Optimization of Steelmaking Using Fastmet Direct Reduced Iron in the Blast Furnace

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Steelmaking contributes by more than 5% to the world’s anthropogenic CO2 emissions, so new ways to reduce the emissions in this industrial sector must be found. During a transition to more sustainable production concepts, also economic factors must be considered. In this paper the potential of using direct reduced iron (DRI) from the FASTMET process with rotary hearth furnace (RHF) technology, as a partial substitute of pellets in a blast furnace (BF) was studied. Simplified mathematical models of the different operations in a steel plant, including RHF, are combined with a more detailed model of the BF and the entire system is optimized by non-linear programming with respect to costs. The objective of the presented study is to analyze the prerequisites for an economical operation of an integrated steel plant equipped with an RHF, under different raw material prices and varying costs of CO2 emission allowances. The blast furnace operation parameters are also analyzed for different amounts of DRI charged. The results illustrate the conditions under which it would be beneficiary in a steel plant to integrate the RHF and BF technologies.

KEY WORDS: blast furnace; DRI; RHF; optimization; CO2 emissions.

1. Introduction

Global crude steel production has fully recovered after two years of declining (2008–2009) caused by the economic recession. World crude steel production reached 1,548 million metric tons in 2012 which is a new record for global crude steel production. Further growth is forecast and crude steel output is expected to exceed 1.6 billion tons in 2013.2,3) Figure 1 shows the development of the crude steel produced through different steel production routes from 2000 to 2011.2,3) In 2011, 69.4% of the steel was produced through the main primary production route Blast Furnace (BF) - Basic Oxygen Furnace (BOF), while Electric Arc Furnace (EAF) steel production accounted for 29.4% of the total amount. The use of Open Hearth (OH) technology is steadily declining and it accounted for only 1.1% of the total crude steel production.

The growth and expansion of steel production have resulted in new challenges for the producers, including the availability and costs of raw materials and energy sources as well as restrictions of CO2 emissions. Steel production is a highly energy intensive industrial process: The iron and steel sector is the second-largest industrial user of energy after the chemical and petrochemical sector.4) Steel production gives rise to greenhouse gases that are deemed to contribute to global warming. The greenhouse gas of most relevance to the world steel industry is carbon dioxide, as the CO2 emissions account for 99% of all steel industry greenhouse gas (GHG) emissions. According to the International Energy Agency the iron and steel sector is the largest industrial source of CO2 emissions, accounting for approximately 5% of the global CO2 emissions.4,5)

Fig. 1. World crude steel production by process as well as production of direct reduced iron (DRI) since 2000.2,3) DRI scale appears on the right side of the graph (Online version in color).

According to the sustainability indicators of World Steel Association the energy intensity of steelmaking was 20.7 GJ per ton of steel cast and the amount of CO2 emissions was 1.8 tons of CO2 per ton of steel cast in 2011.2) These indicators are calculated using route-specific energy and CO2 intensities for different steel production routes: basic oxygen furnace, electric arc furnace and open hearth furnace. Indicators are also weighted based on the production share of each route.
Figures 2 and 3 present the typical distribution of energy consumption and direct CO$_2$-emissions in Ruukki Raahe integrated steel works. Most of the total energy used in ore-based steel production is used in the blast furnace but only ~20% of overall direct CO$_2$ emissions is attributed to this process. CO$_2$ emissions from the blast furnace are only related to the flue gas of the hot stoves. The carbon in the blast furnace gas will be emitted as CO$_2$ by the power plant being the end user of this off-gas. Power plant is responsible for over 40% of the total direct CO$_2$ emissions. If the power plant is not taken into account the blast furnace together with the coke plant and sinter plant are the major sources of emissions.6)

The steel industry is currently under a continuous social pressure to improve efficiency and decrease energy consumption and gas emissions. Energy efficiency has been a target for improvement long before climate change emerged as a global threat. As a result, over the past three decades steel companies have halved the specific energy consumed (i.e., per ton of steel produced). However, due to this dramatic improvement in energy efficiency, it is estimated that there is now only room for marginal further improvement on the basis of existing technology. For instance, an efficient blast furnace is already working close to its theoretical limits of carbon utilization and, thus, it is extremely difficult to further lower the energy consumption and CO$_2$ emissions by improving the process efficiency. This means that without new production routes major advances in these fields cannot be achieved. In the longer term it will be necessary to identify and introduce breakthrough technologies that are viable. The alternative ironmaking processes are therefore expected to play an increasingly significant role in the iron and steel industry, especially since it is unlikely that new blast furnaces will be built in the developed countries due to high capital costs and environmental regulations.

One of the alternative technologies is direct reduction. World Direct Reduced Iron (DRI) production has grown almost continuously since 1970 being 73.3 Mt in 2011 (Fig. 1). Although the vast majority of DRI is used in the EAF, direct reduced iron can also be charged into BOF as a scrap substitute and into BF in order to increase productivity. In this paper the influence of the usage of DRI in the blast furnace on the Reducing Agent Ratio (RAR), CO$_2$ emissions and production cost will be studied through a holistic optimization of the entire system under different raw material and emissions costs. This sheds light on the overall economics of an integration of RH and BF technologies.

2. DRI in the Blast Furnace

DRI has many positive attributes that speak for its use in steelmaking. DRI is a feed material with controlled and consistent size. DRI can also be continuously metered when discharged. It can be stored in bins and transported easily for continuous charging into any melt furnace.

When the burden used in a blast furnace consists of 100% iron oxide, approximately 45% of the total energy used in the BF is consumed in reduction reactions. Reducing the amount of charged oxides would therefore result in a decrease in the specific coke rate as well as an increase of productivity. This is the reason why replacing part of the total burden with direct reduced iron is justified.7)

The application of DRI as feed to blast furnaces was proven in the 1960’s. However usage of DRI in blast furnaces did not become common commercial practice until 1989 due to very limited merchant supply of DRI/HBI. AK Steel has added HBI to the charge mix of their Middletown blast furnace over 20 years. They began using HBI in 1989 and throughout the 1990’s increased the amount of HBI in the charge. The use of HBI in blast furnace was found to increase productivity about 8% and decrease coke rate about 7% for each 10% of iron charged into the blast furnace as metallic iron, as indicated in Fig. 4.8) The solid circles added to the picture represent the fuel rate decrease calculated from the results of the present study.

More recently blast furnaces in Canada, Western Europe
and Japan have also begun using HBI in their blast furnaces. DRI has been used as up to 70% of the charge in research blast furnaces but it has been used as no more than 30% of the charge in a full scale commercial unit.9)

The actual benefits of charging partially reduced burdens to the blast furnace depend on the type of raw materials that are replaced, the chemical and physical characteristics of DRI, the operating conditions of the furnace and several other related factors.10)

3. Reducing Agents

As mentioned previously, one of the main reasons to use DRI in blast furnaces is to lower the amount of reducing agents, e.g., coke needed. Simultaneously with the coke rate decrease the CO₂ emissions from the blast furnace also decrease. Another option to achieve lower emission rates and reduced RAR of the whole process chain is to use a high reactivity reductant, such as wood charcoal.

Wood charcoal can be charged in mini blast furnace to replace coke and also in coal based DRI processes like in Rotary Hearth Furnace (RHF) to replace coal. The effect of metallization degree on productivity of RHF for wood charcoal and coal reductants is presented in Fig. 5. It can be seen that at the same metallization degree productivity is significantly higher for wood charcoal than for coal.11)

In addition to high reactivity wood charcoal is also considered as renewable because the carbon cycle of wood is short, 5–10 years, compared to fossil coal’s cycle of approximately 100 million years. According to Norgate and Langberg,12) replacing non-renewable carbon with charcoal carbon creates 3.8 kg CO₂/kg steel benefit in Global Warming Potential (GWP). There is, however, the challenge to develop and manage a sustainable biomass source. The availability of biomass suitable for charcoal production is one of the critical issues affecting the adoption of charcoal in steel production. Also the production technology of charcoal has to be developed so that the production has lower environmental impacts and lower costs than the production methods currently used. One of the issues also affecting the economy of charcoal use is the transportation of charcoal to steel plants. Norgate et al.13) have studied the GWP of charcoal production. Current charcoal production technologies range from batch technologies to continuous processes. The difference between these technologies is in the recovery of by-products such as bio-oil and gas. These by-products become significant for the GWP impacts of charcoal production when the electricity generated from the gas replaces electricity generated from fossil coal and bio-oil replaces diesel. With these acts the overall net credit of charcoal production results in negative values, namely −1 006 t CO₂/t charcoal. The magnitude of these by-product credits is dependent on the yields of by-products, which, in turn, depend on a number of factors, such as the nature of the pyrolysis process and composition of biomass feed.13)

For this investigation two different charcoals, Brazilian charcoal and European charcoal, were selected. The selection was made based on the different prices of these charcoals. The production processes of charcoal were not investigated further.

In this paper the use of charcoal replacing coal in the RHF is studied, while the effect of charcoal in the blast furnace was not investigated.

4. Process Alternatives

Figure 6 shows the flow sheet of the two process alternatives compared in this study. The first process (left part) is a conventional blast furnace route where pellets and coke are charged at the top and oxygen enriched air and heavy oil are injected through the tuyeres. In the basic oxygen process, hot metal and steel scrap are fed to the converter and the carbon content is reduced by blowing oxygen into the metal. After the converter, secondary steelmaking processes are applied to the molten steel to make fine adjustments of the steel temperature, composition and cleanliness. Molten steel is then cast into solid slabs, blooms or billets. The final stages are the forming operations such as hot or cold rolling, machining, coating and heat treatment. The main purpose of
these operations is usually to achieve large shape changes, e.g., from billet to steel wire and to give the steel component its final shape and properties.\textsuperscript{14)}

In the second process alternative, part of the pellet feed to the blast furnace is substituted by direct reduced iron. In previous studies the coal-based FASTMET process was found to be economically more feasible than the gas-based Midrex process, due to the high natural gas price in Europe.\textsuperscript{15)} This was the reason why the FASTMET process was selected for the present study. The Rotary Hearth Furnace (RHF) also seems to be one of the promising processes for treating dust. The option with the DRI plant is depicted in the right part of Fig. 6 within dashed lines.

FASTMET is a rotary hearth based process, where the feed pellets (composite agglomerates made from iron oxide fines and a carbon source such as coal, charcoal or other carbon-bearing materials) are charged into the hearth, one to two layers deep, and as they move on the hearth they are heated by burners firing above the hearth. Combustion of volatiles from the reductant and carbon monoxide from the iron reduction supplies the primary energy to the RHF for the reduction reactions. FASTMET DRI is continuously discharged from the RHF using a water-cooled screw. The FASTMET process is illustrated in Fig. 7.

When considering the investment costs of a FASTMET plant it must be noted that they vary significantly depending on the capacity of the plant and the location planned. The total economy of the FASTMET process is also influenced by the raw material used. The composite agglomerates used in the process can be made using recycled iron bearing materials instead of virgin iron ore. Most typically FASTMET plants process steel mill wastes and the feed rate is 0.2 Mt per year. The carbon-bearing materials used in the RHF can be of lower grade than the materials used in coking coal and therefore also cheaper.

This paper studies the optimal operation of the system with respect to raw material and energy costs, without considering the feasibility of the investment.

5. Modeling

5.1. System Studied

In the present study, mathematical models of the different unit processes in an integrated steel plant are combined (Fig. 8) to create a system model, which is optimized by minimizing the specific operation cost, $F$, of rolled steel production.
\[ F = \frac{m_{\text{pel}} + \frac{c_{\text{pel}}}{t}}{t/h} + \frac{m_{\text{coal}} + \frac{c_{\text{coal}}}{t}}{t/h} + \frac{m_{\text{cokext}} + \frac{c_{\text{cokext}}}{t}}{t/h} + \frac{m_{\text{coke,ext}} + \frac{c_{\text{coke,ext}}}{t}}{t/h} + \frac{m_{\text{quartz}} + \frac{c_{\text{quartz}}}{t}}{t/h} + \frac{m_{\text{scrap}} + \frac{c_{\text{scrap}}}{t}}{t/h} + \frac{m_{\text{CO}_2} + \frac{c_{\text{CO}_2}}{t}}{t/h} + \frac{m_{\text{DRI}} + \frac{c_{\text{DRI}}}{t}}{t/h} + \frac{m_{\text{red}} + \frac{c_{\text{red}}}{t}}{t/h} + \frac{P}{MW} \left( \frac{c_{\text{el}}}{t/MWh} \cdot \frac{Q_{\text{fuel}}}{MW} \cdot \frac{c_{\text{fuel}}}{t/MWh} \right) \left( \frac{m_{\text{steel}}}{t_{\text{steel}}/t} \right) \]  

where \( m \), \( V \) and \( \psi \) are mass, volume and heat flow rates, \( P \) is electrical power, and \( c \) are cost factors. DRIf denotes the DRI feed material while red denotes the reductant used in the RHF.

The optimization was done with MATLAB, a generic modeling environment, with respect to the inputs of the blast furnace model (Table 1) at different production rates, \( \text{CO}_2 \) emission allowance costs and DRI feed costs. The fixed cost factors (c) of Eq. (1) are presented in Table 2. The price of reductants used in the RHF was set to 90 €/t for regular coal and for the price of charcoal two different values, 200 €/t and 343 €/t, were used. These values represent the price range for Brazilian charcoal and European charcoal.

Three cases were studied: Case 1 was the normal blast furnace operation with 100% pellet burden and 100 kg/thm briquettes charged to the furnace to utilize the fines arising in the different process steps. In Cases 2 and 3 DRI was used in the blast furnace together with pellets and the fines were used as a feed material in the RHF. In Case 2 coal was used in the RHF and in Case 3 charcoal was used. The coke plant operation was adjusted so that all the coke produced is used in the process.

### 5.2. Process Models

The core of the mathematical description of the steel plant is the blast furnace model, which is described in detail in the Appendix of Helle et al. It implements the basic features of the operation diagram introduced by Rist and co-workers. It applies a division of the process into two main control volumes, an upper preparation zone and a lower elaboration zone, separated by a reserve zone where the temperatures of solids and gas are (almost) equal and known, and the gas composition can be calculated from an approach to equilibrium. The model also considers pre-reduced burden by taking into account only heating of the charged metallic iron and wüstite in the preparation zone. Table 1 lists some of the blast furnace variables together with the constraints used in the optimization.

The other unit processes were modeled with simple equations describing the outputs as linear functions of the inputs. In the FASTMET model it was assumed that 1.31 ton of DRI feed is required for each ton of DRI produced. Scrap is charged to the BOF and the liquid steel mass is estimated to be 14.5% higher than the hot metal (hm) mass from the BF. The losses in casting are estimated to be 5% of the liquid steel mass and in rolling 6% of the rolled slabs. These coefficients together with the hot metal production reported in Table 1 yield a production range of 130 to 170 tons of rolled steel per hour for the plant studied.

### 6. Results and Discussion

The results in this section were obtained by minimizing the costs of Eq. (1) with respect to the unknowns of the system, considering the constraints set on the operation. Figure 9 depicts the minimum cost of rolled steel as a function of the steel production rate with the cost of DRI feed compared to blast furnace pellets varying in the panel columns. The figure shows that the use of DRI produced with FASTMET is more economical in the BF when the steel production rate is high and the cost of DRI feed stays low. The use of pre-reduced burden becomes more economical when the production rate of the plant increases, because it enhances the productivity in the blast furnace and thus relaxes internal constraints. Increasing emission costs (moving downwards along the rows of panels in Fig. 9) decrease the potential of DRI usage since the total emissions increase when FASTMET DRI is used. The effect of the higher productivity of the RHF with charcoal (Fig. 5) on the costs

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**Table 1.** Variables and constraints for the blast furnace model. Input variables in the optimization are marked by an asterisk (*).

| Variable                  | Range          |
|---------------------------|----------------|
| *BF production rate, tsw/h| 127–166        |
| Specific DRI rate, kg/tmn | 0–400          |
| Blast oxygen, %           | 21–32          |
| Specific oil rate, kg/tmn | 0–120          |
| Blast temperature, °C     | 850–1200       |
| Specific coke rate, kg/tmn| ≥ 0            |
| Flame temperature, °C     | 1850–2300      |
| Top gas temperature, °C   | 115–250        |
| Bosh gas volume, km³/n    | 150–250        |
| Solid residence time, h   | 6.0–9.5        |
| Slag rate, kg/tmn         | ≥ 175          |

**Table 2.** Fixed cost factors used in optimization of Eq. (1)

| Variable                  | Cost          |
|---------------------------|---------------|
| Pellets (c_{pel}), €/t    | 120           |
| Coking coal (c_{coal}), €/t| 145           |
| External coke (c_{ext,coal}), €/t | 300    |
| Oil (c_{oil}), €/t        | 150           |
| Limestone (c_{limestone}), €/t | 30        |
| Quartzite (c_{quartz}), €/t | 30           |
| Oxygen (c_{oxygen}), €/km³/n | 50           |
| Natural gas (c_{natural gas}), €/km³/n | 200 |
| Scrap (c_{scrap}), €/t    | 100           |
| Reductant (c_{reductant}), €/t | 90/200/343   |
| Electricity (c_{elec}), €/MWh | 50        |
| District heat (c_{district heat}), €/MWh | 10      |
even out since the price of charcoal is much higher than the price of coal. The effect of using charcoal in the RHF can be seen in some of the lower panels (dashed lines) as the cost of steel decreases due to lower emissions. When the emission cost is 40 €/ton of CO₂ (third row of panels in Fig. 9) the minimum cost of rolled steel produced with DRI is equal when DRI is produced with coal or cheaper charcoal. For emission cost of 60 €/ton (bottom row) the cheaper charcoal DRI becomes more economic than regular coal. For steelmaking with the more expensive charcoal to become economical, the emission cost should become even higher than the alternatives investigated here.

Figure 10 illustrates the influence of CO₂ emission cost on the optimal DRI rate in the plant. When coal is used in the RHF (top row of panels) the optimal DRI rate decreases as the emission cost increases (solid → dashed → dash-dotted → dotted lines). This is due to fact that DRI increases the overall carbon consumption of the steel plant. However, at high steel production rates the DRI use becomes more economical. By contrast, if cheaper charcoal is used in the
RHF (middle row of panels), the optimal DRI rate increases with increasing emission cost. In case of the expensive (343 €/t) charcoal used in the RHF (bottom panels), the only situation where the optimal DRI rate reaches the maximum is when the steel production rate is high, DRI feed is cheap and emission cost is high (bottom rightmost panel). The optimal state is seen to show abrupt changes with respect to the DRI rate. This is partly due to transitions between different states that show very similar and low costs, even though a nonlinear model is used. Another reason is that results have only been illustrated for discrete points for the cost of DRI feed compared to blast furnace pellets ($c_{\text{DRI}}/c_{\text{pel}}$).

Figure 11 illustrates the connection between the optimal DRI rate (upper panels) and RAR (lower panels) for Case 2 as a function of the production rate and the relative cost of DRI feed for three different CO$_2$ emission costs, $c_{\text{CO}_2} = 0$ €/t, 20 €/t and 40 €/t. When the relative cost of DRI feed is low, the DRI rate reaches its maximum level for all of the emission cost levels and production rates. As the relative cost of the DRI feed increases the optimal DRI rate increases as a function of the production rate. When the cost of DRI feed reaches the pellet cost (i.e., $c_{\text{DRI}}/c_{\text{pel}} = 1$) the optimal DRI rate decreases to the minimum value (60 kg/thm). The effect of an increasing emission cost can be seen in a decrease of the region where the maximum use of DRI is optimal, namely the high plateau areas in the upper panels of the figure. This is due to the fact that the emissions of the process increase when FASTMET DRI is produced with regular coal.

The behavior of the RAR in the BF is opposite that of the DRI rate, as can be seen in the lower panels of Fig. 11. (Note that the figures have been viewed from a different angle to facilitate the illustration.) This clearly shows the positive influence of DRI use on the BF performance: the region of high DRI rate in the upper panels can be seen as the low plateaus of RAR, and vice versa.

For Case 3, with a low-cost charcoal (200 €/t) used in the RHF, the optimal DRI rate and RAR are presented in Fig. 12. The effect of emission costs on the optimal solution is strong, because the charcoal used in the RHF is significantly more expensive than coal. Without penalty for emissions ($c_{\text{CO}_2} = 0$ €/t), the optimal DRI rate increases as a function of the steel production rate and the DRI rate reaches its maximum level only if the relative cost of DRI feed is low. As the emission cost grows, the region where the maximum DRI feed is optimal extends to lower steel production rates and higher DRI feed costs. The relative cost of DRI feed determines the limit where it is no longer optimal to use DRI. When DRI is produced with coal the cost of DRI feed can be the same as the pellet cost (cf. Fig. 11), but when it is produced with charcoal the relative cost limit increases with increasing emission cost. When the emission cost is 40 €/ton of CO$_2$ the optimal DRI rate is the same when DRI is produced with coal or charcoal.

As in Fig. 11 the behavior of the RAR is opposite that of the DRI rate as can be seen in the lower panels of Fig. 12. The stronger decrease in the coke rate achieved in this study (cf. Fig. 4) is likely due to the higher carbon content of the FASTMET DRI, which contains a substantially higher amount of carbon than DRI produced with a typical natural gas-based direct reduction process, which was presumably used in the earlier investigations.

Figure 13 illustrates the specific CO$_2$ emission from the system as a function of the steel production rate and the cost of DRI feed compared to blast furnace pellets. It clearly shows the negative influence of using FASTMET DRI produced with regular coal in the BF (thin solid lines vs. thick solid lines in the panels of Fig. 13). Figures 11 and 12 showed the decrease in the RAR when the DRI rate increases, but the main problem is that the need for coal in the FASTMET exceeds the amount of saved coke in the BF. The production of 1 ton DRI with FASTMET requires 382 kg coal. If 400 kg/thm DRI is used, 153 kg coal is needed to produce the DRI. On the other hand, only 106 kg coke is saved.

Fig. 11. Upper panels: Optimal DRI rate. Lower panels: Optimal RAR as a function of the production rate and relative cost of DRI feed for Case 2 (Online version in color).
in the BF. The increase of the emission cost is a factor also in the CO₂ amount calculations, because the model is optimized by minimizing the operation cost of rolled steel. As the emission cost increases the optimal DRI rate increases when the DRI is produced with charcoal as this leads to lower emissions. By contrast, when DRI is produced with coal the effect of emission cost is opposite because the use of DRI increases the total CO₂ emissions. If the DRI is produced with the cheaper (200 €/t) charcoal, the specific CO₂ emissions are lower than in the basic BF case almost throughout the examined region. Running the RHF on the expensive (343 €/t) charcoal is only favorable (compared to the normal BF operation) when the steel production rate is high, DRI feed is cheap and emission cost is high.

Table 3 reports in detail some of the central variables for the blast furnace process in the optimized state, where the steel production rate is 150 tsteel/h and cDRIf/cpel = 0.8. The three cases shown are the normal BF operation, DRI produced with regular coal and DRI produced with the cheaper charcoal. The latter two the states correspond to those indicated by circles in the middle column of panels in Fig. 10. The table clearly shows the decrease in coke rate and specific blast volume in the BF along with DRI use, and also the decreased need for blast oxygen. DRI use increases the top gas CO utilization, which, in turn, lowers the top gas heating value, resulting in a lower flame temperature in the hot stoves. The increase in the top gas temperature is due to

Fig. 12. Upper panels: Optimal DRI rate. Lower panels: Optimal RAR as a function of the production rate and relative cost of DRI feed for Case 3 with the cheaper charcoal (200 €/t) (Online version in color).

Fig. 13. CO₂ emissions at optimal costs. Thick line: Case 1. Thin lines: Operation with DRI (solid: Case 2 with coal in RHF, dashed: Case 3, charcoal 200 €/t in RHF, dash-dotted: Case 3, charcoal 343 €/t in RHF). Emission costs for the panel rows in descending order are cCO₂ = 0 €/t, 20 €/t, 40 €/t and 60 €/t (Online version in color).
The fact that the residence time of the burden has reached its upper limit, which imposes a small increase in the coke rate. The effect of DRI use on the overall performance of the steel plant is, thus, quite complex.

Table 3. Optimal operation state of the blast furnace at a production rate of the steel plant of 150 tsteel/h, where \( \frac{c_{\text{CO}_2}}{c_{\text{DrIf}}} = 0.8 \) (cf. circles in Fig 10). The three cases shown represent normal BF operation, DRI produced with regular coal and DRI produced with the cheaper charcoal.

|                  | \( c_{\text{CO}_2} = 0 \, \text{€/t} \) | \( c_{\text{CO}_2} = 20 \, \text{€/t} \) |
|------------------|----------------------------------------|----------------------------------------|
|                  | Case 1 | Case 2 | Case 3 | Case 1 | Case 2 | Case 3 |
| Pellet, kg/tthm  | 1334   | 883    | 1327   | 1334   | 910    | 1036   |
| DRI, kg/tthm     | 0      | 400    | 60     | 379    | 283    |
| Briquette, kg/tthm| 100    | 0      | 0      | 100    | 0      | 0      |
| Coke, kg/tthm    | 297    | 234    | 301    | 297    | 233    | 231    |
| Oil, kg/tthm     | 120    | 83     | 120    | 87     | 120    |
| Limestone, kg/tthm| 19     | 48     | 56     | 19     | 49     | 52     |
| Quartzite, kg/tthm| 10     | 21     | 21     | 10     | 21     | 22     |
| Steel slag, kg/tthm| 50     | 50     | 50     | 50     | 50     | 50     |
| Blast volume, km³/n/thm | 0.83  | 0.72   | 0.83   | 0.84   | 0.72   | 0.73   |
| Blast temperature, °C | 1200  | 1162   | 1200   | 1200   | 1200   |
| Blast oxygen, % | 28.5   | 25.8   | 28.0   | 28.0   | 26.1   | 28.0   |
| Flame temperature, °C | 2253  | 2207   | 2232   | 2239   | 2224   | 2166   |
| Bosh gas volume, km³/n/thm | 1.22  | 1.02   | 1.22   | 1.24   | 1.02   | 1.09   |
| Solid residence time, h | 7.9    | 9.5    | 7.8    | 7.9    | 9.5    | 9.5    |
| Compressor power, MW | 6.17   | 5.59   | 6.22   | 6.3    | 5.52   | 5.47   |
| Flame temperature, stoves, °C | 1337  | 1306   | 1326   | 1331   | 1312   | 1352   |
| Slag, kg/tthm     | 178    | 175    | 175    | 178    | 175    | 175    |
| Slag basicity, -  | 1.09   | 1.08   | 1.09   | 1.09   | 1.09   | 1.10   |
| Top gas volume, km³/n/thm | 1.32  | 1.08   | 1.33   | 1.34   | 1.09   | 1.15   |
| Top gas temperature, °C | 115.7  | 132.0  | 115.0  | 122.4  | 129.3  | 151.3  |
| Top gas CO, %     | 23.2   | 22.3   | 22.9   | 23.0   | 22.3   | 22.7   |
| Top gas CO₂, %    | 24.7   | 21.8   | 24.9   | 24.5   | 22.2   | 23.2   |
| Top gas H₂, %     | 7.2    | 6.3    | 7.2    | 7.2    | 6.6    | 8.3    |
| Top gas N₂, %     | 44.9   | 49.6   | 45.1   | 45.4   | 48.9   | 45.8   |
| TG needed in stoves, km³/n/thm | 0.39  | 0.34   | 0.39   | 0.40   | 0.35   | 0.33   |
| Direct reduction, % | 29.3   | 26.1   | 29.3   | 29.4   | 26.5   | 25.5   |

7. Conclusions

The potential of using direct reduced iron (DRI) from the FASTMET process in a blast furnace to substitute iron oxide pellets was studied by simulation and optimization. Mathematical models of the unit operations in the steel plant were combined to yield a description of the entity, and the arising system was optimized with respect to production costs. When DRI is used in the blast furnace the overall economy of the process is improved if the DRI raw material is cheap enough compared to the pellets, which the DRI will replace. The main problem is the energy demand of the FASTMET process, which leads to increased emissions in the steelmaking site, i.e., more coal is used by the RHF than is saved in the blast furnace by the use of DRI. However, if the DRI is produced with a renewable reductant, such as charcoal, the overall emissions may decrease significantly. The results also show the complexity of the system studied and how the optimal DRI rate changes as a function of production rate, and costs of the DRI feed and emission allowances.

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