30 % increased C3 and C4 area. The cooler modification is further described in the section below. Without modification to the cooler, the benefit in extracting heat from the C3-DDD stream was deemed negligible. No successful process model simulations were obtained for the double intercooler case.

5.2 Temperature profiles and oxidation

In the direct recirculation concept, the lower oxygen content in the kiln causes the pellets to be less oxidized (approximately 5% smaller fractional oxidation compared to the unmodified process) when they enter the cooler. In the latter the oxygen content is then suddenly increased while temperatures are still high, leading to more oxidation in the cooler than usual. This oxidation heat may be considered wasted, as high pellet temperatures are desirable in the grate and kiln and not in the cooler. The oxidation model is however a cause for uncertainty, and experimental confirmation would be valuable in the future.

By comparing the process concepts to the unmodified process in Figure 5.4 it is rather clear that the air preheater case is beneficial to promote oxidation on the grate, should this be desirable. The main differences in oxidation heat lies in the TPH zone, but for the direct recirculation case oxidation in the PH zone is suppressed. Because of how the process model is set up, the air preheater causes the kiln to consume less oxygen for combustion which then leads to a higher than normal oxygen content in the air led to PH. In practice a reduction in fuel input may have to be accompanied by a lowered airflow past the burner to keep a stable flame, which might mitigate this effect. Hot air may then be bled from the C1-burner stream to the C2-TPH stream, further increasing the temperature in TPH.

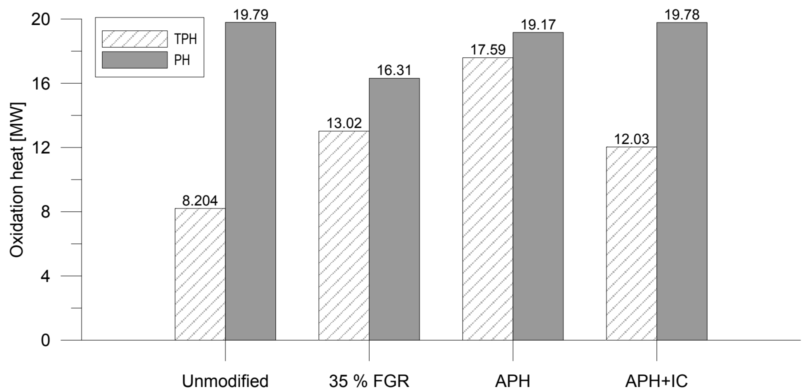


Figure 5.4: Oxidation heat released by pellets in the different zones of the grate. The unmodified case is from Haaf's process model [5].

By using a special modification of the process model where the air fed to C1 could be diluted with additional nitrogen to decrease the oxygen content, the oxidation process' dependency on oxygen and temperature could be decoupled. It was found that a lower oxygen content alone had a completely negligible impact on the pellets' temperature profile, which contradicts the results obtained regarding the flue gas recirculation case. The cause of the low waste heat utilization experienced with flue gas recirculation is thus not completely investigated. The uncertain accuracy of the oxidation model is thought to be part in this behaviour.

Increased oxidation in the TPH zone is also thought to be a cause of the higher temperature in the air preheater concept when compared to the 35 % recirculation case. Because oxidation rate increases with temperature an increase in oxidation should accelerate further oxidation, and these effects combined are seen as the main cause of both the increased temperature and oxidation heat released in TPH and PH and the reduced fuel consumption of the process.

Figure 5.5 shows a contour plot of the temperature distribution in the cooler for two cases: ambient air at 0 °C and preheated air at 575 °C. The isotherms displayed exhibit the expected behaviour; when C1 air enters at a higher temperature, cooling is worsened in that zone and the contours are pushed to the right, giving higher temperatures in the whole cooler but keeping the general shape of the distribution.

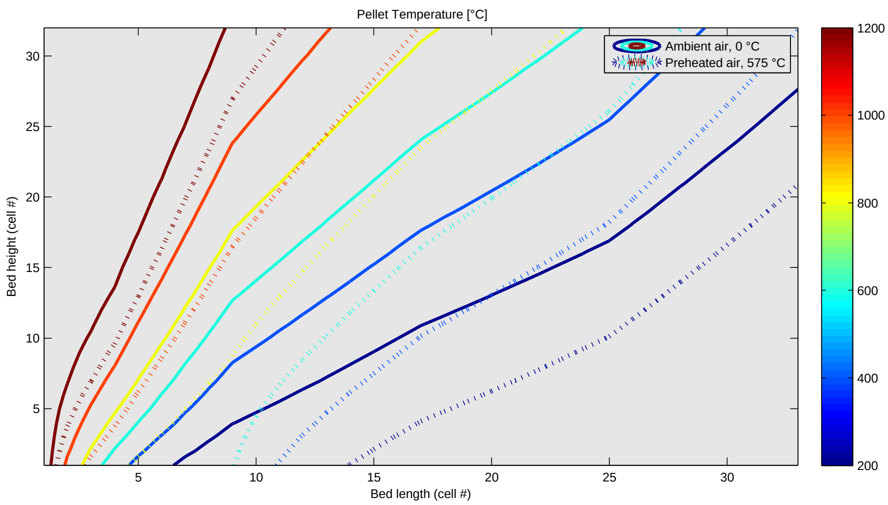


Figure 5.5: Comparison between the pellet bed isotherms in the cooler with ambient and preheated air.

5.3 Restoring pellet cooling

The increase in product temperature experienced when heat is recovered from PH flue gases is compensated by various modifications to the cooler analyzed with the cooler model. Table 5.1 shows the different input parameter setups used in the various runs, corresponding to the concepts investigated in section 5.1 above.

Table 5.1: Boundary conditions for the cooler model of the investigated cases.

Case	T_{C1}	$x_{O2,C1}$	F_{ox}
Unmodified	0 °C	20.9 %	83.3 %
35 % FGR	325 °C	17.0 %	79.5 %
APH	575 °C	20.9 %	88.8 %
APH+Intercooler	410 °C	20.9 %	84.8 %

5.3.1 Cooler modifications

The different operational parameter adjustments used to reduce the product temperature to its nominal value are described in the paragraphs below.

Increased mass flow over constant area

Table 5.2 presents how much increase in airflow through C3 and C4 is required to keep the product temperature to the original level.

Table 5.2: Product temperature obtained in each case before compensating measures along with the required mass flow boost in C3 and C4 to bring the temperature down to the same level as in the unmodified case. The table also shows the resulting gas temperatures leaving C3 and C4 after flow has been increased. The unmodified case is also presented for comparison.

Case	$T_{product}$	Flow increase	$T_{C3,out}$	$T_{C4,out}$
Unmodified	90.3 °C	N/A	523 °C	278 °C
35 % FGR	130.6 °C	40 %	545 °C	256 °C
Air preheating	157.2 °C	60 %	552 °C	242 °C
APH+Intercooler	138.8 °C	50 %	545 °C	244 °C

Increasing the mass flow by an equal factor in both C3 and C4 has the effect that C3 off-gas attains a slightly higher temperature than when unmodified, while the temperature from C4 becomes somewhat lower. In the real process (KK2) the air to UDD and DDD must currently be diluted to bring its temperature down, so this is not seen as a problem. The main drawback with this solution is the rather large increase in mass flow required coupled with a nearly doubled pressure drop over the bed.

Increased area with constant mass flux and longer residence time

Table 5.3 shows results obtained from this trial, conducted analogously to the case with mass flow boost.

The key difference here, practical concerns aside, is that the temperature now increases both from C3 and C4 and in the case of C3 by quite a significant amount. As the mass flux is kept constant when the area increases, the streams are also larger. The extra heat contained in the C3-DDD stream may therefore in this case also be a suitable heat source for an intermediate extraction in the double intercooler case. Bringing the C3-DDD stream down from 613 °C to 523 °C will release approximately 5.9 MW for use in e.g. a steam generator.

Table 5.3: Product temperature obtained in each case before compensating measures, along with the required area boost in C3 and C4 to bring the temperature down to the same level as in the unmodified case. The table also shows the resulting gas temperatures leaving C3 and C4 after area has been increased. The unmodified case is also presented for comparison.

Case	$T_{product}$	Area increase	$T_{C3,out}$	$T_{C4,out}$
Unmodified	90.3 °C	N/A	523 °C	278 °C
35 % FGR	130.6 °C	25 %	626 °C	296 °C
Air preheating	157.2 °C	40 %	652 °C	308 °C
APH+Intercooler	138.8 °C	30 %	613 °C	297 °C

6

Design suggestions

This chapter proposes concepts that are of interest to investigate further to either decrease the fuel consumption of the process or to generate a valuable source of high-temperature heat. Besides energy efficiency special attention is given to how changes in temperature and oxygen profiles experienced by the pellets will affect the product.

6.1 Proposed process modifications

Three process concepts have been subject to a comparative study. Because of the larger fuel savings with an air preheater than with direct flue gas recirculation, and since conditions for heat exchange are rather good with large driving forces, an air preheater was chosen as the basis for all recommended concepts. The concepts in order of the amount of extra equipment required for implementation are:

1. Implementation of an air preheater to gain extra pellet heating in the TPH and PH zones.
2. Implementation of 1. plus an intercooler to minimize the impact on the grate.
3. Implementation of 1. and 2. plus lengthening the cooler and using the additional temperature gained in C3 to extract more heat before the gas reaches the grate.

6.1.1 Air preheating

Implementing an air preheater lowers the fuel input needed to heat the pellets in the kiln at the same time as it favours oxidation on the grate. This process concept is rather simple to implement as it does not require internal modifications to the grate-kiln unit but only requires additional piping and a heat exchanger. Conditions for gas-gas heat exchange are relatively good compared to many power plant air preheater applications and such devices are commonly made for large flow volumes, so the equipment should be available from suppliers of boiler auxiliaries. The thermal performance of the heat exchanger can be chosen by selecting a different minimum temperature difference; increasing the driving force to 100 K was still found to save

25 % of the fuel while using only 65 % of the heat exchanger area of the 50 K case. Heat exchanger area can here be seen as approximately proportional to investment cost, and there is thus an opportunity to balance the cost of the saved fuel against the investment. Going further to 200 K minimum temperature difference saves 19 % fuel at only 30 % of the base case's area.

The hotter air fed to the grate promotes oxidation in TPH, while the lower fuel input causes less oxygen to be consumed in the air passing the kiln. The temperature and oxidation profiles of the pellets are therefore significantly altered, which may pose a problem to the pellet heat treatment. Furthermore, no cooler modification is suggested with this proposal, leading to higher product temperatures.

- 30 % reduction in fuel with 50 K minimum temperature difference.

+ Large fuel saving potential with simple measure and readily available equipment.

− Pellet heat treatment process may be disturbed.

− Large product temperature elevation without cooler modifications.

6.1.2 Air preheating with intercooler

This case does not focus on decreasing the fuel consumption of the process, but instead creates a valuable and useful stream of high-temperature heat suitable for e.g. electricity production. This is achieved by heating the air going to C1 with PH's flue gas like in the air preheater case to lift the overall temperature level in the cooler, causing air to leave C2 with a higher (+150 °C) temperature. The air is then brought down to the unaugmented temperature in a second heat exchanger, likely designed as a heat recovery steam generator.

Using an air preheater with intercooling between C2 and TPH provides a rather large amount of heat ($\sim$ 10 MW) at a very high temperature, suitable for evaporation and superheating of steam. Common unfired heat recovery steam generators can operate at gas inlet temperatures well below the temperature level in question, so this system can be considered a relatively standard piece of equipment as well.

If an additional stream of intermediate-temperature heat becomes available it could be used for feed water heating and economizing, which would enable more steam to be produced in total without changing the mass flow or temperature of the gas leaving C2 or the total fuel input to the process. This proposal also leads to a fuel reduction of 15 % while still avoiding reconstruction of the grate and kiln. Without cooler modification proposals this concept also leads to a higher product temperature.

- 15 % reduction in fuel and 10 MW heat extraction at a high temperature.

+ Effective waste heat upgrade to a high temperature using standard equipment.

+ Reduced change to pellet temperature profiles.

- Uses multiple gas-gas heat exchanger systems.
- Large product temperature elevation without cooler modifications.

6.1.3 Air preheating with double intercoolers

It was found during the case study using the cooler model that by making C3 longer while maintaining the same superficial velocity of the gas, the air leaving it would increase in temperature. This would in turn enable the inclusion of an intercooler into the C3-DDD channel as well, or in practice the use of this stream in the heat recovery steam generator e.g for feed water heating or in a dual-pressure system. The second intercooler could extract a new stream of approximately 6 MW at an intermediate temperature. Making the cooler longer would lead to a product temperature close to the original level without increasing the pressure drop. However, this design suggestion is much more difficult implement as the cooler is circular and likely has to be reconstructed.

- 10 MW plus 6 MW heat extraction at two temperature levels.

+ Recovers close to half of the fuel's heating value at a high temperature.
+ Incorporates additional pellet cooling to ensure a low product temperature.

- Requires difficult cooler modification.
- Uses multiple gas-gas heat exchanger systems.

7 Conclusions

The present work has evaluated direct and indirect heat recovery of waste heat in the grate-kiln process through process simulations of LKAB's KK2 unit.

The process modelling showed that utilization of the waste heat contained in PH's flue gas could reduce the fuel consumption of the process by up to 30 %. By increasing the temperature of the gas entering C1 the amount of heat contained in all the streams leaving the cooler can be increased, which boosts the pellet temperature and the oxidation on the grate. With hotter pellets entering the kiln less fuel is needed to reach the temperature required for sintering.

Direct flue gas recirculation to C1 leads to poor utilization of the available waste heat, presumably as the oxygen content of the air is reduced. The use of a heat exchanger appeared a promising solution, and the three process modifications finally suggested all make use of this approach. A higher oxygen content in the C1-kiln-PH gas stream than with direct flue gas recirculation was thought to be the reason behind this improvement, but it was found that the process model does not capture any change in oxidation behaviour when the temperature profile is kept unaltered and the oxygen content of the gas is lowered.

Because of the cooler's dual function in supplying the grate and kiln with hot air and cooling the pellets, the latter function had to be evaluated in terms of performance. With increased C1 temperature the cooling power was decreased. The cooler model showed that lengthening the C3 and C4 zones to increase the residence time was the most beneficial approach to maintain the cooling effect. The thermal inertia of the air was also found to be much more of a limitation for pellet cooling than heat transfer.

7.1 Future work

Future work to ensure successful implementation of the proposed concepts should focus on two main aspects: how the product is affected by altered temperatures and oxygen levels throughout the process, and improvement of the process model in terms of robustness and flexibility.

7.1.1 Experimental investigation

Any modifications to the process will alter the temperature profile of the pellets travelling through the process and the oxygen content of the surrounding air. The modelling tools used in this project can not adequately describe how the quality of the product will be affected by these changes. Experiments should therefore be conducted to find how temperature and oxygen variations, mainly in the grate and kiln, will impact the product.

7.1.2 Process model

Although the model made in EBSILON Professional gives acceptable results, the model is based on several simplifications and its results become less reliable when changes are made to the simulated process. Furthermore, the process model is designed after the KK2 unit and alterations to certain boundary conditions, such as air flow and duration time, causes severe convergence problems. This low robustness limits the model's usability in investigating energy-efficiency improving measures.

As the oxidation of magnetite emits a large amount of energy and stands for more than half of the heat needed in the process, it is one of the most crucial parameters influencing the process behaviour. The current oxidation function should be evaluated further and if need be, replaced or improved. The results from this thesis also showed that the heat supplied to the grate has a large impact on the fuel input, so work on the model should be focused on improving the accuracy and reliability of this part of the process. Another factor which should be improved is the constant specific heat for the pellets. By implementing a more accurate specific heat function the oxidation modelling, strongly dependent on temperature, should gain in accuracy as a result.

7.1.3 Cooler model

While the cooler model was decided to be adequate within the scope of this thesis, a more accurate description of the actual cooling process could be helpful in further development of the grate-kiln units. A few key points of improvement were identified and are described below.

Oxidation
The way that oxidation is implemented in the cooler model is incomplete, with only heat release and oxygen consumption but no conversion between magnetite and hematite in terms of physical and chemical properties. It may well be so that this crude implementation is sufficient to model the small amount of oxidation thought to take place in the cooler, but this is currently a point of insecurity.

A better subroutine for oxidation would encompass a pellet stream containing both magnetite and hematite, with the stream's properties decided by the fractional oxidation.

Boundary conditions

The uncertainty in e.g. temperature levels and mass flows present in the grate-kiln process as exemplified by KK2 both makes it difficult to find accurate boundary conditions for process modelling and hinders evaluation of simulation results against the modelled process. Development of a better, more complete parametrization of KK2's operational parameters could serve to greatly facilitate future modelling work on the subject.

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