Analysis of Oxygen Enrichment and its Potential Influences on the Energy System in an Integrated Steel Plant Using a New Solution Space Based optimization Approach

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With oxygen enrichment in hot stoves the high calorific coke oven gas can be saved due to the possibility of using lower calorific gases which enables replacement of other imported fuels such as oil or LPG. The application of increased oxygen use in hot stoves or increased O_2 in blast, will also potentially lead to lower coke rate. Central to the performance in system optimisation is the ability to analyse and properly describe the system variations. The demand for coke oven gas is depending on both internal operation logistics but it also has outdoor temperature dependence through a heat and power plant producing district heat to the community. An analysis of the influence of increased oxygen enrichment on the entire energy system has been carried out by use of an optimization model. A method of achieving a high time resolution in MILP optimisation is applied in the analysis. Different strategies have been suggested for minimum energy consumption at the studied steel plant and the nearby CHP plant.

1. Introduction

An integrated steel plant often consists of various process units, such as coking plant (CP), blast furnace (BF), basic oxygen furnace (BOF), secondary metallurgy (SM), continuous casting (CC), and rolling mill (RM). Most plants also have some auxiliary units on site, for instance, lime kiln, oxygen plant and sinter plant. There are process gases generated from process units of CP, BF and BOF i.e. coke oven gas (COG), blast furnace gas (BFG) and basic oxygen furnace gas (BOFG). These gases are generally used as fuel at different process units within the plant. It is also quite common to have a power plant or combined heat and power (CHP) plant at the site to utilize the process gases for production of power, process steam and/or heat, which are used internally within the plant and sometimes also for external users in the community. Thus, the energy system for the integrated steel plant is large and complicated.

Oxygen has been used in integrated steelmaking in various process units. For instance, in the BOF, oxygen is blown onto the metal bath at high pressure through a subsonic lance to remove carbon from the hot metal by oxidising the dissolved carbon to carbon monoxide. Oxygen is also used to enrich the blast by addition in the cold blast before the blowers or through a separate lance in the tuyers together with reducing agents such as pulverized coal (PCI), oil, gas (COG, natural gas, etc.) or plastics. In addition, it is also possible to add oxygen in the combustion air at different combustion process units, such as hot stoves (HS), lime kiln, reheating furnaces, etc. to allow for higher combustion efficiency and productivity.

In this work, oxygen enrichment in the HS-BF system is investigated. The purpose is to analyse the influence of increased oxygen enrichment on the entire energy system by using an optimization model. A method of achieving a high time resolution in MILP optimisation is applied in the analysis. In order to illustrate different strategies for minimum energy consumption by the oxygen enrichment, the energy system covers an integrated steel plant and a nearby CHP plant.

2. Methodology

2.1 MILP modelling of the integrated steelmaking system

The model developed in this work is based on a previous model designed for SSAB EMEA Luleå works (Larsson and Dahl, 2003). The different processes included and the main process flows in the model are shown in Figure 1. The model core is an overall mass- and energy balance for the production chain and separate sub-balances for the main processes which makes it possible to perform a total analysis for the steel plant and to assess the effect of a change in the operation practice for the different processes. In this work, the modelling system has been extended to include a rolling mill (RM) to enable modelling of a traditional integrated steelmaking system. The entire energy system is simply shown in Figure 1. As shown in the figure, two different boundaries are given based on the final products of either slab after CC or hot rolled coil (HRC) after RM.

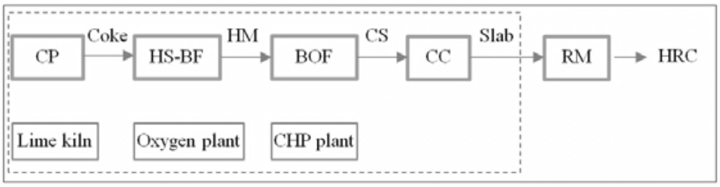

Figure 1: Simple schematic process units within the steel plant

2.2 Specific details regarding the modelling of the hot stoves and CHP plant

In the BF system hot blast is produced in the hot stoves. Hot stoves typically use low calorific BFG combined with higher calorific value COG. Oxygen can be increased in the combustion air to allow for a lower heat value in the fuel gas and still reach the required hot blast temperature, i.e. replacing the COG used by increasing the oxygen use (Zai, 2008; Wang et al., 2011). For this study alternative firing of the hot stoves allowing for increased oxygen in the combustion air are included.

The CHP planted is fired by process gases generated from the steel plant, as shown in Figure 2. The process gases of BFG, COG and BOFG are blended in the mix gas holder to before entering the boiler. Oil is used when heat load is higher, when there is lack of mixed gases or when the heat value of the process gases are too low. Electricity can be generated from the steam turbine by two different modes, back pressure and condense mode. The figure also illustrates the heat demand curve versus the out-door temperature. As shown in the figure, the maximum heat supply from the CHP plant is 220 MW, and the minimum heat supply is 20 MW. When the outdoor temperature varies in the interval of [-18, 17] °C, the heat demand curve can be linearized. Alternative description of the varying heat demand is included in the study.

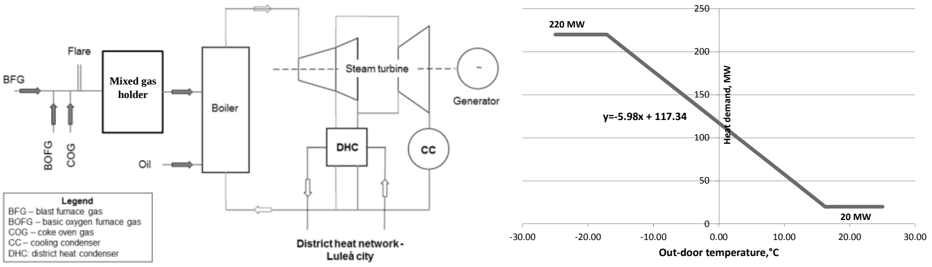

Figure 2: Left: The scheme of CHP plant linked to the studied steel plant; Right: The correlation between out-door temperature and heat demand in the district heat network

2.3 Modelling with the solution space method

An important factor in the modelling is defining a suitable time step resolution. A low time step resolution may result in insufficient detail in the modelling output. However, increased resolution also increases the amount of input to the model and model complexity. An increase in time step scales the amount of input data to the model linearly. This might result in vast amount of boundary values to be changed, e.g. changing from yearly average to daily increases the need for input by a factor 365.

An alternative method has been proposed by Sandberg et al. (2011) where the linearity of MILP models is considered. The idea is that a finite number of optimal solutions of the MILP formulation can be used to create any solution to the system by interpolation. Such a collection of finite solutions is referred to as an Optimal Solution Space, OSS and the collection of equation systems that the OSS relies on Problem Space, PS. Consider the case of the varying outdoor temperature, the change in the heat demand for the district heating system changes with the temperature. An OSS that holds a finite number of optimal solutions under varying outdoor temperature can be used to calculate the optimal solution for any temperature by interpolation. The number of optimal solutions needed to span such an OSS is dependent of the system under analysis. In this problem the outdoor temperature dependence has been limited to only heat demand variation in the CHP. The OSS consists of four solutions (compare Figure 2), one for each break point in the heat demand curve.

2.4 Optimization

Any industrial system should be operated in a way that minimizes the energy use at reasonable cost. In this study the objective, the minimization goal, is minimization of the energy use of the total system. Due to the varying outdoor temperature there is a climate dependence on the specific energy use. The main parameters and coefficients included in the objective function are showed in Table 1.

Table 1: Energy coefficient used in the model

Energy carrier	Coefficient	Unit
Coking coal	27.0 – 35.9	GJ/t
External coke	40.9	GJ/t
PCI	28.2	GJ/t
Oil	3.6	GJ/MWh
Electricity purchased	3.6	GJ/MWh
Own electricity to grid	-3.6	GJ/MWh
Flaring	1	GJ/unit

3. Energy system and HS-BF operating scenarios

3.1 Description of different scenarios

The oxygen plant supplies oxygen to various process units: HS-BF, BOF, CC and RM. This work is focusing on oxygen enrichment in HS-BF system. Table 2 lists different HS-BF operating scenarios included in the optimization model.

Table2: Key parameters in hot stove – blast furnace system in different scenarios

Parameter	Unit	S1	S2	S3	S4	S5
Coke	kg/thm	309.0	300.4	309.0	279.1	477.3
PCI	kg/thm	149.0	149.0	149.0	180.0	0.0
BFG generated	Nm^3/thm	1470	1430	1470	1430	1680
Heating value	MJ/Nm^3	2.97	2.97	2.97	3.10	2.60
Blast amount	Nm^3/thm	924	887	924	871	1155
Blast temperature	°C	1104	1200	1104	1104	1104
BFG consumed in HS	Nm^3/thm	332.9	358.2	547.5	353.3	470.0
COG consumed in HS	MJ/thm	642.6	642.6	0	356.5	642.6
O2 in the blast	Nm^3/thm	37.4	35.9	37.4	53.8	0
Steam in the blast	kg/thm	8.2	7.9	8.2	7.9	29.2
O_2 in comb. air	Nm^3/thm	0	14.8	39.0	0	0

thm: t hot metal; S1-5: Scenario 1-5

Scenario 1 is the reference case, business-as-usual (BAU) scenario. In this scenario, blast is enriched by oxygen according to normal operation practice and PCI injection rate. With oxygen enrichment into the combustion air to hot stoves, the high calorific COG can be saved due to the possibility of only using lower calorific BFG or can be used to achieve a higher blast temperature. In Scenario 2, oxygen enriched combustion air is used to raise the blast temperature; the same amount of COG is used as in reference case. A high blast temperature will reduce the coke rate in the BF. In Scenario 3, the oxygen enriched combustion air is used to save COG. The saved COG will enable replacement of other imported fuels such as oil or LPG. Scenario 4 to 5 shows two possibilities of changing oxygen-enriched level in the blast. In Scenario 4, a high PCI rate is injected into BF through tuyers which requires higher oxygen enrichment. This results in lower coke rate by replacement with PCI in BF. There is a slight increase in BFG heat value which influences the COG consumption slightly in the hot stoves. Scenario 5 illustrates all coke operation, which means that there is no PCI injection. In this scenario, there is no oxygen enrichment in the blast. The steam amount in the blast is increased to adjust the raceway adiabatic flame temperature. For all other scenarios the specific steam (g/Nm^3 blast) are the same, but since the specific blast volume (Nm^3/thm) changes the total amount of steam shows small changes compare to each other.

4. Results and Discussions

The optimization model is run to minimize the energy consumption in the integrated steel plant and CHP plant. There are two main driving forces in the model, heat demand due to varying out-door temperatures and the final products of slab/HRC. The two different boundary conditions are set in the modelling work. The first is to produce slab as the final product, as indicated by dotted system boundary in Figure 1. Integrated steelworks often has a RM on site where COG is used. To investigate the potential influence of oxygen enrichment in HS-BF system on both CHP plant and RM from the total energy consumption point of view, the model boundary is further expanded to include RM.

For each boundary condition, the model has been run for two cases. They are, reference case (Ref), and optimized case (Ref_opt) for the slab production's condition; and reference case (Ref_RM), and optimized case (Ref_RM_opt) for the HRC production's condition. Figure 3 shows the selected result of the fuel input to CHP plant when producing slabs as final product. Compared to the reference case, the BF is operating with the mixed scenario of high blast temperature (S2) and high PCI rate (S4) until the outdoor temperature becomes -7 °C. This is to achieve the lowest possible coke consumption in BF. When the outdoor temperature is further colder than -7 °C meaning a further increased heat demand, the BF operation turns to an operation where COG is saved in the HS and instead used in the CHP plant to replace oil (S3). In the optimised cases, where the scenarios S2 and S4 are chosen, less COG is used in the HS due to a lower specific blast volume needed. This leads to more COG available to the CHP plant for condense power generation which will reduce the power purchased from the grid, thus contribute to low energy consumption. Comparing the two cases it is noticed the amount of oil needed is significantly reduced. In the reference case oil is needed already at -7 °C and at the highest heat load demand the oil required corresponds to 100 MW. In the optimised case the oil is needed at outdoor temperatures of -12 °C and the maximum oil needed is decreased to 50 MW.

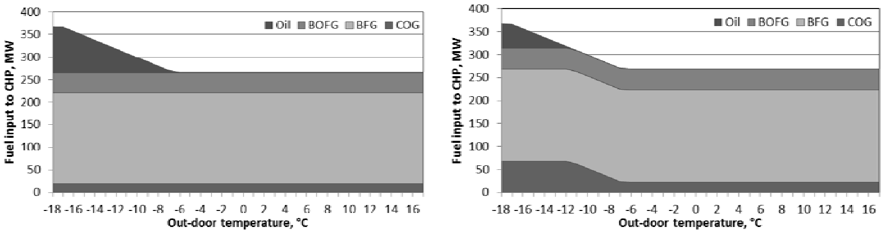

Figure 3. Fuel input to CHP plant. Left: reference case; Right: the optimised case. (The modelling results for the boundary conditions of slab production.)

When the rolling mill is included in the steelmaking site the slab is further treated to produce HRC. The fuel consumed in the reheating furnace is oil and/or COG, as shown in Figure 4. In the reference case around 80% fuel used is oil, the rest is COG. However, this is changed in the optimized case in which more COG is used. As for the CHP plant, there is no COG consumed in reference case and optimized cases. Instead oil is used in larger extent. Oil usage starts at outdoor temperature of -5 °C and the maximum oil usage in CHP plant is 120 MW. It is also noticed that less power is generated. The interpretation of this is that it is better to use COG internally in the steelmaking, i.e. to replace oil in RM than producing electricity and heat in a CHP plant. Compared to the reference case, the extra COG used in RM comes from COG saved in BF operation (S3 in Table 2) by oxygen enrichment in hot stoves. A high PCI rate BF (S4) is also noticed, but with very small amount share to have a reduced coke rate.

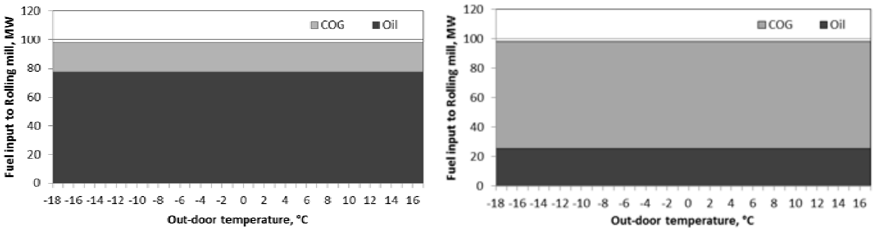

Figure 4. Fuel input to RM. Left: reference case; Right: the optimised case. (The modelling results for the boundary conditions of HRC production.)

5. Conclusions

The solution space based optimization approach for increased resolution has been applied to investigate the influence of oxygen enrichment in HS-BF system on the entire energy system by checking out-door temperature dependent heat demand at a CHP plant. The strategy of using oxygen enrichment to achieve decreased energy consumption varies depending on the heat demand at the CHP plant and the boundary system. Oxygen is being used to replace coke in BF (through achieving high blast temperature in hot stove or as a consequence of increased PCI rate) or oil in CHP plant or RM (by saving COG in the HS). Since oxygen production is mainly electricity based, electricity is used to replace these fossil sources of energy i.e. oil or coke. This is shown in the cases comparing a system with gas surplus (COG being use in the CHP plant) and a system with gas deficit (RM included in the system). The condition of using oxygen in hot stoves to save COG is only when there is a significant deficit in the system (winter case or with RM). When there is gas surplus within the plant, it is always preferably to use oxygen for lower coke rate in the BF instead of aiming for to COG saving. Thus increased oxygen usage can be expected to have positive influence on the CO_2 emissions reductions on site.

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