Efficient Utilization of Active Carbon in a Blast Furnace through a Black-Box Model-Based Optimizing Control Scheme ⋆

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Abstract: the daily operation of blast furnaces in the steel industry is only partly automated. The thermal control of the process is yet carried out manually by the operators. Their decisions may lead to an oversupply of carbon-based fuels, causing surplus production of carbon monoxide. The unexploited excess of carbon monoxide in the iron oxide reduction reactions increases the total carbon supply, hence the cost and the CO_2 emissions. To maximize the carbon monoxide efficiency in the reduction reactions, the authors propose a dynamic optimizing control scheme and evaluate its performance by simulation studies using real operational data. The optimizer adjusts the fast dynamics of the blast furnace to prevent the inefficiency of the utilization of carbon monoxide that is influenced by the slow dynamics, subject to process productivity and safety constraints. Simulation results demonstrate that the control scheme can lead to the full conversion of the reduction reactions as well as a reduction of the total carbon supply.

Keywords: Blast furnace, Carbon minimization, Black-box modeling, Optimizing control, Operational constraints.

1. INTRODUCTION

The iron-making blast furnace (BF) is an extremely energy-intensive metallurgical gas-solid process in which iron ore and hot blast air undergo a wide range of complex physical and chemical interactions to produce liquid iron, the so-called “hot metal” (Peacey and Davenport, 1979; Geerdes et al., 2015). The blast furnace has one of the largest environmental impacts among all processes in the steel industry due to its utilization of carbon-based fossil fuels, i.e. coke and pulverized coal (Song et al., 2019). Carbon-based materials are used to produce carbon monoxide (CO) as the main reducing agent for the reduction of iron ore. Additionally, they are used to provide heat to maintain the endothermic reactions. The supply of coke and pulverized coal is an essential factor for the stability of the thermal status of a blast furnace. Due to the corrosive environment inside the BF, the thermal status of the process must be assessed via the measurements at the furnace boundaries (Saxén et al., 2012). The hot metal quality indices, i.e. silicon composition and temperature, are among the most important indicators of the internal thermal status of the BF (Saxén et al., 2012). A deviation from the permissible ranges of the hot metal quality indices indicates an instability of the thermal status of the BF. To improve the thermal stability, the operators take corrective actions by regulating the feeds of the carbon-based fuels based on the variations of the hot metal indices (Gasparini et al., 2017). One of the challenges in the thermal control of a BF is the multi-scale dynamics of the process, where the residence time of the gas phase is orders of magnitude shorter than the residence time of the solid phase. Therefore, the outcome of changes in the solid feed is only observable after 6-8 hours when the corresponding product leaves the process. Besides, the effectiveness of the corrective carbon supply is highly dependent on the operators' experience. It is often the case that they apply an excess amount of carbon-based fuels to improve the stability of the thermal status of the BF, which however causes large fluctuations in the BF conversion profile (Gasparini et al., 2017). As a result of an excessive supply of coke and pulverized coal, CO is often produced in excess, i.e. it is present in the process more than needed for the thermodynamic equilibrium of the reduction reactions. The excess amount of CO has the capacity to react, but cannot be consumed due to thermodynamic limitations, imposed by the iron-oxide reduction reactions (Peacey and Davenport, 1979). It is important to feed coal and coke such that the needs of the reduction reactions and the heat requirements are met. Due to the high production rate of blast furnaces, even small relative savings of fuels have significant economical and environmental benefits.

The composition of the gas that leaves the top of the BF is analyzed online in the industrial blast furnaces and can

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be used as a measure of the efficiency of the utilization of the carbon feed. It signifies the fraction of carbon from coke and coal that is involved in the reduction reactions, the so-called "active carbon", and thus reflects the reaction stoichiometry and thermodynamic. The ratio of the carbon monoxide and carbon dioxide concentrations (CO/CO_2) of the BF top gas provides a fast observation of the status of the blast furnace that can be used for thermal control and fuel-saving. Coke is fed into the BF to support the solid bed, to generate CO and to provide gas permeability (Geerdes et al., 2015). Since coke is an expensive fuel resource in this process (Yang et al., 2014), it is desired to use it efficiently. To ensure an efficient use of CO in the reduction reactions, and thus to prevent excessive fuel supply, fast dynamic variables including the hot blast flow rate and its co-injected enriching oxygen and coal supplements as well as the top gas pressure can be adapted fast based on the top gas composition.

In Gasparini et al. (2017), a thermo-chemical model was developed to assist the operators in their decision-making on the required carbon supply. However, the applicability of the approach relies only on the anticipation of the carbon requirement from the top gas composition. The scheme does not consider the impact of other operational parameters on the fuel supply and the efficient consumption of CO in the process. In the last decade, Bernasowski et al. (2011), Vehec and Zhou (2011), Cavaliere and Perrone (2014), and Béchara et al. (2020) developed optimization-based methodologies to mitigate fuel consumption and gas emissions, however, without considering dynamic optimization. To go one step further, we propose a model-based dynamic optimization scheme that mitigates the unexploited excess of active carbon by maximizing the CO efficiency while keeping process productivity and safety constraints. It comprises a surrogate model that represents the conversion of the iron-oxide reduction reaction as a function of the CO/CO_2 ratio, and a black-box model that characterizes the BF operation status in terms of the top gas temperature, the pressure drop, and the gas composition, based upon a set of fast and slow dynamic input variables. The scheme suggests corrective actions by the fast dynamic variables such as the hot blast flow rate, the oxygen enrichment, the pulverized coal, and the top gas pressure to counteract a possibly inefficient CO consumption, imposed by the slow dynamic solid phase variables. The fast dynamic variables are then set such that the process conditions favor a better use of CO, a lower CO/CO_2 ratio, and a lower carbon supply. Comparing the optimization results with plant measurements by thyssenkrupp Steel Europe demonstrates the potential of the approach for the reduction of the carbon supply by around 3% while satisfying productivity and safety constraints as well as achieving the full conversion of the iron-oxide reduction reactions.

This paper is structured as follows. Section 2 provides a detailed process description. In Section 3, models that are used in the optimization process are explained. The optimization problem for the maximization of the carbon monoxide efficiency is discussed in Section 4. The performance of the proposed optimization scheme is evaluated by simulation studies in Section 5. At last, conclusions and outlook on future research are given in Section 6.

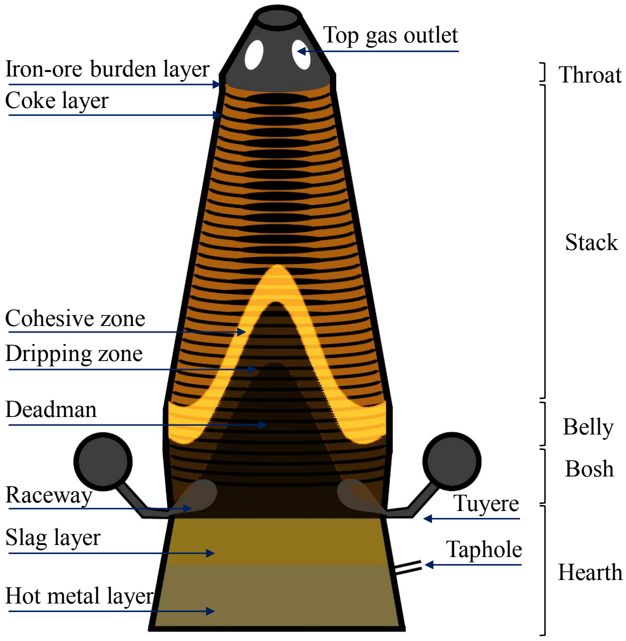

Fig. 1. Sketch of a blast furnace and related terminology

2. PROCESS DESCRIPTION

A sketch of a blast furnace is shown in Fig. 1. Iron-bearing material (lump ore, sinter, and pellets) and coke are charged in an alternating fashion from the top until the BF is filled up to the throat. Hot blast air with supplementary enriching pure oxygen and pulverized coal is injected into the furnace through the tuyeres at the bottom at $1000-1300\,°C$. In the raceway region, the injected hot blast gasifies all carbon-based materials (coke and coal) into gaseous carbon monoxide at $1900-2300\,°C$. At the softening/melting temperature ($1000-1100\,°C$) in the belly and bosh regions, the ascending gas phase, containing only CO, reacts with the molten wustite ($Fe_{0.947}O$) through the direct reduction reaction (1), and the Boudouard reaction (2), to produce the molten iron (Fe). Thereafter, the carbonaceous gas phase with the equilibrium composition of at least 70% CO and 30% CO_2 (see Fig. 2) ascends above the $1000\,°C$ isotherm, where the Boudouard reaction stops.

$$Fe_{0.947}O + CO \rightarrow Fe + CO_2 \quad (1)$$

$$CO_2 + C \rightarrow CO \quad (2)$$

In the stack region, between the $800-1000\,°C$ isotherms, the indirect wustite reduction reaction (3) occurs. The carbonaceous gas phase leaves this region with a CO/CO_2 ratio within the interval $[1.5, 2.3]$.

$$Fe_{0.947}O + CO \rightarrow Fe + CO_2 \quad (3)$$

Ascending to the first quarter of the furnace from the top, the gas phase has more than enough carbon monoxide ($CO/CO_2 \in [(\approx)1, 1.5]$) to drive the indirect reduction reactions of hematite (Fe_2O_3) and magnetite (Fe_3O_4), as in (4) and (5).

$$Fe_2O_3 + CO \rightarrow Fe_3O_4 + CO_2 \quad (4)$$

$$Fe_3O_4 + CO \rightarrow Fe_{0.947}O + CO_2 \quad (5)$$

The stoichiometry of this series of reactions is in favor of more production of $Fe_{0.947}O$ than of Fe. Below this region where wustite is the only iron oxide, the so-called

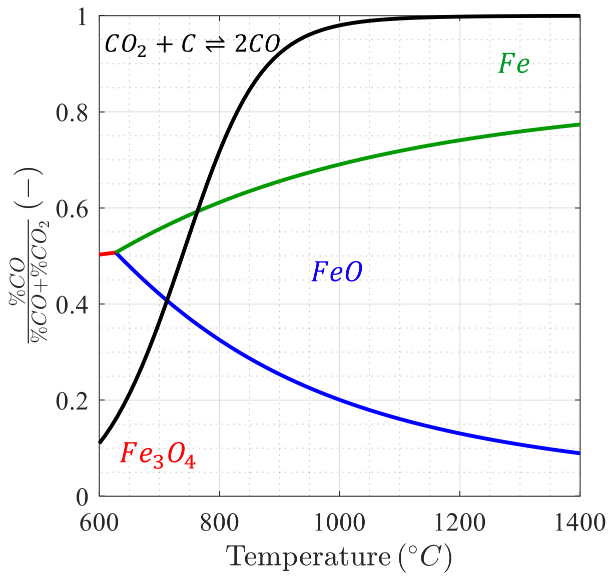

Fig. 2. Equilibrium curve of iron oxide and Boudouard reactions

"chemical/thermal reserve zone" is created (Kanfer and Muravev, 1974). In the chemical reserve zone very little reaction takes place and the temperature is almost constant. The presence of the thermal reserve zone (TRZ) plays an essential role in the BF operation. It is crucial to ensure that the excess of CO is consumed efficiently so that the higher iron oxides (Fe_2O_3 and Fe_3O_4) are fully converted to wustite before entering the TRZ region. The hot blast flow rate, the oxygen enrichment, and the top gas pressure play a role in making the reaction conditions and the gas-solid contact time suitable for efficient consumption of the active carbon in the form of CO. After going through the aforementioned sequence of reactions, the gas leaves the top of the furnace after 6-8 seconds. On the other hand, in the solid phase, when the oxygen is completely removed from the iron oxides and the materials are molten, the liquid iron and slag, which is mainly made from the solid gangue materials (CaO, MgO, SiO_2, and Al_2O_3), drip down through the coke bed and accumulate in the cavities of the inactive coke bed (deadman) in the hearth. The hot metal is cast from the tap-holes at around 1500 °C. The residence of the solid is 6-8 hours.

The harsh inner environment of the BF makes online direct internal measurements demanding, if not impossible. Therefore, online measurements are limited to the process boundaries. These measurements mainly include the top gas analysis (composition, temperature, and pressure) and the tuyere injection analysis (hot blast flow rate, temperature, pressure, oxygen enrichment, and pulverized coal). The offline measurements are related to the composition of hot metal and slag. Further information about the blast furnace process can be found in Peacey and Davenport (1979) and Geerdes et al. (2015).

3. MODEL DESCRIPTION

In this section, the process models that are used in the optimizing control scheme are discussed.

3.1 Degree of Higher Oxide Indirect Reduction Reaction

As explained in Section 2, the degree of the higher oxide indirect reduction reactions before entering the chemical reserve zone can be identified by the CO/CO_2 ratio within the interval $[(\approx)1, 2.3]$, which can only be monitored at the gas outlet on top of the furnace. In this definition, $CO/CO_2 \approx 1$ corresponds to the almost complete conversion of hematite and magnetite to wustite, and $CO/CO_2 =$ 2.3 indicates the situation where the post processed gas after the indirect reduction of wustite leaves the process with no further reaction. The degree of reduction can be defined by the amount of oxygen that is removed from the iron ore, as in:

$$\gamma = (\frac{O}{Fe})^i - (\frac{O}{Fe})^f \qquad (6)$$

where $(\frac{O}{Fe})^i$ is the mole ratio of oxygen to iron in the initial iron oxide, i.e. $(\frac{O}{Fe})^i = 1.5$ for Fe_2O_3, and $(\frac{O}{Fe})^f$ is the mole ratio of oxygen to iron in the iron oxide that enters the chemical reserve zone. The values of γ in (6) for the two steps of the higher oxide indirect reduction reactions are given in Table 1.

Industrial operational data of the blast furnace Schwelgern 2 of thyssenkrupp Steel Europe were used to establish a relationship between the degree of the conversion of the higher oxide reduction reactions (γ) and the CO/CO_2 ratio (ζ) by the linear equation in (7):

$$\gamma = h_1(\zeta) = -0.328 \cdot (\zeta) + 0.754 \quad (R^2 = 0.986). \qquad (7)$$

Since the degree of conversion is bounded to be within $[0, 0.44]$, (7) is only valid for $\zeta = CO/CO_2 \in [0.96, 2.3]$, which is compatible with the previous discussion of the equilibrium composition of the carbonaceous gas phase before the chemical reserve zone.

3.2 Regression Model of Carbon Supply

Carbon in the BF process consists of two major categories. The inactive carbon is the portion that is dissolved in the hot metal (Peacey and Davenport, 1979). The active carbon is the major portion of total carbon supply that is converted into CO and CO_2 and leaves the BF at the top. To compute the amount by which the total carbon supply can be reduced by an efficient CO consumption, a regression model between the total carbon supply and the CO/CO_2 ratio (ζ) was developed based on industrial plant data of the blast furnace Schwelgern 2 of thyssenkrupp Steel Europe:

$$C = h_2(\zeta) = 100.8 \cdot (\zeta) + 238.5 \quad (R^2 = 0.945) \qquad (8)$$

where C represents the total carbon supply per ton of hot metal (kg/tHM). The negative slope of the regression line in (7) and the positive slope in (8) emphasize that the lower the CO/CO_2 ratio, the higher the conversion of the reduction reactions, hence the lower the total carbon supply and thus the more efficient the process.

Table 1. Degrees of higher oxide indirect reduction reaction after each step

Step	Reaction	γ
1	$Fe_2O_3 \rightarrow Fe_3O_4$	0.17
2	$Fe_3O_4 \rightarrow Fe_{0.947}O$	0.27
Total	$Fe_2O_3 \rightarrow Fe_{0.947}O$	0.44

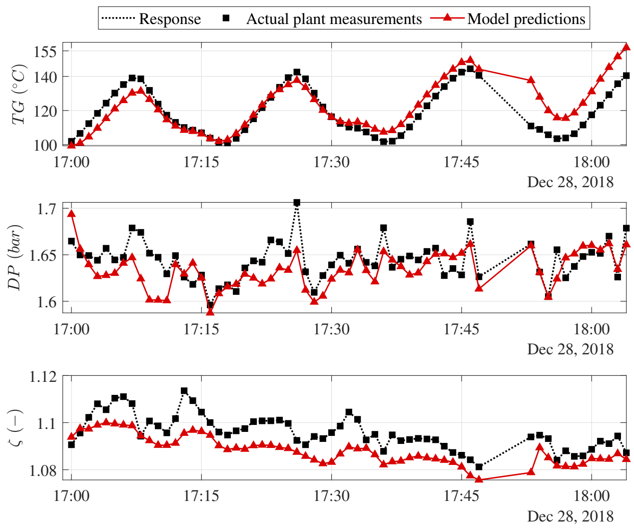

Fig. 3. Validation results of the data-based dynamic model, developed by (Azadi et al., 2020), for a horizon of 1 hour (TG: top gas temperature, DP: pressure drop, ζ: CO/CO_2 ratio)

3.3 Data-based Dynamic Model of the Blast Furnace Operation Status

Now that both the degree of conversion of the indirect reduction reactions and the total carbon supply have been related to the composition ratio of CO to CO_2, it is required to develop a model that relates the CO/CO_2 ratio to a set of process input variables. Recently, Azadi et al. (2020) developed and validated a nonlinear autoregressive neural network with exogenous input (NARX) for the multistep prediction of the BF operation status. This model predicts the top gas temperature (TG) in °C, the pressure drop between the tuyere level and the furnace top (DP) in bar, and the carbonaceous composition of the top gas ($\zeta = CO/CO_2$) as indicators of safety, productivity, and efficiency of the BF process. The mathematical form of the model is shown in:

$$\underline{Y}(t) = f(\underline{Y}(t-1), ..., \underline{Y}(t-d_y), \underline{U}(t), ..., \underline{U}(t-d_u)) \quad (9)$$

where $\underline{Y} = \{TG, DP, \zeta\}$ is the set of model outputs and $\underline{U}$ is the set of fast and slow dynamic exogenous input variables, as shown in Table 2. According to the dynamics of each variable, different time delays (d_y and d_u) were chosen. A prediction horizon of 1 hour, where the model is validated by real plant measurements of the large-scale blast furnace Schwelgern 2 of thyssenkrupp Steel Europe, was chosen for the simulation studies of the proposed optimization scheme. The validation results are shown in Fig. 3. The accuracy of the model is evaluated for each output in terms of the normalized root mean squared error (NRMSE) in Table 3. Despite the influence of unknown disturbances, the model reliably captures the dynamic of the system and its accuracy is sufficient. Therefore, the model can be used in a model-based optimizing control scheme.

4. OPTIMIZATION PROBLEM

The efficient consumption of active carbon, i.e. exploiting the carbon monoxide potential in removing oxygen in the indirect reduction reactions of the higher iron oxides as much as possible, is the prime objective of the proposed optimizing control scheme. To ensure the applicability of the approach, productivity and safety process constraints are incorporated into the optimization problem. As explained in Geerdes et al. (2015), the pressure drop can be considered as a productivity constraint. If the pressure drop is less than its lower threshold, the driving force for pushing the gas through the solid bed is diminished, resulting in less productivity. When the pressure drop exceeds the maximum threshold, the burden descent is hindered and the productivity will decrease. The top gas temperature is one of the indicators of a productive and safe process. Top gas temperatures less than the boiling point of water (100 °C) are an indicator of a less efficient furnace and process abnormalities. It is vital to ensure that all of the burden moisture is driven off in the early stages of the process as wet burden material raises the risk of process instabilities (Geerdes et al., 2015; Schwalbe et al., 2015; Azadi et al., 2020).

Table 2. Set of model input variables

Variable name	Symbol	Unit
Blast volume	VB	Nm^3/h
Top pressure	PG	bar
Oxygen enrichment	OE	Nm^3/h
Coal injection	PCI	t/h
Blast moisture	MB	g/Nm^3
Burden depth	BD	m
Coke reactivity index	CRI	–
Coke mass flow	Coke	t/min
Sinter mass flow	Sinter	t/min
Pellet mass flow	Pellet	t/min
CaO mass flow	CaO	t/min
MgO mass flow	MgO	t/min
Al_2O_3 mass flow	Al2O3	t/min
SiO_2 mass flow	SiO2	t/min
FeO mass flow	FeO	t/min
Permeability index	PI	-

Table 3. Data-based model accuracy with respect to each output

Output	NRMSE(%)
Top gas temperature	7.1
Pressure drop	1.27
CO/CO_2 ratio	0.78

Due to the very short residence time of the gas, only the fast dynamic input variables such as the hot blast volumetric flow rate, the top pressure, the oxygen enrichment, and the coal injection, i.e. $\underline{u} = \{VB, PG, OE, PCI\} \in \underline{U}$, are taken into account as manipulated variables. The fast dynamic inputs realize corrective actions to the process to compensate for the CO inefficiencies that are caused by the fixed evolution of the slow dynamic variables. The objective function of the optimization scheme for the efficient consumption of the active carbon in a blast furnace is defined as the sum of the degree of conversion of the higher oxide indirect reduction reaction (γ_i) over the prediction horizon (N_P). An additional term is considered to dampen excessive control variations. Since the optimization is set up as a maximization problem, a negative sign for the damping term appears. The optimal control inputs $\underline{u}^*$ are computed by solving the optimization problem:

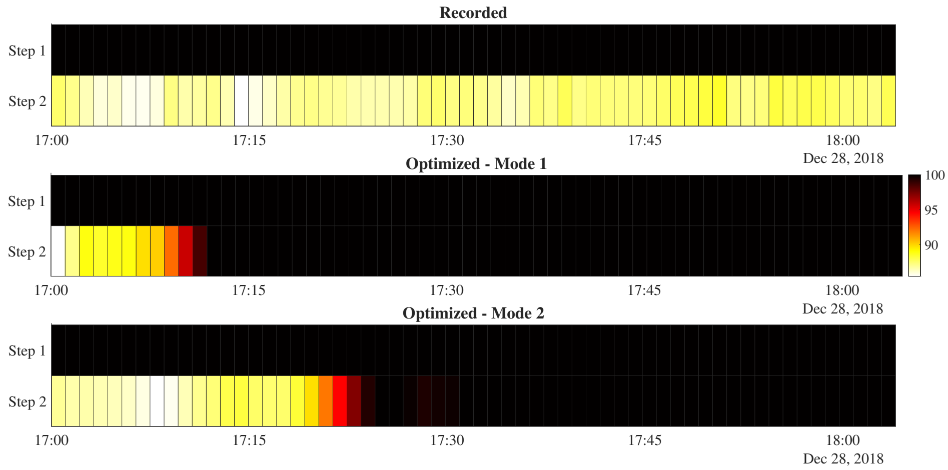

Fig. 4. Conversion degree of the higher oxide indirect reduction reaction before and after optimization modes (step 1: $Fe_2O_3 + CO \rightarrow Fe_3O_4 + CO_2$; step 2: $Fe_3O_4 + CO \rightarrow Fe_{0.947}O + CO_2$)

$$
\begin{aligned}
\max_{\underline{u}\in\underline{U},\underline{Y}} \quad & \sum_{i=1}^{N_P}\alpha_i\gamma_i - \sum_{j=1}^{N_C}\sum_{k=1}^{N}\beta_{k,j}\Delta u_{k,j}^2 && && \text{(10a)}\\
\text{s.t.} \quad & \underline{Y}_i = f(\underline{U}_i), && i=1,\ldots,N_P, && \text{(10b)}\\
& \gamma_i = h_1(\zeta_i), && i=1,\ldots,N_P, && \text{(10c)}\\
& DP^{lb} \le DP_i \le DP^{ub}, && i=1,\ldots,N_P, && \text{(10d)}\\
& TG_i \ge T^{bp}, && i=1,\ldots,N_P, && \text{(10e)}\\
& \zeta^{lb} \le \zeta_i \le \zeta^{ub}, && i=1,\ldots,N_P, && \text{(10f)}\\
& \underline{u}^{lb} \le \underline{u}_j \le \underline{u}^{ub}, && j=1,\ldots,N_C, && \text{(10g)}\\
& \underline{\Delta u}_j = \underline{u}_j - \underline{u}_{j-1}, && j=1,\ldots,N_C && \text{(10h)}
\end{aligned}
$$

where $\underline{Y}_i$ is the vector of the outputs of the data-based model f at time point i including the top gas temperature TG_i, the pressure drop DP_i, and the CO/CO_2 ratio ζ_i. $\underline{U}_i$ represents the complete set of model input at time point i that consists of the set of manipulated variables $\underline{u}_i = \{VB_i, PG_i, OE_i, PCI_i\}$, bounded by $[\underline{u}^{lb}, \underline{u}^{ub}]$, and the set of solid phase variables as parameters. Equations (10d) and (10e) correspond to the productivity and safety constraints, where DP^{lb} and DP^{ub} are the minimum and maximum allowable pressure drop in the BF operation and the T^{bp} is the boiling point of water. The domain of (7), explained in Section 3.1, is considered in (10f). α and β represent the weights on the terms in the objective function. N_C is the control horizon and N the number of control inputs.

5. SIMULATION RESULTS AND DISCUSSION

The proposed optimization scheme was applied to operational data of the blast furnace Schwelgern 2 of thyssenkrupp Steel Europe, shown in Fig. 3. The acceptable range of the pressure drop for this case study, with a safety margin, is $[1.6, 1.8]$ bar. The dynamic optimization problem was solved by the simultaneous approach, where a full discretization is carried out on both control input trajectories $\underline{u}$ and outputs $\underline{Y}$, resulting in the discrete time interval of one minute. The optimization problem was solved by the constrained nonlinear solver in MATLAB® (fmincon), using the interior-point algorithm. The performance of the optimizer was evaluated in two modes:

- Mode 1: only the prime objective, i.e. the maximization of the conversion of indirect reduction reaction, is taken into account. The optimizer does not consider the damping of excessive control actions.
- Mode 2: the damping term is considered in the objective function (10a) by tuning of the β values.

Fig. 4 illustrates the intensity of the higher oxide indirect reduction in each step before and after optimization. The reduction of Fe_2O_3 to Fe_3O_4 (step 1) at temperatures below 570 °C on top of the furnace is exothermic and thermodynamically easy (Peacey and Davenport, 1979), which justifies its full conversion in all three scenarios in Fig. 4. It is a prerequisite for the reduction of Fe_3O_4 to $Fe_{0.947}O$ (step 2) and is involved in the optimization. As shown in Fig. 5, in the first mode of optimization, the optimizer drastically changes the control inputs to drive the process as fast as possible towards the full conversion of the second step in the indirect reduction sequence. This leads to instabilities such as irregular burden descent and varying direct reduction in the high temperature region below the cohesive zone. In mode 2, the indirect reduction sequence reaches the full conversion with a smooth transition of the control inputs, but a slight delay in comparison to the first mode. Such a delay has, however, a negligible impact on the total carbon supply. The carbon supply was calculated by (8) and is shown cumulatively in Fig. 6. The optimization in mode 1 results in 3.5% savings in the total carbon supply, while the reduction in mode 2 is 3%. The outcomes of the optimization, i.e. the full conversion of reduction reaction and the total carbon supply saving, are related to the optimal control input trajectories. When the hot blast volume is decreased, lower blast pressure leads to a lower flow rate of gas and a better contact to the burden. Satisfying the pressure drop constraint leads to the adjustment of the top pressure to a lower value. Generally, oxygen enrichment limits the nitrogen, which supplies the required enthalpy to the chemical reserve zone. Such a limitation requires a compensating heat supply by burning more carbon. The optimizer diminishes the oxygen enrichment to ensure that enough high-temperature nitrogen is injected to the furnace with reduced hot blast volume. Such an action results in less coal consumption. It has been confirmed by

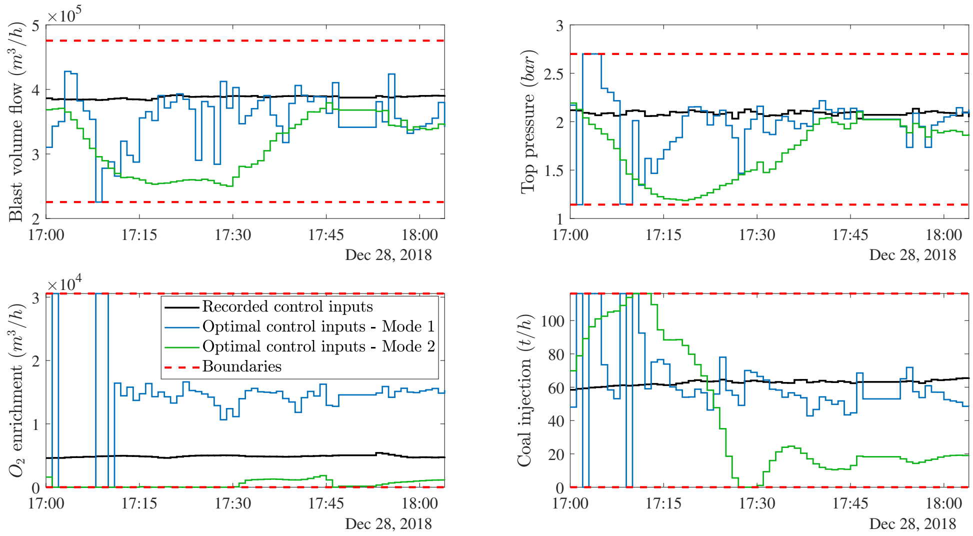

Fig. 5. Control input trajectories for the historic operation and in different optimization modes

thyssenkrupp Steel Europe that the optimal control inputs are in line with expected operational practices.

6. CONCLUSION AND OUTLOOK

A model-based optimizing control scheme was developed and evaluated for the efficient consumption of carbon monoxide in the blast furnace process. The simulation results for real plant measurements demonstrate 3% saving in the total carbon supply thanks to optimal control input trajectories. In the future, we plan to improve the scheme by a more comprehensive objective function to diminish the adverse influence that the computed control input trajectories might have on other process aspects, and to embed the scheme into a model predictive control platform where the future optimal control inputs at each sampling instant are computed by a receding horizon strategy.

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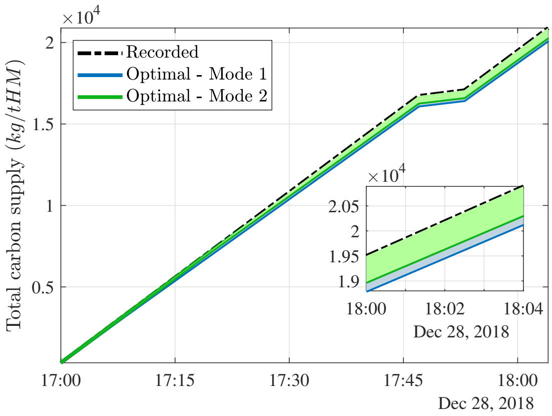

Fig. 6. Total carbon supply before and after optimization