Energy system optimization for a scrap based steel plant using mixed integer linear programming

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Abstract: In this work a mathematic model to simulate and optimize the energy system of a scrap based plant has been developed. Scrap based steelmaking is an energy intense production system. The potential for energy saving by system optimization is therefore high, even if the percentage of saved energy is relatively small. The model includes scrap pre-treatment, electrical arc furnace, ladle furnace and continuous casting units. To estimate the chemical compositions of the scrap charged into the EAF a statistical model based on an existing EAF plant has been used to provide the inputs to the model. Distribution factors have been used to describe the distribution of elements and oxides between the steel, slag and off gas/dust. To calculate the energy consumption in the electrical arc furnace a combination of an empirical and theoretical energy formula has been used. The model represents a general description of the most common process in electric steelmaking. It is suited to be adapted for specific plants with adjustments to the model parameters. The model gives reasonable results which follow the chemical composition of steel and slag and yield. The model can be a powerful tool to optimize the scrap mix and injectants towards energy and costs.

Keywords: *Energy systems, optimization, steelmaking, EAF, MILP, linear programming*

1. Introduction

Energy has been and will always be one of the most important production factors in the iron- and steel industry. In Sweden approximately one third of the total steel production is produced in electrical arc furnaces (EAF) and two thirds in basic oxygen furnaces (BOF) [1].

In the steel industry system, several processes are often connected together. A change in one process unit may result in unpredicted changes in other parts of the system. A literature study has been made of the best available technique and state-of the-art processes to decrease the specific energy consumption in the electrical arc furnace steel making.

The purpose of this work is to create a mathematic model to simulate and optimize the energy system of an EAF plant. In the past similar work has been made on the integrated blast furnace route energy system [2]. It is likely to presume that the scrap based steelmaking will increase in the future and more efforts will be spent to optimize the energy used in this area.

For the scrap based steel plant, it is often difficult to know the exact chemical compositions of the scrap charged into the EAF. In this work a scrap material statistical model based on an existing EAF plant has been used to provide the inputs to the model. The process steps in scrap based steelmaking are raw materials handling, pre-treatment EAF scrap melting, steel and slag tapping, ladle furnace treatments and casting.

1.1. Scraped based steel plant

With respect to the end-products, distinction has to be made between production of ordinary, so-called carbon steel as well as low alloyed steel and high alloyed steel/stainless steel. In the EU, about 88 % of steel production is carbon or low alloyed steel.

1.1.1. Energy consumption in electrical steelmaking

Electric arc furnace steelmaking uses heat supplied from electricity that arc from graphite electrodes to the metal bath to melt the solid iron feed materials. Although electricity provides most of the energy for EAF steelmaking, supplemental heating from oxy-fuel burners and oxygen injection is used. To produce EAF steel, scrap is melted and refined, using a strong electric current. Several process variations exist, using either AC or DC currents and fuels can be injected to reduce electricity use.

EAF steelmaking can use a wide range of scrap types, as well as pig iron, direct reduced iron (DRI/HBI) and hot metal. The EAF operates as a batch melting process, producing heats of molten steel with tap-to-tap times for modern furnaces of 30 minutes [3]. Current on-going EAF steelmaking research includes reducing electricity requirement per ton of steel, modifying equipment and practices to minimize consumption of the graphite electrodes, and improving the quality and range of steel produced from low quality and low cost scrap.

The best practice EAF plant is state-of-the-art facility with eccentric bottom tapping, ultra high power transformers, oxygen blowing, and carbon injection. The “best practice” is to use as much scrap as possible, as melting of DRI/HBI requires more energy. An efficient electric steelmaking plant with 100 % scrap as iron bearers has an electrical energy consumption of 409 kWh/t liquid steel for the EAF and 65 kWh/t liquid steel for gas cleaning and ladle refining, as well as 42 kWh/ton liquid steel of natural gas and 8 kg/t liquid steel of carbon [4].

There are various techniques to decrease the energy consumption for scrap based steelmaking. The Best Available Technique (BAT) to consider is to preheat the scrap and to replace the continuous casting, hot rolling, cold rolling and finishing with thin slab casting, also called near net shape strip casting [5]. The two most common methods to preheat steel are the CONSTEEL process and the post combustion shaft furnace (FUCHS). The electricity savings reported are 60 and 100 kWh/t liquid steel respectively [6]. An example of a thin slab casting technique is the Castrip® process. Potential energy savings are estimated to be 80 to 90% over conventional slab casting and hot rolling methods [7].

2. Methodology

The method used in this work is a model for industrial systems where the process is described as a network of nodes (sub-processes) which are connected by energy and material flows. The potential of this method is that it enables a simultaneous representation of the total industrial system, and that it makes it possible to optimize the whole system, in contrast to the optimization of each sub-process individually. The method is described by Nilsson [8], and later developed for complex material production systems by others [9]-[11].

The method is based on Mixed Integer Linear Programming (MILP). The model described in this paper contains no integers. There are four main nodes that symbolize the different processes in the system. These are a pre-treatment node, an electric arc furnace node, a ladle furnace node and a continuous casting node. There are nodes that provide the main processes with resources such as raw material, slag formers, alloys, energy sources and destination nodes for products and by-products.

2.1. Scrap pre-treatment

The scrap pre-treatment nodes main function is to summarize the different ingoing elements and oxides from each scrap grade and slag former, and transport them to the EAF node. There is one flow for each element or oxide. There is also a possibility to restrict the amount of each scrap grade or slag former going into the EAF. As well as it is possible to set boundaries on each scrap grade it is also possible to set a fixed scrap recipe. Fig. 1 describes the ingoing and outgoing flows for the scrap pre-treatment node.

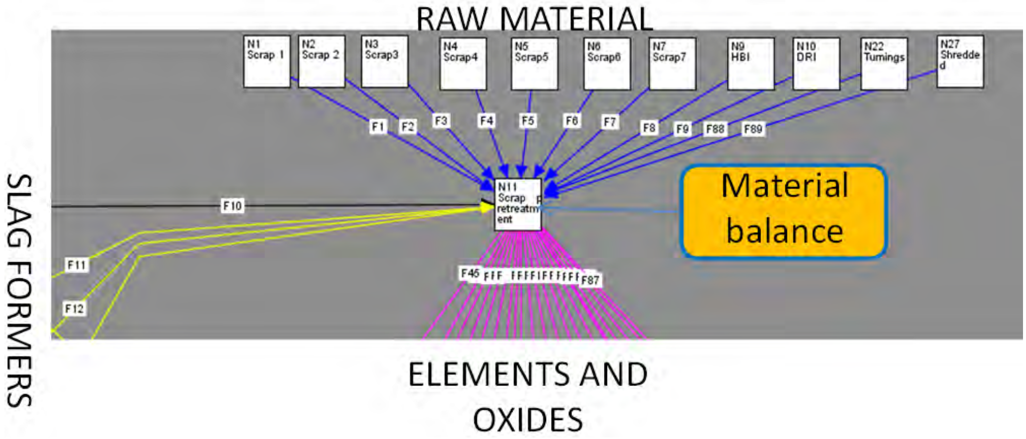

Fig. 1. Ingoing and outgoing flows for the scrap pre-treatment node

The chemical composition of scrap grades have a tendency to vary over a period of time as well as from heat to heat. For the raw material with well-known chemical composition the content are written according to that [12]-[14]. For scrap grades that have a more uncertain chemical composition the values have been estimated with multiple linear regression (OLS – Ordinary Least Squares) or "by hand".

Process data from approximately 1400 melts have been used in the OLS regression analysis. The data contained information about both scrap mix and steel analysis and an assumed distribution factor for each element/oxide to steel in the EAF for each element. From this information a material balance was made. The outgoing flows from the pre-treatment node represent the weight of each element and oxide and total weight of charged material.

2.2. Electric arc furnace

Ingoing raw material to the EAF node is the different amount of each element and oxide that is determined in the pre-treatment node. As ingoing material there are also three types of slag formers. Carbon and fuels in form of natural gas, LPG and oil are represented. The electrode consumption is also represented as an ingoing flow. The ingoing gases are nitrogen for stirring, oxygen from lance and air leakage from slag door and from off-gas duct opening after the 4th hole. There are three different flows for by-products; flue-gas, slag and dust. Fig. 2 describes the ingoing and outgoing flows for the electrical arc furnace.

All incoming elements and oxides from all sources are treated in a material balance. A very central part of this node is the distribution factor table between steel, slag and off-gas/dust. This table decides how much of each element that remains in the steel and how much that are transferred to the slag or off-gas. The distribution factor for an element/oxide applies for the sum of that element/oxide for all incoming flows. The distribution coefficients have been determined statistically by calculation of average weights and concentration of elements and oxides in steel, slag, dust and off-gas.

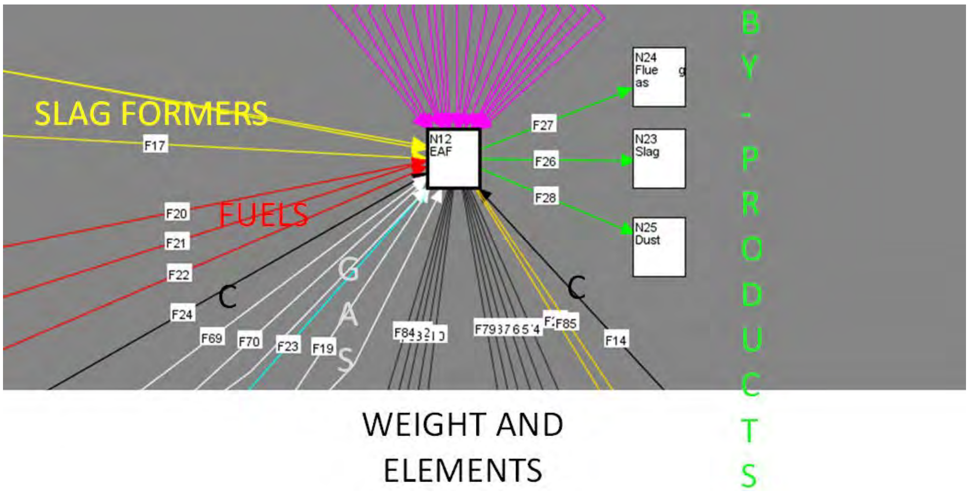

Fig. 2. Ingoing and outgoing flows for the EAF node

2.2.1. Energy calculation

For calculations regarding energy consumption for the electric arc furnace one empirical formula (Köhle-Formula) [3, 15] and a theoretical formula (Adams' formula) [16] has been used. Köhle's formula determines the electrical energy demand based on the use of other energy carriers, added materials, tapping temperature and tap-to-tap time. The Adams' formula determines the total energy consumption where quantities of non-electric energy are converted into kWh. The coefficients in the Adams formula have been used to assign "energy costs" for chemical fuel (kWh/kg or kWh/Nm^3) so that a "cost function" (kWh) for total energy consumption can be defined.

All the values that are needed for the formula are selected from the calculations or flows in the model. The values that are fixed constants are tapping temperature, power on time and power of time. Hot metal is not included in the model but there is a possibility to add it in the pre-treatment node along with the chemical analysis and also include it as a factor in the Köhle formula.

In the EAF-node there is an equation for pre-heating of scrap. The user can choose the preferred pre-heating end temperature of the charged scrap. If this function is activated this will also affect the electric consumption that is calculated. The energy added to the scrap is calculated with a fixed heating value (Cp) for the scrap mix. The Cp value has been estimated as the average value in the temperature range of 0 to 500 °C [17]. The reduced electric energy is calculated from the added energy value multiplied by the efficiency factor of the electric arc furnace.

2.2.2. Assumptions

It should be noted that factors for Oil and LPG are included in the Adams formula but not in the Köhle formula. Factors for Oil and LPG were therefore added to the Köhle formula as well. For calculation of these additional factors to the Köhle formula it was assumed that the heat transfer efficiency to the scrap/steel is the same for all kinds of chemical fuel (natural gas, oil and LPG). Then the factors for oil and LPG in the Köhle formula can be estimated as the factor for natural gas in the Köhle formula multiplied by the ratio of the factors for oil/LPG and natural gas in the Adams formula (11/10.5 for oil and 8/10.5 for LPG).

It is possible to set specifications for the steel chemistry. This is made by restricting the calculations to fit the minimum and/or maximum allowed concentrations of each element in the steel. The slag weight must be greater than 7% of the steel weight and the amount of MgO in the slag must be greater than 8% of the slag weight. The slag basicity (CaO/SiO_2) is restricted to a constant that is determined by the user.

There are calculations regarding the off gas in two stages of the process, one calculation at the so called 4th hole and the other after the slip gap of the off gas duct. The calculations have been made in this way to show the post combustion energy potential of the off-gas before the air leakage in the slip gap. The calculations of the flue gas are depending on a number of assumptions. All C and H from the incoming flows leave the steel bath as CO and H_2 except the contribution from the burner fuel, which is completely combusted to CO_2 and H_2O. All Zn from ingoing flows that ends up in the dust leave the steel bath as Zn(g). These gases react with the air coming from the slag door and with the post combustion oxygen from the burners. At this point all the Zn(g) is oxidized to ZnO and the O_2 that is left reacts with CO and H_2 and generates CO_2 and H_2O. This reaction occurs according to a fixed distribution where a defined percentage of the remaining oxygen after Zn oxidation reacts with the CO and the rest with H_2. At the slip gap at the off gas duct it is assumed that there will be enough air flow for a complete combustion of the remaining CO and the H_2 in the off gas. The amount of excess oxygen in the flue gas after the slip gap is set to a constant.

2.3. Ladle furnace

The steel is going into the ladle furnace node with one flow for each element represented in the liquid steel. In this node there is a function where the user specifies the final steel weight. If a specified scrap weight and scrap mix is used there is a need to disable this function for the model to work properly. There is the opportunity to use the three slag formers that are used in the EAF node as well as a synthetic slag former. The model offers the user to add different kinds of alloys to the steel. The most common alloys that are available have been added but it is possible to add additional ones if that is needed. The chemical composition of the included alloys can also be changed. Fig. 3 describes the ingoing and outgoing flows for the ladle furnace.

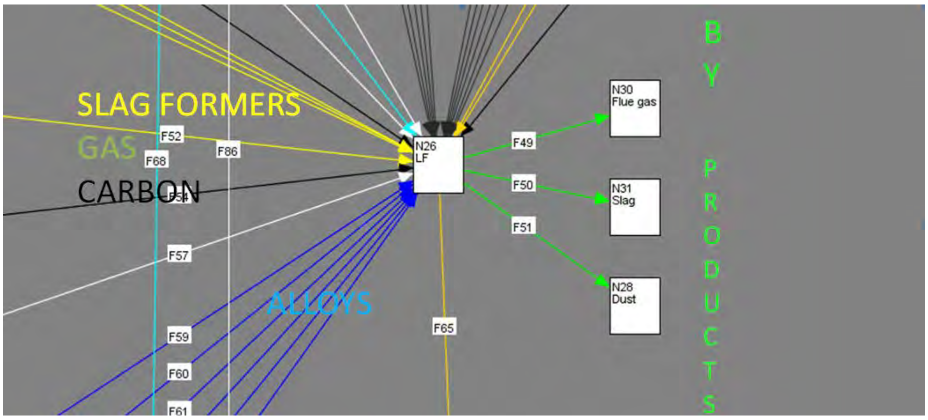

Fig. 3. Ingoing and outgoing flows for the LF node

The material balance in this node is as in the EAF node based on a distribution table between steel, slag and off gas/dust. The distribution coefficients have been estimated by empirical knowledge. The distribution coefficients refer to the materials that are added in the node. The contents of the ingoing steel are therefore not affected by any distribution factor. The exception from this is sulfur that has distribution coefficients also for the amount that is transferred with the steel into the ladle furnace node.

The ingoing temperature of the liquid steel to the ladle furnace is decided by the tapping temperature from the EAF which is reduced by a constant factor due to temperature loss during tapping of the EAF. The final temperature is decided by the demands of the following operation. It is also assumed that an average amount of slag is transferred along with the liquid steel from the EAF to the LF during tapping. There is a calculation of the electrode consumption that is based on a constant amount of electrode per kWh.

In the model it is assumed that argon is used for stirring the melt during the ladle furnace operation. The consumption is based on a fixed volume per ton of steel. This assumption is made from an average calculation from the process data. The amount of air that leaks into the system is also a constant per ton of steel.

2.3.1. Energy calculation

The electric energy consumption in the ladle furnace is based on the amount of steel and the increase in steel temperature needed to reach the final temperature. At first there is the difference between the ingoing temperature and the final temperature. But also the effect of the added material will contribute to a temperature drop. The temperature drop caused by each added material is based on an individual material constant. This constant determines how large the temperature drop, or in some cases a temperature raise, will be depending on the percentage of material added to the liquid steel. The temperature drop constants have been estimated by empirical knowledge.

2.3.2. Assumptions

It is possible to set specifications for the steel chemistry. This is made by restricting the calculations to fit the minimum and/or maximum allowed concentrations (wt. %) of each element in the steel. This is also possible in the EAF node so the user can choose if the specification is to be set at the LF or both. The slag weight is set to be greater than 2% of the steel weight and the slag basicity (CaO/SiO2) is restricted to a constant. The amount of elements and oxides in the off gas/dust that leaves the steel bath is calculated according to the same principles as the off gas in the EAF node. However, the reactions with infiltrated air are not considered.

2.4. Continuous casting

The continuous casting (CC) unit is treated in a simple way in the model. For the material flow, a material loss in percentage based on the total liquid steel amount from the LF unit is assumed when casting. A specific oxygen consumption (Nm^3 O_2/ton-slab) based on the final product (slab in this case) is assumed to calculate the total oxygen consumption. The oxygen is needed when cutting the slabs. For the electricity consumption in CC, it is based on assumed specific electricity consumption (MWh/ton slab).

3. Results

Simulations have been run in CPLEX with three different scrap mixes corresponding to average mixes for three different steel grades at Höganäs AB EAF plant in Halmstad. The model calculations in terms of chemical analysis of steel and slag and metallic yield have been compared with real data from Halmstad. The model calculates reasonable results which correspond well to real data.

An optimization test with the objective to minimize the total energy consumption (kWh) in the system (for a given quantity of a specific steel grade at Halmstad) was performed. During the optimization scrap preheating function was turned off and the EAF tapping temperature was constant.

In the optimized solution, the use of shredded scrap is maximized because of the lower specific energy consumption for this scrap grade (-50 kWh/ton compared to "normal" scrap) in the Köhle formula [3]. The maximum amount of shredded scrap is limited by the quality restrictions (chemical analysis) of the steel grade. The use of HBI/DRI is minimized (zero consumption) because of their higher specific energy consumption (+80 kWh/ton compared to "normal" scrap) in the Köhle formula [5].

For all chemical fuels (oil, natural gas and LPG), the optimizer chooses zero consumption in the EAF This is because the energy content according to Adams [16] for natural gas (10.5 kWh/Nm^3) is higher than the reduction of electrical energy consumption it gives according to the Köhle formula (-8 kWh/ Nm^3) [3]. As the efficiency of oil and LPG in the EAF burners are assumed to be the same as for natural gas it follows that the energy content of all chemical fuels are higher than their reduction of electrical energy consumption in the EAF.

The optimizer chooses to add as much post combustion (PC) oxygen through the burners in the EAF as possible, because burner PC oxygen has zero energy content and will reduce the electrical energy consumption (-2.8 kWh/Nm^3) according to the Köhle formula. The limit of PC oxygen is set by the available amounts of post-combustible gases (H_2, CO and Zn) in the furnace, as the amount of these substances in the 4th hole off-gas must be zero or higher. The amounts of post-combustible gases in turn are determined by the charge material mix and the amount of air leakage through the slag door.

The lance oxygen consumption is minimized in the optimized solution. This is because the energy development for oxygen injection (5.2 kWh/Nm^3) according to Adams [16] is higher than the reduction of electrical energy consumption that it gives according to the Köhle formula (-4.3 kWh/Nm^3) [3].

4. Concluding remarks

Scrap based steel plants around the world differs a lot in terms of scrap mixes and final products. The model described in this paper represents a general description which shall be adapted for specific cases. The model is built up to easy adjust to the processes of interest. To use the model correctly the incoming data needs to be correct and the model parameters (raw material analysis, slag basicity, air leakage, etc.) must be adjusted to represent the conditions of the specific plant. Then the model can be a powerful tool to optimize the scrap mix and injectants towards minimized energy consumption or production cost. In upcoming work the model will be used to optimize specific processes and plants.

The future work will also include further development of the scrap preheating function and move it to a separate node. A cost function for monetary units for all incoming flows will be added so that the total production cost can be optimized. Nodes for alternative solidification processes such as ingot casting and atomization will be considered and coefficients for specific energy consumption for different scrap grades in the EAF will be adjusted and added. Interaction with external systems like district heating can also be added.

Moreover different feeding and charging systems and a water cooling system for EAF are planned to be implemented and the processes after casting such as transport, heating and metalworking processes needs to added to complete the system.

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