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Abstract booklet

Content

Session I

Development of a modular mathematical model for the EAF process

V.-V. Visuri, L. Hekkala, M. Aula, T. Fabritius

Process Metallurgy Research Unit, University of Oulu,
PO Box 4300, 90014 University of Oulu, Finland
ville-valtteri.visuri@oulu.fi

INTRODUCTION

Electric arc furnace is the main process in scrap-based steelmaking and accounts for roughly 30% of total crude steel production. Over the years, numerous mathematical models have been proposed for the EAF process, ranging from models focusing on different aspects of the process to comprehensive process models, which aim to account for all the main phenomena affecting the course of the charge. An exhaustive review of the mathematical process models for the EAF process has been published recently by Hay et al. [1]. They concluded that while modern models can predict well the distribution of energy and changes in metal, slag, and off-gas compositions with reasonably good accuracy, the description of kinetics could be improved based on approaches developed for other metallurgical processes and by making use of new online measurements.

This work aims at developing a fundamental mathematical model of the EAF process for online use. The model is based on stand-alone modules for 1) scrap melting, 2) gas-phase reactions in the freeboard, and 3) metal–slag reactions. The model is executed in the Python programming language.

SCRAP MELTING

The scrap melting module was executed by Ringel [2]. This module focuses on the stage, in which the electrode has already bored into the scrap pile and the molten surface is exposed. The furnace is assumed to be a cylindrical vessel without the step formed by refractory lining.

The radiative heat transfer from the electrode to the various surface is calculated based on view factors and radiosities. The effect of slag on heat radiation is neglected. To simplify the treatment of view factors for heat radiation, the AC furnaces are modelled as having only one large electrode. The electrode is described as a cylinder with homogeneous current and temperature. The arc voltage is calculated based on the current and arc length according to the Bowman [3] correlation using parameters from Jones et al. [4]. The length of the arc is then solved iteratively from the voltage and current, while the arc radius is solved based on arc length and current. The view factor calculation was validated through comparison with CFD simulations [5].

The model features also a description for burners operating with natural gas. The natural gas is treated as pure CH_4 and the burner efficiency is calculated using a hyperbolic-tangent approximation [6].

To supply the module with reliable thermochemical data, a thermochemistry module developed in earlier work [7] was converted into Python and revised to account for the following elements and compounds:

- Fe, C, Si, Cr, Mn, and P in the metal phase,
- FeO, SiO_2, Cr_2O_3, MnO, P_2O_5, CaO, MgO, and Al_2O_3 in the slag phase, and
- N_2, O_2, CO, CO_2 and CH_4 in the gas phase.

The time integration of the differential equations for mass, energy, and geometry is carried out using an explicit Runge-Kutta method with adaptive step size.

GAS-PHASE REACTIONS IN THE FREEBOARD

A module for the gas phase reactions in the freeboard was executed withing the framework of the Master´s thesis of Jussila [8]. This module is based on Gibbs energy minimization using a Lagrangian steepest-descent method proposed by White et al. [9]. The definition of initial values for the minimization routine is conducted according to the method proposed by Blecic et al. [10].

METALï SLAG REACTIONS

Multiple reactions occur between liquid steel and slag in the EAF process. The aim of the work started by Hekkala [11] was to develop a dynamic module to observe chemical reactions between metal and phases during the flat bath stage. To obtain a low computational expense, the mass transfer constrained equilibrium was formulated according to the effective equilibrium model by Robertson et al. [12], which has been used extensively in mathematical models for converter and ladle processes [13]. The activities of species in the metal and slag phases were described using the UIP formalism [14] and the regular solution model by Ban-Ya [15], respectively. The metal–slag reaction module will also account for the addition of slag forming agents.

PRELIMINARY RESULTS

The module for scrap melting was tested using data from an AC EAF in operation at Ovako Imatra Oy Ab in Imatra, Finland. The furnace is equipped with three gas burners. Lime additions are used during the melting stage, while carbon injection is used for foaming the slag at the end of the heat. Fig 1 shows an example of a dynamic simulation for scrap melting. The charging of a second scrap basked is visible as a sudden jump in the amount of scrap.

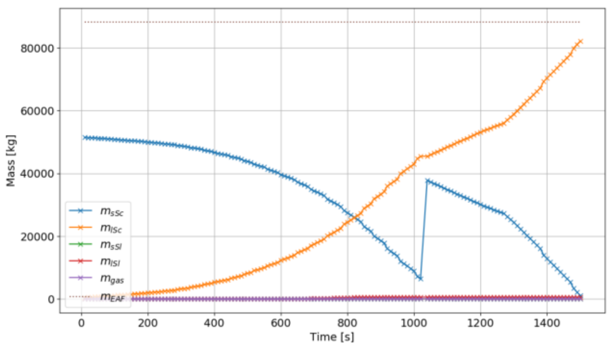

Fig. 1 Simulated scrap melting as a function of time in an example heat.

To provide a functional validation for the gas phase reaction module, a comparison was made with earlier studies based on an example case for the combustion of hydrazine and oxygen by White et al. [9]. The results obtained for this case exhibit a nearly perfect agreement with the results by White et al. [9] and an exact match with the results by Blecic et al. [10] obtained using the same calculation routine (see Table 1). The case shown in Table 1 was re-calculated using the Gibbs energy data from HSC Chemistry 9 and the results were found to be in excellent agreement with those predicted by the HSC Chemistry 9. These results indicate that the Gibbs energy minimization routine was executed correctly.

Table 1 Equilibrium composition for combustion of hydrazine and oxygen at 3500 K and 750 Psi.

Species	Abundance		
	This work [8]	White et al. [9]	Blecic et al. [10]
H	0.040655	0.040668	0.040655
H_2	0.14771	0.14773	0.14771
H_2O	0.783187	0.783153	0.783187
N	0.001414	0.001414	0.001414
N_2	0.485248	0.485247	0.485248
NH	0.000693	0.000693	0.000693
NO	0.027397	0.027399	0.027397
O	0.017941	0.017947	0.017941
O_2	0.037309	0.037314	0.037309
OH	0.096857	0.096872	0.096857

As a next step, the gas phase reaction module was applied for predicting gas-phase equilibria relevant for EAF steelmaking using the off-gas data by Kirschen et al. [16]. The results were found to be in excellent agreement with those obtained using the HSC Chemistry software.

CONCLUSIONS AND OUTLOOK

This work aims at developing a fundamental mathematical model of the EAF process for online use. So far, stand-alone modules have been developed for scrap melting, gas-phase reactions in the freeboard and metal–slag reactions. The next step in the model development is to couple the modules together into a single model, apply the model for predicting the EAF process from charging to tapping, and validate the results with measurement data.

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On the importance of the heat exchange modeling assumptions in electric arc furnace process models

Jesús D. Hernández

a) Process Dynamics and Operations Group, Department of Biochemical and Chemical Engineering, Technische Universität Dortmund, Emil Figge-Str. 70, 44221 Dortmund, Germany

e-mail: jesus.hernandez@tu-dortmund.de

INTRODUCTION

Electric steelmaking is the second most used method to produce steel worldwide. Despite its long history, one of the main challenges in modern electric steelmaking is identifying how to operate the process best, such that its economics and environmental impact are improved. This challenge can be addressed effectively and at a low cost using modern computational tools. On the one hand, process models can be developed to clarify the energetic phenomena taking place in an electric arc furnace (EAF). On the other hand, dynamic optimization can be employed to compute an optimal mode of operation that reduces the energy demand of the process. By improving the energy efficiency of the process, the economics and the environmental impact are also enhanced.

EAF PROCESS MODEL

The main target of the EAF process is to melt solid scrap and refine the chemical composition of the resulting liquid metal. To achieve this target, an EAF uses various energy and materials inputs. From a macro perspective, the net energy contribution from each energy input to the process can be computed as the multiplication of the energy content in the energy carrier by its corresponding efficiency factor – which changes throughout the batch. These efficiency factors can be estimated from mathematical models that describe the mechanisms of heat exchange in the process. Fig. 1 Presents such a modeling approach.

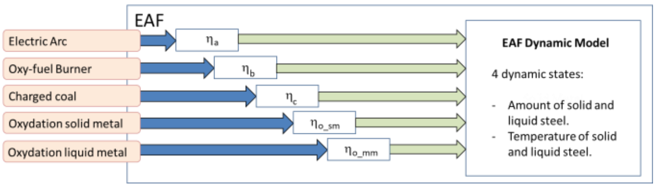

Fig. 1 Energy inputs and energy efficiencies for each input

HEAT EXCHANGE ASSUMPTIONS AND THEIR IMPACT IN MODELLING AND OPTIMIZATION

One of the fundamental assumptions in EAF process modeling is the mechanisms of heat exchange that dominate in the process. Even though significantly different assumptions may lead to equally accurate predictions of the terminal states of the process, the dynamic evolution (path) followed by key state variables can vary significantly from one to another. For example, very similar batch times, liquid metal temperatures, or final chemical compositions can be achieved assuming that the electrical energy from the arc is transferred to the solid and liquid metal phases in the EAF through either conduction, convection, radiation, or a mix of these [1]. On the other hand, for optimization purposes (advanced process control), a given set of assumed heat exchange mechanisms can lead to significantly different paths, and consequently, to sub-optimal or even- not optimal control solutions.

Clarifying heat exchange mechanisms is key to obtaining an accurate estimation of unmeasured variables during the process and adequately identifying relevant control variables (optimization parameters). While radiative heat exchange between the arc and the metal phases can be manipulated using control variables that change the geometry of the arc, convection heat exchange can be enhanced by manipulating the setpoints of the off-gas fans, the oxy-fuel burners, or the aperture of the de-slagging door. This is because the latter group depends on the temperature and the speed of the gaseous atmosphere.

THE KEY BUILDING BLOCK, RADIATIVE EXCHANGE BETWEEN THE ARC AND THE METAL PHASES.

Electrical energy is the primary energy input in the EAF process. It supplies between 40-60% of the total energy demand of a batch of steel. Because of its relevance, finding an accurate description of these phenomena is critical in any optimization attempt of the process. Although convection and conduction have traditionally been regarded as the main mechanisms of heat exchange in EAF process models, physicists have suggested that thermal plasmas, those occurring in the EAF process, are radiation-dominated [2]. If the assumption that the electric arc losses 100% of its electrical input power via radiation mechanisms is made, it is straightforward to find mathematical relationships between real control variables and the electrical energy efficiency of the process. This can be done by integrating an EAF process model that considers only radiation mechanisms [1] with and a model of the arc model that estimates how the voltage and impedance setpoints of the arc affect the geometry and temperature of the electric arc [3].

On the practical side, operational experience also suggests that radiation is the primary mechanism of heat exchange in the EAF. In practice, the furnace´s operators are well versed in improving the melting performance of the process by changing the electrical setpoints of the electrical arc. The correlation between electrical setpoints and melting performance can be justified as follows: as the electrical setpoints are changed, both the electrical power and the geometry of the arc are changed. Furthermore, as the geometry of the arc is varied, the efficiency of the exchange also varies. It can be demonstrated that the longer the electric arc is, the more efficient the melting process is.

IMPACT OF MODELLING ASSUMPTIONS IN OPTIMIZATION APPROACHES

Assuming that radiation is the dominant mechanism of heat exchange in the process, optimal modes of operation from an energy perspective can be computed, solving an optimization problem that aims to minimize the electrical energy losses during a batch of steel. As suggested in [4], the problem can be formulated as

$$\text{minimize} \quad \int_{t=0}^{tf} \dot{Q}_{loss}(P_a(t), t_f) \tag{1}$$

subject to
- Dynamic model
- Algebraic equations
- Linear relation: $l_a(P_a)$
- Operative constraints
- Terminal constraint

Using dynamic optimization to optimize the performance of the process has already been proposed in the literature [5]. Despite the similarities in the mathematical formulation of the strategy, in [5], a conduction-convection dominated EAF model with a fixed electric arc geometry was used. On the other hand, [4] employs a radiation-dominated EAF model with variable arc length, which depends on the operative power level.

Another difference between [5] and [4] is that while in the first, the most critical heat transfer mechanisms are estimated using process data and assumed to be constant throughout the optimization, in the latter, they are not. In fact, the first principles model utilized in [4] capture the dependency of the heat exchange on the control variable at all times.

VALIDATION OF RESULTS IN THE REAL PROCESS

The main difference between the computed results in [5] and [4] is that while the first optimization yielded an optimal mode of operation that kept almost constant the electrical power input through the batch, the second reduces the operative power level as the batch time progresses. The computed optimal control profile was implemented in a fully operative EAF to validate the results of the optimization framework (1). For a group of 19 test batches, the energy demand and the batch time of the process were reduced by approximately 4% compared to the average energy demand and batch time using the standard mode of operation. In the tested EAF, the common operative practice followed a similar operational philosophy to that computed in [5], aiming to maintain an almost constant power level throughout the batch. The energy and batch time improvements using the formulation (1) in the real process are presented in Fig 2.

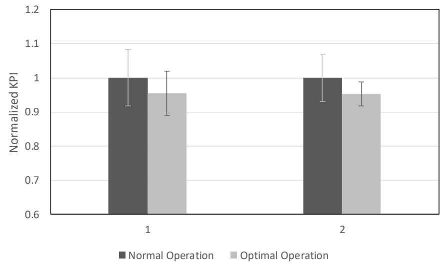

Fig. 2 Batch time and Energy demand improvements for one family of SS. KPI 1: Batch time. KPI 2: Energy demand. Taken from [4].

CONCLUSION

One of the essential assumptions when developing an EAF model is the heat exchange mechanisms between the various energy inputs and the metal phases in the process. Proper modeling of the heat exchange mechanisms is key to obtaining an accurate prediction of the evolution of the process and, thus, to the results obtained within a model-based optimization framework.

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EAF Process Model and Simulator

T. Hay[a)], T. Echterhof, H. Pfeifer

RWTH Aachen University,
Department for Industrial Furnaces and Heat Engineering
hay@iob.rwth-aachen.de

INTRODUCTION

The EAF process consumes large amounts of energy and other resources and while it is significantly more efficient that the blast furnace route, there still is potential for further optimization. Due to the conditions within the furnace, including high temperatures and strong electromagnetic fields, it is often difficult to obtain the information necessary for such optimization through measurements.

Process models have proven useful in providing a better understanding of different phenomena that characterize the process but cannot be documented through measurements. Furthermore, such models can be applied for training and education as well as when evaluating alternative operating strategies or input materials, as an alternative to costly industry trials.

Numerous different modelling approaches both for the complete processes as well as isolated phenomena have been developed. These include the application computational fluid dynamics (CFD), statistical models as well as analytical process models. CFD models allow detailed insights into complex processes, they are however computationally demanding with calculations too time-consuming for online applications.[1] Statistical models often applied to for example examine the energy consumption[2] in turn are highly efficient in predicting certain characteristics but do not allow the extrapolation beyond the data used for training of the model or offer any insight into the underlying physical processes.[3] Analytical process models represent a middle ground by reducing complexity through assumptions and simplifications but providing additional information and extrapolation capability, as the physical and thermodynamical relationships that they are based on are not limited to a certain process window or plant.

The model presented in the following provides a comprehensive and flexible modelling approach that is applicable both to off-line examination and optimization as well as on-line use such as process control and a real-time simulator for operator training.

MODEL DEVELOPMENT

The model is based on the approach published by Logar et al.[4-8] and further refined by Meier[9-13]. A total of eight model zones, each homogenous in temperature and composition are defined. These include the solid scrap, steel melt, solid and liquid slag, electrode and water-cooled furnace roof and walls. Between these zones, heat and mass transfer rates are determined for each iteration considering the radiative, conductive and convective heat transfer, phase changes, chemical reactions as well as the addition and removal of mass flows from the furnace such as the off-gas extraction and the injection of oxygen or carbon.

Meier improved the description of the gas phase and the radiative heat transfer, validating the adjusted model based on extensive industrial plant data from a 140 t DC arc furnace.[9, 10, 13] Based on Meier's model and the same validation data, the thermochemistry of the bath and slag was modelled and validated in more detail.[14] Furthermore, model stability and speed where increased allowing the development of a real-time simulator with input not from recorded data but through a user interface with direct feedback of the simulation results.[15]

In addition to the simulation based on measured data or user input, an algorithm has been developed that allows the automatic creation of operating strategies based on furnace parameters such as maximum energy and mass flows, desired temperature and carbon content and charged masses. This allows a large number of different scenarios to be generated and evaluated automatically, so that optimized operation charts can be developed for varying conditions.[15, 16]

RESULTS

Figure 1 shows the measured and simulated CO content of the off-gas averaged for 149 heats, reproduced from reference[10]. Meas. indicates a measured value, sim. a result of the simulation, Anthr. heats using anthracite coal as a carbon carrier charged with the scrap and PKS the use of palm kernel shells as an alternative carbon source. The graphs show that the model is capable of reproducing the qualitative characteristics of the differences between the two carbon carriers, illustrating the applicability as an off-line tool for process optimization and evaluation of alternative materials and operation strategies.

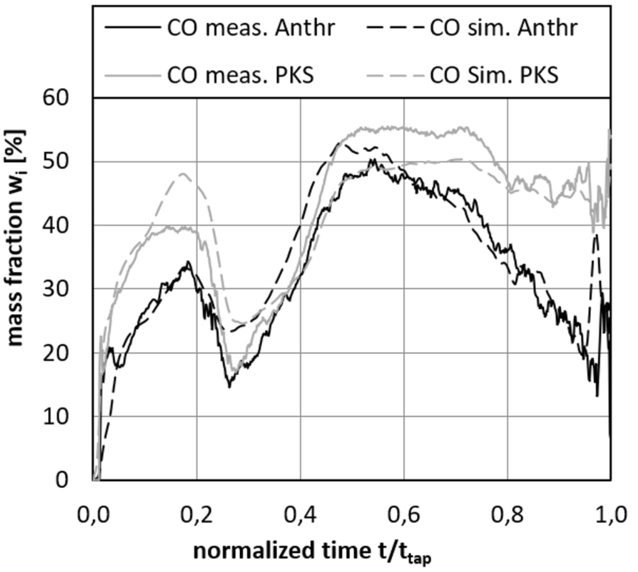

Fig. 1 Measured and simulated CO content

Figure 2 shows the simulated Temperature of a heat based on a measured operation chart (Case 0), on an operation chart developed automatically to match the measured case (Case 1) and on one developed to adjust for the use of a different oxygen source with a higher nitrogen content (Case 2). It shows how the model can reproduce a chart comparable to real-life operation and automatically adjust it for different conditions to give a similar result as is described in more detail in reference[15].

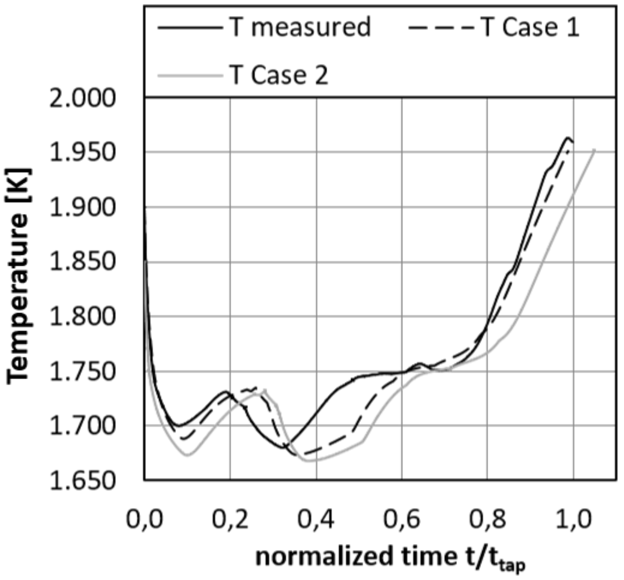

Fig. 2 Measured and simulated CO content

CONCLUSION AND OUTLOOK

A fast and comprehensive EAF process model can be useful for a wide range of applications such as off-line optimization, on-line process control and operator training. The presented model allows the simulation of a heat of 60 minutes in less than one minute on an office computer, making on-line applications possible. It has been validated using extensive process data from industrial EAF and different modes have been developed using the same core model to allow the simulation based on measured data, direct user input through a simulator interface and the automatic generation and adjustment of operation charts for different conditions.

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Session II

The adaptible and efficient EAF for the future
H. Beile

ISMELT – Inteco Scrap MELting Technology evolution
M. Manazzone, A. Valoppi

New plant developments integrated with Industry 4.0 solutions to the EAF of Acciaierie di Calvisano
M. Bersani, C. Senes, L. Angelini, P. Frittella, A. Zurru, G. Miglietta, C. Di Cecca, G. Tsymokh, F. Fredi, A. Ventura, D. Ressegotti, J. Brhel

The future of electric steelmaking ï Is the all-in-one solution existing?
-The adaptable and efficient EAF-

e-mail: hannes@triples.solutions
mobile: +49 151 28298507

INTRODUCTION

Lowest operational costs, high productivity, perfect raw material flexibility, environmentally friendly with lowest emissions, safe and nearly man less with a perfect level of automation

- One furnace must fit all needs -

One type of electric arc furnace designed for all kind of possible raw material distributions. From 100% scrap operation to 100% virgin material input, more than 70% hot metal usage, low operational costs, improved chemical power input, and safety improvements are key features in the future together with lowest possible overall and especially CO_2 emissions. Smart automation tools for nearly man-less operation but with increased efficiency coming on top.

Continuous charging furnaces, shaft furnaces, single-bucket EAF, hybrid furnaces, twin furnaces, continuous production furnaces – a plenty of different furnace types are available on market which could be fed with different raw materials. This results in many possible variabilities but what are the benefits? What are the possibilities, if the environmental boundaries are very strict or CO_2 taxes are coming in future? What to do with hydrogen reduced DRI in an electric arc furnace which is most probably coming more and more in future? This paper gives an overview of the most common furnace types operated and designed for different raw material scenarios and with different environmental limitation. The different raw materials themselves and the possible integration of electric steelmaking in integrated plants will be outlined as well.

TYPES OF ELECTRIC ARC FURNACES

Nowadays the diversity of different types of electric arc furnaces available on the market is huge. Each of the big five global suppliers have minimum two rather three or four different kind of electric arc furnaces in their portfolio for carbon steel solutions only. Local supplier solutions coming on top. The customer may decide between many solutions – or in better words: the customer must decide, and the customer has to select carefully in order to make the right choice for such a big investment. Several influences and effects driving the decision like capital investment, product quality, raw material flexibility and availability, environmental boundaries, operational costs, flexibility in productivity, industry 4.0 and many more. How to choose the best solution?

POSSIBLE RAW MATERIALS AND SUITABLE FURNACE TYPES

Scrap is the original basis of all raw materials for an electric arc furnace. Steel scrap was the reason for the invention and the boom of the EAF and the whole Mini-Mill history. Scrap is as well the reason why the process itself and advanced calculations in terms of timing and steel quality in an EAF is not that easy. The variation of the input material is at a level which no other steelmaking equipment is facing. Plenty of raw materials are available (Scrap, HBI, hot metal, pig iron, hot and cold DRI) and until a certain percentage all could be charged and melted down in an EAF. In terms of raw material flexibility there is no better solution available on market like an EAF minor adaptions or modifications in one or the other direction.

FUTURE STEELMAKING

In the whole steelmaking world, the environmental topic is growing continuously and one of the topics is steelmaking without CO_2 emissions. The ironmaking with hydrogen is one of the most promising ways for a nearly CO_2 -free production. It seems to be a great solution to further reduce the carbon dioxide emissions for the steel industry - but what should be done with the DRI pellets afterwards? Steelmaking in a converter is not possible anymore because of missing carbon in the raw material and how to treat it efficiently in an EAF?

CONCLUSION AND OUTLOOK

The large variety of different EAF-types makes it increasingly difficult to keep the overview and to find the best technical solution for its own situation in terms of space issues, raw material availability, electrical or chemical power availability and so on. On top of that the marketing strategy of many suppliers is strong with the background to sell new equipment which ends up in a unique selling point against all competitors. This presentation outlines that different electric arc furnace types for different raw material scenarios makes sense for some scenarios. It outlines as well that the best solution for raw material flexibility especially for DRI/HBI and hot metal combination together with scrap usage is a slight modified conventional EAF with adapted furnace volume, hot heel, correctly designed electrical and chemical power package which could work hand in hand with some special tools to increase the efficiency or to decrease the non-productive times. Back to basics with minor adaptions is even nowadays not the worst scenario – the adaptable EAF.

Different raw materials with different properties and qualities have as well different melting behaviours. If a combination is used for steelmaking the melting behaviour could easily change because the raw material influences each other. HBI and PI for example create immediately icebergs in the furnace shell if they touch each other during melting even if they are used with 10% of the overall raw material only. There is and will never be a furnace available where DRI, HBI and PI for its own could be charged via bucket above a certain percentage. 100% DRI feeding is nothing new and done successfully since many years, especially in the middle east. Electric arc furnaces operated up to 90% hot metal is as well existing many years - the presentation describes what is really needed to increase the efficiency for such a process in an EAF - the only important questions are:
1) At which level the economics is lost?

2) Is this the process route for the next 10-20 years?

3) Is it a transitional solution currently to change the complete steelmaking setup?

ISMELT ï Inteco Scrap MELting Technology evolution

M. Manazzone, **A. Valoppi**
michele.manazzone@inteco.at
antonello.valoppi@inteco.at

INTRODUCTION

The electric furnace in the course of melting process produces great amount of fumes that are emitted into the Fume Treatment Plant and that represent a net loss of energy equal to ca. 20% of the total EAF power.

The attempt to recover the energy of these fumes by trying to pre-heat the ferrous scrap prior being charged into the electric furnace has always been of great interest.

Different plant engineering solutions with various and disputable results have been implemented in the course of the last 50 years, all of them suffering from great limitation in terms of both environmental nature the reliability of the plant itself.

In particular, the scrap pre-heating plant should meet three following conditions:

- Energy recovery due to efficient pre-heating process;
- Reliable design to withstand in time to the impacts of mechanical and thermal stresses without losing its efficiency
- Environmental compatibility due to emission of less amount of harmful substances

First and second are the points that actually promote the investment due to the cost reduction through energy recovery efficiency, while the last render it compatible towards the environment.

It is well known from the technology that combustion process at medium temperature (i.e. btw. 400 and 800°C) of plastic materials, paints, etc. generates the substances harmful for health, such as dioxins and furans, accompanied by bad smell as inevitable corollary. Expressly the conditions of scrap pre-heating. The efficient treatment of such fumes prior to their emission into the environment is as efficient as it is reduced their amount to be treated, which depends on the plant engineering soundness of the system.

1ST SECTION

In the past Inteco developed a scrap-preheating system among its products portfolio that did not produce the desired results in terms of either efficiency or environmental compatibility.

This system is commercially known as COSS. There the scrap is pushed in the EAF by means of a hydraulic actuator called pusher.

The system allow a preheating of the scrap up to 500°C.

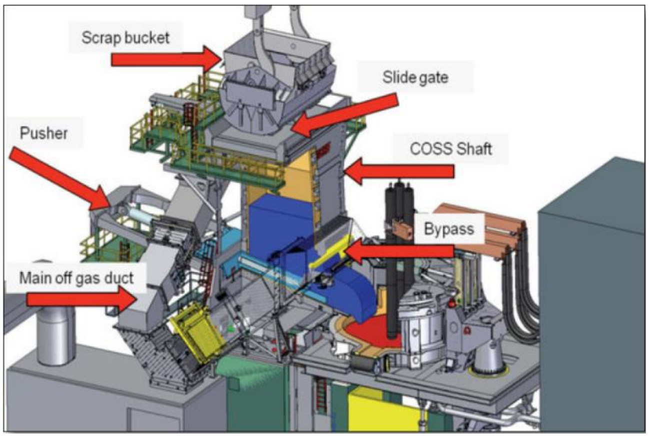
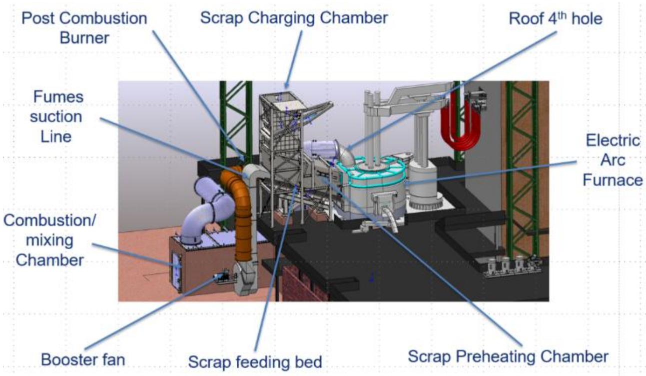


Fig. 1 COSS Scrap Preheating System

2ND SECTION

In recent years, a new system has been developed to improve the reliability of the COSS, the ISMELT.

The scarp pusher has been replaced by an oscillating bottom to smoothly feed the scrap into the furnace.



With this system the scrap is uniformly fed in the shell and a retractable car allow the tilting of the platform when tapping and deslagging phase are required.

Simulation of the process and application study has been presented and introduced in the market in 2018.

RESULTS

Performance in terms of energy savings are in line with the COSS, and indicated around 60 KWh/t. To avoid excessive preheating temperature and the scrap melting risk a second fumes suction system is foreseen at the tunnel, close the EAF shell.

Furtherly a third suction is applied at the scrap charging incoming, to capture the emission escaped from the preheating tunnel due to the rising of the hot gas into the charging column.

CONCLUSION AND OUTLOOK

It's clear that where the mechanical parts are installed nearby the molten steel bath the consequent thermal and mechanical stress are the weak points of any preheating system.

This new ISMELT solution represent the new frontier of the scrap preheating, where combination of the energy savings meets the reliability of the equipment.

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New plant developments integrated with Industry 4.0 solutions to the EAF of Acciaierie di Calvisano

M. Bersani [a)], C. Senes [a)], A. Zurru [a)], G. Miglietta [a)], P. Frittella [b)], L.Angelini[b)], C. Di Cecca[b)], G. Tsymokh[b)] , F. Fredi[b)] A. Ventura[c)] D. Ressegotti[c)] J. Bhrel[d)]

a) Acciaierie di Calvisano
b) Feralpi Siderurgica
c) Rina Centro Sviluppo Materiali
d) HTT Engineering

INTRODUCTION

The improvement of modern EAF technology needs a new approach coupling several applications as components able to realize more efficient chemical processes inside the reaction volume in terms of melting and metallurgy, but also systems able to suggest how to modify operating practices and control rules.

Due to this reasons for a modern EAF technology several applications are needed in terms of plant modifications, new measurements systems but also Industry 4.0 solutions able to improve capability of online process control coupled with a simulation approach to evaluate and manage the process phenomena occurring inside the EAF.

Acciaierie di Calvisano has implemented all these developments in the recent R&D project Steelpro4.0 co-financed by the Italian Region Lombardia in order to obtain performances improvement in EAF process.

EAF plant improvements

Main technology developments realized in EAF plants of Acciaierei di Calvisano have included a review of several areas of the process including scrap charging in basket, both electrical and chemical energy management and also new process facilities.

In terms of basket scrap charging modifications have been applied in the scrap treatment and cranes of basket scrap charging with new weight measurement and automatic information transfer to the system for steelmaking process data acquisition and management.

In particular modifications have been applied in electrical parameters managements with application of new TDR and also modification in application of chemical reactions inside the furnace with new modules coupling Gas, O2, C and CaO injections with a totally new configuration of injectors.

Further modifications have been implemented in the facilities for process management as new system for EBT control and heat restore in order to make tapping procedure more feasible. Furthermore a new robot for automatic steel sampling for a more reliable steel control during the process has been implemented.

To reach the new configuration of the plant in terms of improvements of chemical injections several steps have been applied in last years and in particular starting with implementation of new CaO injection system. This evolution has been demonstrated to be needed for injection of CaO during the process for more reliable process control avoinding the higher amount of CaO charged by busket. This approach with continuous feeding has been in favour to energy balance and to metallurgy treatments (as, slag foaming, dephosphorization and scrap heating).

Furthermore new modules and configurations for O2 and Gas injections has been applied after a period of comparison between different releases of the components necessary to choose the most performant system.

As further step a totally new system of movable head injection modules has been tested and applied in the standard production with Oximo Technology that has given the possibility to flexibly manage the reacting scrap volumes to be involved in the chemical heating.

This application has also given the possibility to make variations in the liquid steel portion involved in O2 injection during refining enlarging the steel bath volume involved in the reactions.

The area of tapping hole (EBT) has been improved with the new automatic EBT cleaning and restore with powder that has given the possibility to realize these operations avoiding the necessity of human presence in the area increasing the safety conditions and reducing time of power off time.

Furthermore the improvements on the area has been reached with introduction of the systems for automatic feeding of additions in ladle during tapping increasing the reliability of the operations and process accuracy.

Improvements on process control with Industry4.0 solutions

Further improvements have been obtained through development of systems for process control and on-line control rules and guidelines.

In particular the on-line system of process management based on KPI's, EAFPro, has been further developed with improvement of process simulation with mathematical model on-line available for estimation of dynamic mass and energy balance applied to have a complete view of the process phenomena occurring during the production.

With this application the status of the process in real time can be obtained heat by heat considering the all process input in terms of materials and energies and also considering the all measurements available (as shell and roof cooling systems).

This approach based on KPI's is used to evaluate several phenomena and process conditions as:

- Steel Thermal status
- Steel and slag mass and compositions
- Off Gas conditions
- Scrap melting evolution
- Slag foaming and arc covering through acoustic measurement.
- Steel oxidation status and dephosphorization
- Unbalances of energy in input on the reacting area.
- Radiation occurring by electrical arcs and energies in input on cooled shell and roof
- Steel decarburization efficiency
- Off gas post combustion through EFSOP monitoring
- Monitoring of trends of electrical and chemical parameters
- Process performances summary through KPI's

With this approach a view of process evolution and performances in terms of final process results and specific technological KPI's are available in order to evaluate behaviour of the components, modifications of operating practices, on-line guidelines to be applied.

RESULTS

With these applications in the frame of last 5 years of production Acciaierie di Calvisano has obtained several process performances improvements in terms of reduction of electrical energy consumption, reduction of Power On time, increase of metallic yield.

Further results obtained included also the improvement of safety conditions for the operators working on the area of the EAF and reduction of environmental impact of the production process with a reduction of CO_2 emissions due to the EAF process.

CONCLUSION AND OUTLOOK

In recent years (since 2016 till 2021) Acciaierie di Calvisano has realized several improvements and implementations on the Area of EAF process for scrap melting both in terms of new plant components and implementation of on-line control systems in order to be able to have a more efficient process and on-line control rules based on KPI's.

These application of advanced components and new technologies also following the modern approach of industry 4.0 solutions coupling advanced process monitoring with mathematical simulation of the process and estimation of relevant KPI's has given also capability to improve process results thanks to a global approach on the process view.

These results obtained also thanks to the support of Regional R&D funding scheme and technological partners collaborations has given a good confidence on the approach followed giving reliability to the continuous process and production developments for Acciaierie di Calvisano addressed to production of new special steel grades in efficient way.

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Session III

Exploring the Physics of the Electric Arc Furnaces
M. Al-Nasser, A. Kharicha, M. Abdi, H. Barati, M. Wu, A. Ludwig, C. Redl, H. Holzgruber, A. Ishmurzin, C. Pichler, G. Hackl, M. Gruber, Y. Tang

The stirring of melts in EAF
A. Chudnovsky

Experimental Study and CFD Modeling of Scrap Melting Behavior in AC EAF
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Exploring the Physics of the Electric Arc Furnaces

Mohamad Al-Nasser[a)], Abdellah Kharicha[a)], Hadi Barati [a)], Mehran Abdi [a)], Menghuai Wu [b)], Andreas Ludwig [b)], Christian Redl [c)], Harald Holzgruber [c)], Anton Ishmurzin [d)], Christoph Pichler [d)], Gernot Hackl [d)], Markus Gruber [d)], Yong Tang [d)]

a) Christian Doppler Laboratory for Metallurgical Applications of Magnetohydrodynamics

b) Chair for Modeling and Simulation of Metallurgical Processes, Department of Metallurgy, Montanuniversitª t,

c) INTECO melting and casting technologies GmbH,

d) RHI Magnesita, Department of Modelling and Simulation

Mohamad.al-nasser@unileoben.ac.at

INTRODUCTION

Electric Arc furnace (EAF) experienced exponential popularity since kicking into industrial metal production in the past few decades. Electric arc furnace technology subsides more than 25 % of steel production currently. Despite the aforementioned, electric arc -the core of EAF- is still operated empirically and profound knowledge in theory and dynamics is still sought for better efficiency of operation. Due to extreme conditions around the arc, numerical modelling provides a helpful tool to study the behaviour of the arc and metal bath during the process. This paper presents a numerical model which is being in continuous advancement and can simulate several important phenomena inside the arc and liquid metal bath for both scientific and industrial enhancement.

Electric Arc Simulation

The physical configuration of the model entails the arc and its micro environment. The domain is modelled as 2D axisymmetric geometry. In addition to the arc gap where the arc propagates, the domain accounts for both the cathode (electrode surface) and anode region (liquid metal surface).

The model is based on the local thermal equilibrium (LTE) assumption in the continuum regime as a single-phase compressible flow. The model is simulated by solving the continuity, momentum and energy equation in addition to the induction equation to solve the electromagnetism and MHD effects. Moreover, due to the high velocity turbulence effect is accounted for through including the K-epsilon (k-Ů) turbulence model.

Two Simulations were performed a temperature dependent density function and ideal gas formulation.

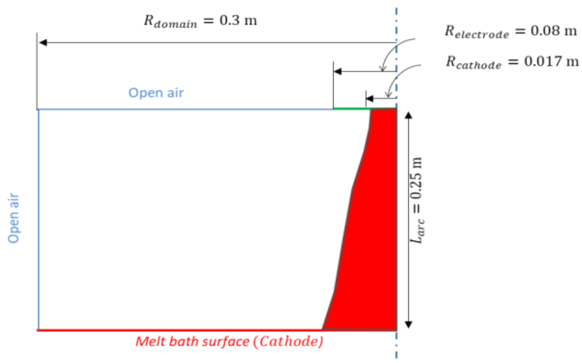

Fig. 1 2D axisymmetric Geometry of arc domain

Conducting Liquid Bath

The conducting liquid bath is simulated in a 2D axisymmetric model consisting of a cylindrical bath in direct contact with two electrodes. The current enters the domain from the top boundary (top electrode), and leaves it from a small bottom electrode. All other boundaries are assumed to be electrically insulated. The dimensions of the domain are taken such that the ratio of the electrode radius, as well as the electrode to the height of the domain is 1 to 5.

The flow inside the conducting liquid is treated as an isothermal flow. In addition to the continuity, Navier-Stokes, the induction equations are solved to predict the electric current density and magnetic fields. Effect of the turbulence is estimated with the SST K-omega model.

Slag and Liquid metal Impingement

The single-phase model used to simulate the electric arc is modified to simulate multiphase and the domain is extended downwards to include slag and liquid metal bath.

RESULTS

1) The single-phase arc simulation shows very similar velocities and behaviour as what have been calculated and observed previously [1]. The arc behaviour and overall structure is preserved when compressibility is accounted. The dynamics of the arc are similar despite that compressibility damps the flow relatively.

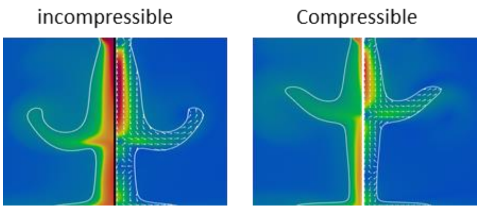

Fig. 2 Hydrodynamic instability for incompressible and compressible flow.

Important effect of Compressibility is additional voltage drop (Fig.3) and this difference explains a problem stated previously [2].

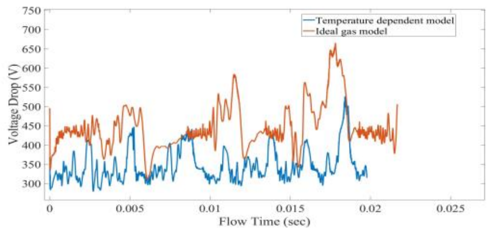

Fig. 3 Arc Voltage drop

2) Applying current inside liquid metal bath induces an electro vortex flow in the absence of magnetic field. In the presence of magnetic field different structures develop inside the bath: tornado, cyclone and inverted tornado. Fig. 4

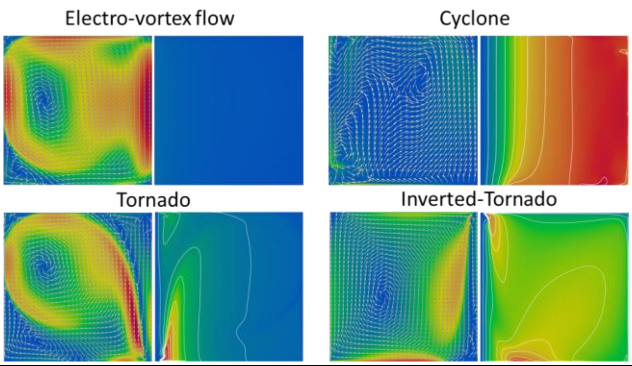

Fig. 4 Flow distribution inside conducting liquid the left is poloidal flow and right is azimuthal flow

3) The multiphase model is able to combine fast dynamics of the arc and its interaction with the liquid bath below it. The results show that the current is the major factor affecting the depth of impingement while the initial arc gap determines the arc stability.

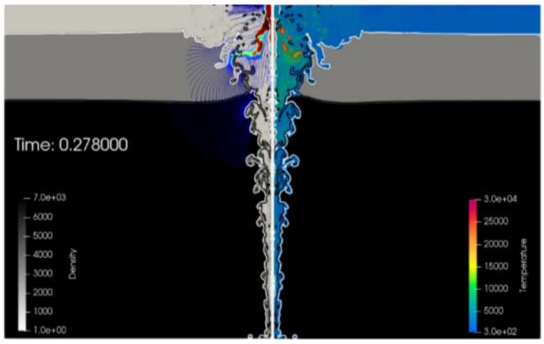

Fig. 4 30 kA arc impinging slag and Liquid metal

CONCLUSION AND OUTLOOK

The model presented in this study proves to be capable of predicting the behaviour of detailed arc dynamics. The arc shape and dynamic instabilities were observed in the simulation. Compressibility appears to answer some previously unanswered questions regarding the voltage drop difference between experimental and calculated values [2].

The model was able to predict precisely the magnetohydrodynamic pumping inside liquid metal bath in addition to the effect external magnetic field on redirecting the flow.

The multiphase model enables two-way coupling of the arc and free surface of liquid. This contributes to capture the arc impingement and the thermo-electrical effect on both the arc and molten metal in a DC-EAF.

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The stirring of melts in EAF

A. Chudnovsky,

JSC LATVO, Ganibu Dambis str., 53, Riga, LV1005, Latvia,
eivf19@gmail.com

INTRODUCTION

An electrically induced vortical flow (EIVF), named also an electrovortex flow, is the inseparable part of EAF. When electrical current passes through a melt, it interacts with a self-magnetic field and generates an electromagnetic force field following by EIVF, [1].

This force field can be used for organizing and controlling of melt stirring. It allows solving many practical tasks effectively and simultaneously. There are the getting of homogeneous melt structure, cleaning a melt of unwanted microelements, protecting of furnace lining from early fracture as well as protecting of built-in bottom electrodes. Chemical additives are added and mixed during a melt stirring process. Finally, both power and material consumptions are decreased. For example, a melt processing in a ladle is not required after steel making in DC EAF UNG (Universal, Next Generation), [2].

From the other hand, additional sources of energy are not required for stirring control. Just the understanding of some basic principles is needed for forming a correct flow pattern. The goal of this article is to describe common principles for EIVF organization and control in a melt bath of various type of EAF.

TASK SETTING

In EAF the melt stirring process is turning on after a scrab melting. Then some basic assumptions become to play a key role in EIVF generation. 1) A melt has constant values of density ρ, viscosity ν and electrical conductivity σ. 2) A thermo-convection can be neglected. 3) There is no a strong deformation of free surface. 4) An electrodynamics approximation $\boldsymbol{V} \times \boldsymbol{B} << \boldsymbol{J} / \sigma$ allows using Ohm's low in a form $\boldsymbol{J} = \sigma \boldsymbol{E}$, where $\boldsymbol{V}$ is flow velocity, $\boldsymbol{B}$ ï self-magnetic field of the current $\boldsymbol{J}$ and $\boldsymbol{E}$ is an electrical field.

So, the electromagnetic force field is calculated (or described exactly) preliminary and expected pattern of EIVF is estimated. Further, the pattern is studied by physical or numerical modelling and a velocity field is checked experimentally by fibre-optical sensor or by thermo-correlation sensor. The governing velocity in EIVF is described by expression

$$V_0 = const * \frac{I}{L} * \sqrt{\frac{\mu_0}{\rho}} \qquad (1)$$

Where **I** is total current, L ï character size, μ_0 ï magnetic constant.

DC EAF WITH AXISYMMETRIC CURRENT SUPPLY

When the EIVF has a pattern of an axisymmetric toroidal vortex, then near-axis jet is directed between arc-melt contact (radius R_1) to a bottom electrode (radius R_2). On a free surface the flow is converging to an axis, so the melt upper layer, heated by arc, with all additions on it are moving down to a bath depth, then along the bottom to a side wall, then turn up to a free surface. Fig.1 shows a scheme and a photo of meridional EIVF cross-section, [3], the axis is dashed.

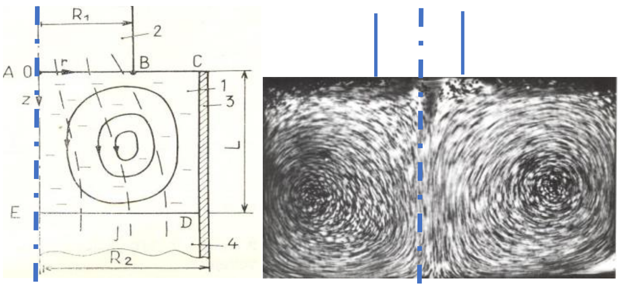

Fig. 1 EIVF in form of toroidal vortex a) a scheme of a meridional plane; b) meridional cross-section , [3]

Maximum velocity V_0 in toroidal vortex exists on the axis in the middle of bath depth. In (1): const = C $\sqrt{M}$, where M = (1 - k^2) / k^2 is an integral flux of electromagnetic vorticity vector through a meridional plane, k = R_1 / R_2 and C å 0,9 is a friction coefficient.

TWIN-ELECTRODES EAF

EAF with two graphite electrodes can be turned on electrically by two ways: when both electrodes are cathodes and an anode is a built-in bottom electrode, or by bifilar scheme. The EIVF in a first case is close to toroidal vortex with doubled (split) upper electrode. The EIVF under bifilar is looking like two diverging fluid jets, Fig.2,a, [1]. Flow circuits near a bottom has a form or two pairs of plane horizontal vortexes,[3]. On an upper view flows are converging to each electrodes, Fig.2,b.

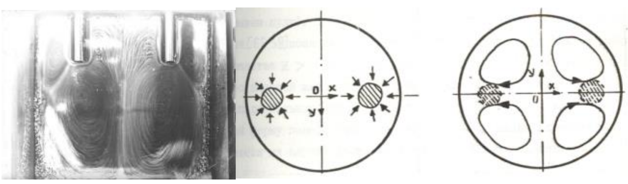

Fig. 2 EIVF near bifilar a) in meridional plane, [1]; flow schemes on free (b) and near bottom (c) surfaces, [3].

The example of physical modelling for bifilar with fully submerged electrodes is described in [4].

3-PHASES EAF

The EIVF pattern in 3-phases EAF can be estimated as a superpositions of three bifilar pairs. The flow circuits at vertical plane is shown Fig.3,a. In near- bottom horizontal plane there are three pairs of plane vortexes, divided by jets of fixed direction (3 points A) and three zones without stirring (3 points B), Fig.3,b. On a free surface the melt is converging to each arc.

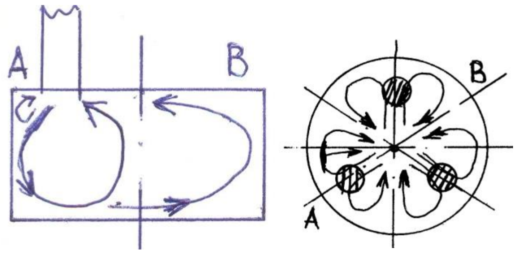

Fig. 3 An EIVF in 3-phases EAF: in a) meridional plane, b) n r bottom surfaces, [3]

Such scheme of melt stirring is not effective. Usually additional melt processing in a ladle is required, sometimes with additional stirring.

THE STIRRING IN DC EAF UNG

There are a central upper graphite electrode with arc and one or any built-in bottom electrodes. A construction allows many variants of EIVF pattern organizing. The result depends on electrode placement and distances between them, low voltage busbar locations, a disbalance between electrode's total currents and other constructive elements of furnace.

Some very specific patterns were observing experimentally during a physical modeling: a horizontal dipole, Fig.4,a, large-scale horizontal self-oscillations, localized vortex with no any liquid movement around it, Fig.4,b-c, and others. In a real furnace the localized vortex concentrates all heat mass transfer from around the melt on itself that leads to quick damage of bottom electrode and washout of furnace lining. Such "a regime of stirring" must be excluded from a process,[3].

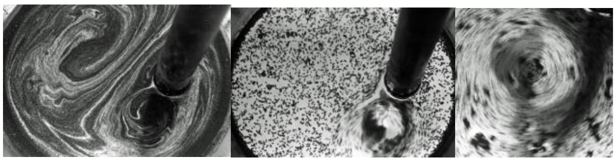

Fig. 4 Some EIVF in DC EAF UNG, [3]: a) dipole on free surface, b) localized vortex, c) large-scaled vortex.

RESULTS

What is a good stirring system? – There must be homogeneous melt microstructure without unwanted microelements (like sulfur, for example) and with protections of furnace lining and bottom electrodes.

That is possible, when the stirring pattern consists of a melt azimuthal rotation around bath axis and the mixing of rotating layers between themselves by toroidal vortexes (under the arc and over each bottom electrodes). Then there are no stable-directed hot jets and zones without stirring. All these requirements are realized in DC EAF UNG. Various EIVF patterns were investigated firstly experimentally by physical modelling and then confirmed by numerical calculations. Finally selected solutions were tested in about 30 industrial DC EAF UNG.

CONCLUSION AND OUTLOOK

The investigation of EIVF was started in 1970th and is not finished still. Not EAF only but many electrometallurgical equipment can be optimized by melt stirring improvement: electrical welding, electro-slag remelting (ESR), furnaces for salt or flux melting, an electric ore smelting in 3-phases furnace, aggregates for slag-metal separation and others. Among EAF equipment the DC EAF UNG has an optimized and controlling stirring system. So, there is a lot of tasks for further investigations and development.

A new physical modelling laboratory was built and run in the LATVO this year, (with low voltage busbar up to 2000 Amperes). It allows to work with laboratory scale experimental models, using cold alloy In-Ga-Sn as a modelling media.

Note also, that many important questions were not described in these two pages abstract. Among them there are an internal structure of velocity field in a toroidal vortex, estimation the influences of thermo-convection and azimuthal rotation, the influence of bath geometry on velocity values, quasi-2D electromagnetic fields around fully submerged electrodes, interaction of counter-moving submerged jets, large-scale non-regular disturbance and many nonlinear effects of flow interactions. These materials will be partly included into a main presentation

ACKNOWLEDGEMNT

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Experimental Study and CFD Modelling of Scrap Melting Behaviour in AC EAF

Yuchao Chen[a)], Steve Ryan[b)], Armin K. Silaen[a)], Chenn Q. Zhou[a)]

a) Center for Innovation through Visualization and Simulation (CIVS),
Purdue University Northwest, 2200 169th Street, Hammond, IN 46323
Phone: 219-989-2665, Email: czhou@pnw.edu
b) NLMK Indiana
6500 S Boundary Rd, Portage, IN 46368, USA

INTRODUCTION

The present study established a new three-dimensional comprehensive model based on the computational fluid dynamics (CFD) to simulate the solid-liquid-gas system in the EAF scrap melting process. The solid scrap was treated as a porous medium that enables the prediction of the liquid and gas permeation and the interactions between phases. The reported study focused on achieving the arc melting simulation, in which the numerical approach based on the heat and mass transfer was applied to capture the local solid scrap melting and the liquid steel re-solidification. An arc module was introduced and coupled into the model to achieve the real-time estimation of the total arc power delivery dependent on the arc current and arc length. In addition, a novel methodology was proposed to dynamically integrate the Monte Carlo method with CFD to predict the share of arc radiation for every computational cell on the scrap surface, wall, and roof based on the electrode movement. A scrap melting experiment was designed and implemented in NLMK 150-ton EAF to collect the necessary data for the model validation. A good agreement was found between the simulation results and the industrial data. The developed model was adopted to visualize the scrap pile profile during the melting for the further prediction of the potential scrap cave-in. Moreover, the arc radiation distribution over time and the liquid steel re-solidification phenomenon was also analyzed in the present study.

DESIGN OF SCRAP MELTING EXPERIMENT

The scrap melting experiment was conducted in the 150-ton NLMK AC EAF to obtain the corresponding data for the subsequent model validation. In order to control the experimental variables and reduce the unnecessary impacting factors, about 70 tons of the same type of scrap (shredded scrap) was used for melting and recording the experimental data during trials. All burners were off to ensure that the arc is the only source of energy input for melting. In addition, a total of three trials with different amperage set points and nominal voltages were performed to obtain different arc power inputs. The accuracy of the proposed model can be validated by comparing the simulated electrode descending and electrode pit size with the corresponding real-time data recording. Under the same furnace operating conditions, the average difference is about 9.9% for the comparison between the measured pit diameters with the simulation results obtain from the present model, and the average difference is about 3.6% for the comparison between the simulated electrode position over time with the corresponding record data.

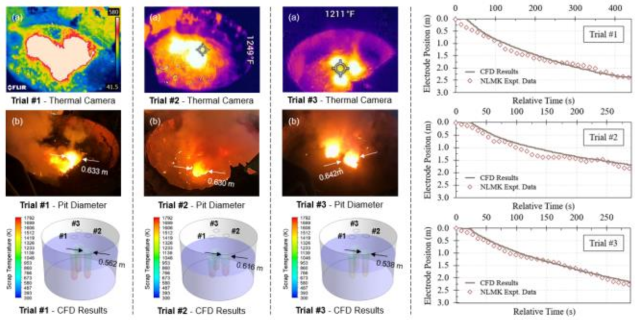

Figure 1. NLMK Scrap Melting Experiment

SCRAP MELTING BEHAVIOUR

Figure 2 plots a series of results to show the melting process of the scrap pile in trial #1 during the electrode bore-down phase. It can be seen that the vicinity of three electrodes is first melted to form three electrode pits. The liquid steel below the pits continuously yields its heat to the cold scrap piece and gas during the dripping process. If the liquid phase temperature in a computational cell is too low to maintain its liquid state, the liquid mass/energy transfer to the solid phase will be triggered to simulate the solidification process. The simulation results also reveal that the liquid steel does not directly drip to the bottom of the furnace. Under the comprehensive effect of external force and heat exchange, the dripping and re-solidification process of liquid steel usually occurs within about 0.8 m starting from the bottom of the electrode pit. During the entire electrode-down phase, the liquid steel will undergo the melt-solidification cycle several times, and the bulk density of the scrap pile may increase as the electrode bores in, which will be illustrated in the later section. When the electrodes get close to the bottom of the furnace, the liquid steel gathers near the vicinity of electrodes to form a molten pool, thereby immersing the solid scrap pieces meanwhile melting them in the bath.

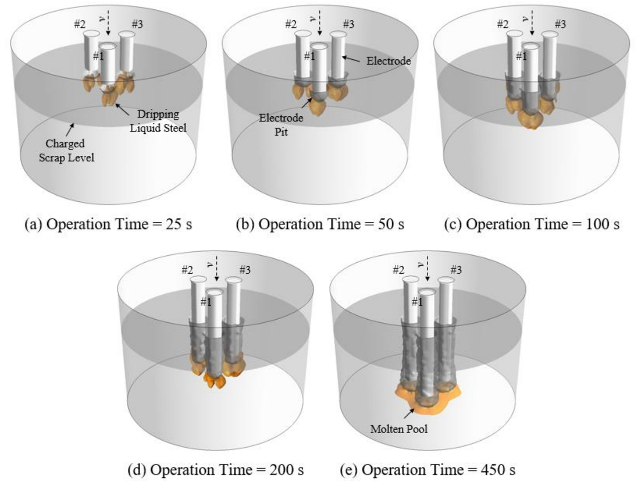

Figure 2. Scrap Melting Behaviour.

ARC RADIATION DURING ELECTRODE BORE-IN

Figure 3 shows the distribution of the arc radiation share on the furnace wall and roof.

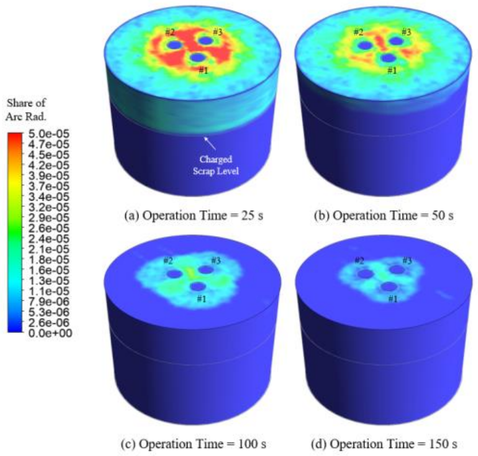

Figure 3. Arc Radiation during Electrode Bore-In.

At the beginning of the electrode bore-down phase, the arc is fully exposed to the freeboard region above the scrap pile. Since the arc is closer to the scrap surface, a large amount of radiative heat is still absorbed by the scrap surface under the electrode tip. Another about 20% of the total arc radiation is distributed on the furnace wall and roof. The strongest arc radiation is located at the roof located around the region of three electrodes, followed by the furnace wall located on the same level as the arc. As the arc gradually bores into the scrap pile, part of the arc radiation previously absorbed by the furnace wall is blocked by the electrode pit, so that the amount of arc radiation to the furnace wall decreases significantly. When there is no longer any visibility between the arc and the furnace wall, the share of arc radiation to the furnace wall reduces to zero. Afterward, only part of the furnace roof above the electrode pits can receive the arc radiation through the pit openings. With the increase of the distance between the electrode tip and the furnace roof, the share of arc radiation on the roof gradually decreases and eventually maintains at a very low level.

LIQUID STEEL RE-SOLIDIFICATION

The dripping liquid steel still has the potential to re-solidify due to the heat exchange with the external environment. Figure 4 shows the variation of the scrap volume fraction over time. In the initial melting stage of the scrap pile, the liquid steel can drop down for a relatively long distance until it solidifies, which is mainly due to the uniform porosity distribution in the pile (the same type of scrap) and the same initial ambient temperature (300 K). The solidification of liquid steel may occur in one or more computational cells along its travel path, which results in the increase of the scrap volume fraction and the corresponding decrease of the porosity. As the porosity decreases, the liquid steel flowing through those regions is more obstructed, further resulting in the corresponding reinforcement of the re-solidification possibility in those regions. The simulation results show that the solidification of molten steel is concentrated in the U-shaped range of 1 meter below the electrode pit. As the melting of the scrap pile continues, the porosity in those regions keeps reducing.

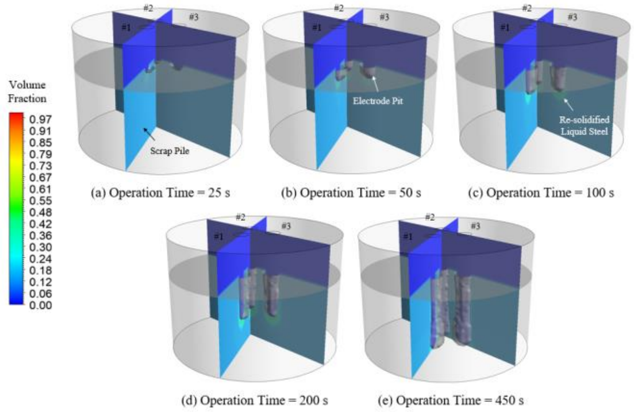

Figure 4. Liquid Steel Re-Solidification.

CONCLUSION AND OUTLOOK

A CFD model was established for the simulation of EAF scrap melting process. The present model integrated an arc module to achieve the real-time estimation of the total arc power delivery and also a Monte Carlo method to predict the share of arc radiation according to the electrode movement. A scrap melting experiment was designed and implemented in NLMK 150-ton EAF and a model validation was conducted, which had a good agreement with the industrial data. The developed model was adopted to visualize the scrap pile profile during the melting. The arc radiation distribution over time and the liquid steel re-solidification phenomenon was also analyzed in the present study.

Session IV

An evaluation of the pneumatic lime injection benefits for the production of C82D2 steel by electric arc furnace
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AN EVALUATION OF THE PNEUMATIC LIME INJECTION BENEFITS FOR THE PRODUCTION OF C82D2 STEEL BY ELECTRIC ARC FURNACE

D. M belli [a)], G. Dall'Osto [a)], G. Villa [a)], C. Mapelli [a)], S. Barella [a)], A. Gruttadauria [a)]
L. Angelini [b)], C. Senes [b)], M. Bersani [b)], P. Frittella [b)], R. Moreschi [c)], R. Marras [c)], G. Bruletti [c)]

a) Politecnico di Milano, Dipartimento di Meccanica, Via La Masa 1, 20156 Milano, Italy
b) Feralpi Holding S.p.A., Via Carlo Nicola Pasini 11, 25017 Lonato del Garda (BS), Italy
c) nicalce S.p.A., Via Ponti 18, 24012 Val Brembilla (BG), Italy
gianluca.dallosto@polimi.it

INTRODUCTION

The pneumatic lime injection during the Electric Arc Furnace (EAF) process by insufflation lances mounted on the furnace walls has gained much interest in the latest years [1]. The main advantages, in comparison to the traditional procedure of lime lumps addition within the scrap bucket, can be summarized in raw materials consumption reduction, foaming benefits, operational cost benefits and improvement in environmental aspects [1,2].

In the proposed work, the advantages of a new lime injection system developed by Unicalce S.p.A. and installed on a 90 t EAF of Acciaierie di Calvisano are analyzed.

PROCEDURES AND DATA COLLECTION

Two different injection procedures labelled INJ1 and INJ2 were used and compared to the traditional practice (STD). In particular, INJ1 procedure used 1 ton of lime less than STD one, whereas INJ2 800 kg less.

Data from more than 600 heats were acquired in order to evaluate the benefits lead by the injection procedures to the electrical, oxygen, methane and lime consumptions for the production of special steels, in particular C82D2 grade.

Statistical analysis has been performed to compare the different procedures by means of the Tukey's method [3] throughout the software MINITAB®. Moreover, the environmental impact was investigated analyzing the Tons of Oil Equivalent (TOE) and CO_2 emission reduction, for electrical and CH_4 savings.

SLAG SAMPLING

The benefits on the slag foamability were evaluated, too. By knowing the chemical composition of the sampled slag, the Isothermal Solubility Diagrams (ISD) were calculated according to the Pretorious's model [4,5]. The ISDs were then validated by comparing the Total Harmonic Distortion (THD) of the corresponding heat [6].

RESULTS

The injection procedures allowed to achieve a saving of about 1 ton of CaO, although this significative reduction, an enhancing of the dephosphorizing effect was observed thanks to the faster dissolution kinetics of the injected lime powder in comparison with the standard lime in lumps addition [7,8].

As can be noted in Fig. 1, the total electrical consumption decreased of 30-35 kWht^{-1} using the INJ1/INJ2 procedures. Most of the electrical savings are concentrated during the refining stage, with a decrease of 20 kWht^{-1} in comparison to the STD procedure. The reason should be related to the initial reduction of 1 ton of lime, which means a lesser amount of material to be melted, together to a better foaming condition. The introduction of lime injection has also allowed a reduction in the power-on time of about 1.5 minutes in comparison with the traditional procedure.

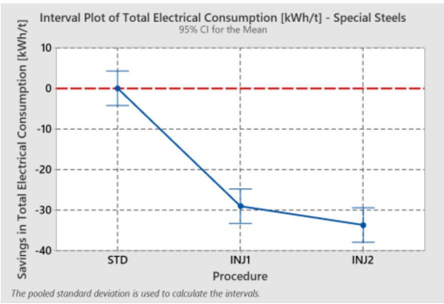

Fig. 1 variation of total electrical consumption switching from STD procedure to INJ1/2 procedures.

Furthermore, the enhancing of the furnace performances, brought by the injection procedure, were compared with the theoretical savings evaluated through the Köhle method [9,10]. By taking into account all the parameters modifications led by the injection procedures, a theoretical electrical savings value of about 15 kWht^{-1} was obtained. Therefore, it is possible to assume that the higher values observed for both INJ1 and INJ2 procedures are due to the enhancing of the slag foamability, which is a parameter not considered in the model.

The reductions observed for the methane consumption can be related to the higher reaction rate achieved thanks to the injection of lime in fine particles, which guarantees an enhancement of the process efficiency. Similarly, the oxygen consumption had a general decrease. However, a weak increase of oxygen consumption between INJ1 and INJ2 procedure was observed. It is possible to assume that due to the lower amount of slag produced, less chemical energy is required for the heating; therefore, explaining the reduction of both the electrical and CH_4 consumptions.

The ISD diagrams highlighted how, during the STD procedure (Fig. 2(a)), the slag was over-saturated in MgO, consequently too "crusty" and prone to collapse even though an enough bubbles dispersion is formed within the slag [11]. On the other hand, during the INJ1 procedure (Fig 2(b)) the slag seems to be correctly saturated with respect of MgO at the end of refining stage, with a subsequent increase of the refractories lifetime. The THD analysis confirmed the above assumption, decreasing its value from 11.5 (partially uncovered arc) to 10.5 (well covered arc) switching from STD to INJ1 procedure.

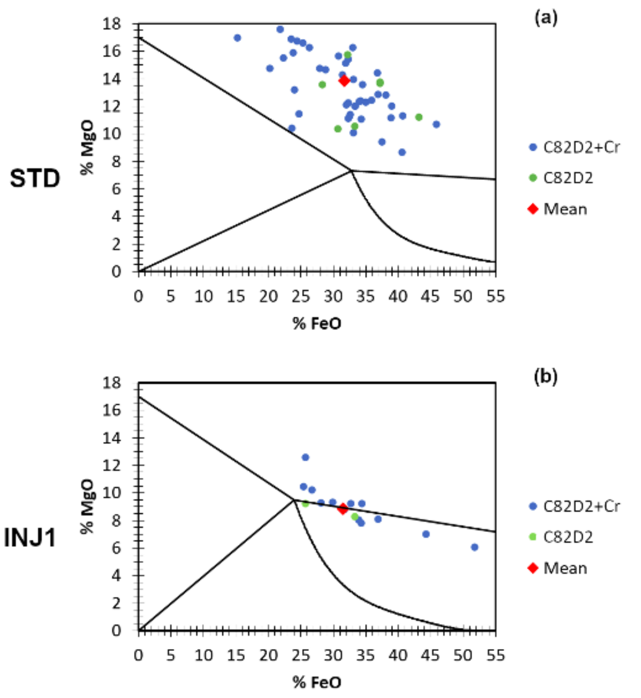

Fig. 2 ISD at 1600 °C: (a) STD, (b) INJ1.

CONCLUSION AND OUTLOOK

In this work, a new method for the injection of fine lime particles in the EAF of the Acciaierie di Calvisano was investigated.

The aim of this study was to analyze and validate the benefits of lime injection compared to the traditional "lump charging" technique.

More than satisfactory benefits have been observed by the application of the injection procedures.

The reduction of 1 ton of CaO, thanks to the injection procedures, allowed to decrease both the electrical and chemical energy demand of the EAF enhancing at the same time the slag foamability.

In particular, the electric consumption was reduced by 20-30 $kWht^{-1}$, with most of the savings concentrated in the refining stage (66.5%); power-on time was also reduced of about 1-1.5 minutes using injected lime. Oxygen and methane consumptions were also reduced of 1.5 m^3t^{-1} and 0.5 m^3t^{-1}.

Taking into account the electrical and methane savings an average of 3,460 t/year and 552 t/year of equivalent CO_2 were calculated. Corresponding to a value of 2,342 and 446 in TOE, respectively. Considering the carbon tax, according to EPA (Environmental Protection Agency) who fixed the CO_2 social cost to 30 €/t (50 €/t not later than 2030 [12]) the not emitted CO2 correspond to a saving of 117,180 €. Alternatively, according to a study by Stanford University [13], the social cost saving associated to not emitted CO_2, can be equal to 722,608 €, for a CO_2 social cost estimated to 185 €/t.

The investigation carried out on the ISDs, validated by the THD of the corresponding heat, highlighted which procedures lead to the best foaming condition. In particular, the optimal slag foamability was reached for the production of special steels by the use of the INJ1 procedure.

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Static dissolution evaluation of dolomite-based materials in EAF-type slag

S. Scheiber[a)], E. Cheremisina[a)], J. Rieger[a)], J. Schenk[b)], F. Firsbach[c)], W. Johnson[c,d)], T. Chopin[c)], M. Nispel[c)]

a) K1-MET GmbH, Metallurgical Competence Centre
b) Montanuniversität Leoben, Chair of Ferrous Metallurgy
c) hoist Business Innovation Center (BIC)
d) hoist North America (LNA)
stefanie.scheiber@k1-met.com

INTRODUCTION

In steelmaking fluxes are added to form a basic slag with desired chemistry to enable refining reactions and subsequent higher steel quality. Thus, CaO and MgO carrying additives, such as lime or dolomite are added, whereas dolomite simultaneously decreases the refractory wear by MgO saturation in the slag. [1]

Raw dolomite comprises mainly the double carbonate $CaMg(CO_3)_2$, which is stepwise transformed to CaO and MgO particles during calcination. The calcination proceeds gradually. In the range of 600–700 °C, magnesium carbonate decomposes first and MgO gets enriched at the outer surface of the material. From 700 °C to 900 °C, the decarbonation of the remaining $CaCO_3$ proceeds. Besides, the specific surface of the additives increases during the calcination. [2–5]

Conventionally, the calcination is executed in rotary or shaft kilns at the production site with subsequent cooling of burned additives for transport to steelmaking industry. The outlined method is accompanied by extensive heat losses and large amounts of CO_2; thus, the direct applicability of raw dolomite is of interest. Assuming that the in-situ decomposition under high-temperature steelmaking conditions leads to high reactivity and rapid dissolution, dense surface layers as well as low overall porosity may result due to the process conditions. These properties immensely decrease the dissolution because cracks and macropores facilitate the infiltration by liquid slag. Additionally, the highly endothermic character of decarbonisation causes locally an extensive drop of slag temperature if the required heat supply is missing. [6, 7]

STATIC DISSOLUTION BEHAVIOUR TESTING

The impact of calcination condition on the dissolution of disc samples made of raw, soft- and hard-burned dolomite (also called dolime) was evaluated in laboratory scale tests under static conditions. The additive samples (cf. **Tab. 1**) were immersed in molten synthetic Electric Arc Furnace (EAF) slag prepared of chemically pure powders with an initial composition of 10 wt.-% Al_2O_3, 25 wt.-% SiO_2, 25 wt.-% CaO, 8 wt.-% MnO and 32 wt.-% FeO at 1,450 °C under N_2 gas atmosphere. After 10 min reaction time, slags were quenched with liquid nitrogen to analyse the current dissolution status on metallographically prepared cross-sections by Scanning Electron Microscopy with Energy Dispersive X-Ray spectroscopy (SEM/EDX).

PROFILE EVALUATION

SEM/EDX analyses using FEI QUANTA 200 in low vacuum were carried out to determine the bulk slag composition. The oxide contents of MgO, Al_2O_3, SiO_2, CaO, MnO and FeO have been examined at defined distances of 2 mm from the crucible wall as a reference line to generate so-called concentration profiles (unknown position of the completely covered sample prior to cutting; cf. **Fig 1**). Hence, the mean oxide values per image were calculated based on at least two analysis areas of constant size (270 µm by 200 µm). Areas with changed morphology and chemistry, i.e. remaining sample parts or slag/sample interlayers, were eliminated. This method enables the evaluation of favourable calcination condition.

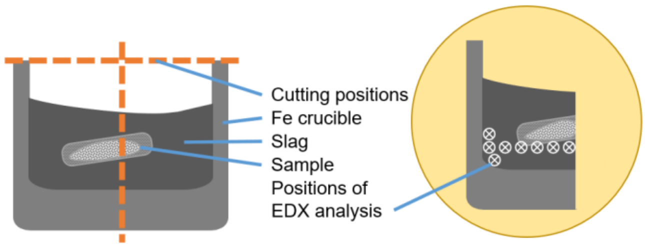

Fig. 1 Schematic preparation of SEM sample and positions of EDX analysis

RESULTS

A static experimental setup using synthetic EAF slag and disc samples was selected. **Tab. 1** shows the theoretical bulk slag compositions (target contents) under assumption of complete additive dissolution calculated from composition and added sample mass. The pure iron crucibles, applied to stabilise the FeO in slag, resulted in unwanted iron uptake in the vicinity to the crucible. Besides, the static conditions led to local enrichments next to the sample-slag interface and thus, higher amounts than the theoretical maximum were partially observed. However, since there was no added magnesium oxide in the starting slag, the total MgO measured via EDX analyses originated from the partial dissolution of dolomite.

Tab. 1 Theoretical slag composition after complete sample dissolution without iron uptake from crucible

No.	Sample	Target content of oxide X [wt.-%]					
		MgO	Al_2O_3	SiO_2	CaO	MnO	FeO
1	Raw 1	3.8	9.0	22.5	28.8	7.2	28.7
2	Raw 2	4.2	9.0	22.5	28.3	7.2	28.8
3	Soft 1	3.4	9.0	22.6	28.9	7.2	28.8
4	Soft 2	4.2	9.0	22.5	28.3	7.2	28.8
5	Hard 1	3.7	9.0	22.5	28.9	7.2	28.7
6	Hard 2	4.1	9.0	22.6	28.2	7.2	28.9

The concentration profile of test no. 2 in **Fig. 2** shows the oxide content fluctuations along the cross-section.

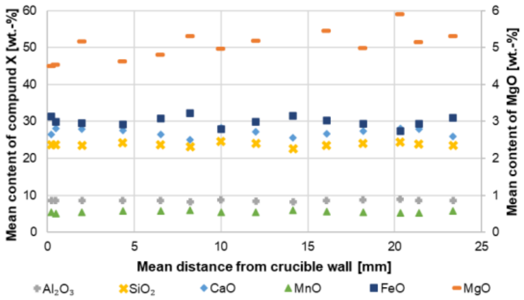

Fig. 2 Exemplary oxide concentration profiles along the cross-section calculated from SEM/EDX analyses of bulk slag areas

Due to the high mobility of iron at temperatures close to its melting point, the slags' FeO contents exceeded the expected values. The amounts of Al_2O_3 and MnO were relatively constant along the cross-sections. The addition of dolomite should lead to a rise in CaO and MgO content. The CaO levels were even below the SiO_2, if soft- or hard-burned dolomites were applied in dissolution tests. The amount of calcium oxide in slag increased due to the addition of raw dolomite samples and exceeded the SiO_2 fraction. Concerning MgO, the concentration profiles differed strongly depending on material condition. The MgO content in slag after the test with raw dolomite 1 showed a smooth profile with 4.4 wt.-% MgO on average. In the case of raw dolomite 2, a further rise in the MgO trend towards the centre of the slag cross-section was observed with the highest total mean MgO value. The experiments with soft- and hard-burned materials showed stronger fluctuations in MgO profiles due to missing oxide equilibration by natural convection and absence of in-situ decomposition gas stirring. Moreover, the total mean contents of MgO were only 2.3 wt.-% and 1.6 wt.-% in case of soft-burned materials. Assuming that the porosity was lower due to increased sintering, the dissolution of hard-burned dolomite should be even lower than that of soft-burned material. The profiles as well as the bar chart of total mean values in **Fig. 3** confirmed the expected trend. The MgO content was below 2 wt.-% on average.

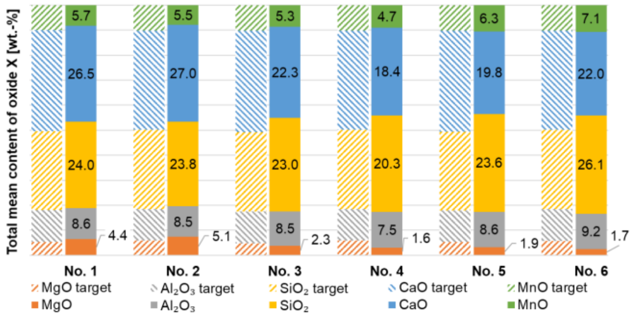

Fig. 3 Total mean oxide contents of bulk slags (FeO excluded) with target contents according to Tab. 1

CONCLUSION

The raw dolomite samples showed a proper dissolution behaviour. It was assumed that released CO_2 due to in-situ decomposition of the carbonates in the raw dolomite samples led to a stirring effect. In contrast, the dissolution performance of hard-burned dolomites without any remaining carbonates was lower in these static dissolution tests. However, the smoother calcination conditions of soft-burned dolomites resulted in higher porosity compared to hard-burned specimens. Their dissolution behaviour was between raw and hard-burned dolomite samples.

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Achieving a new level of process efficiency in EAF steelmaking with sample preparation free slag analysis based on Laser OES

Alexander Schlemminger[a)],

a) alexander.schlemminger@quantolux.de

INTRODUCTION

Resource as well as energy efficiency is one of the most important factors for economical success in today's highly competitive steel making industry. To reach a maximum energy efficiency an effective raw material procurement, motivated employees, modern equipment and last but not least the optimized process control is the key to success. In order to monitor the steelmaking process, a variety of measures and sensors have been introduced in the past. However, the composition of the slag, which is much more important for process control than the analysis of the actual steel itself, could not be analyzed quickly enough to correct the process within the required time. Especially in the electric furnace, important information like the basicity or content of elements like Cr, S and F is missing.

FIRST SECTION

In the event of a deviation, a defective basicity leads to significantly higher energy consumption due to inadequate foaming behavior of the slag and thus to a lack of insulation resulting in high energy losses. Furthermore, it can cause a high consumption of refractory material and thus, lower equipment lifetime on the one hand and lower product quality e.g. due to impurities on the other hand. Especially since EAF steel making is undergoing a significant change within the context of the decarbonization of the steel industry, this is an important point. Among other things, the use of Direct Reduced Iron (DRI) will lead to extended phases of foaming slag, which in turn will increase the negative effect of the delay of slag analysis.

Moreover, the long analysis times of the slags are caused by their heterogeneity. Therefore, they have been analyzed with X-ray-based methods with prior sample homogenization for more than 50 years. The common approach to homogenize heterogeneous materials, samples were crushed, grinded, demetallized and pressed or re-melted. This took 6-30 minutes on average depending on the degree of automation and it was therefore costly due to the amount of equipment required. In addition, each sample preparation also leads to a sample preparation error. This additionally compromises the representativeness of the result and thus the usability.

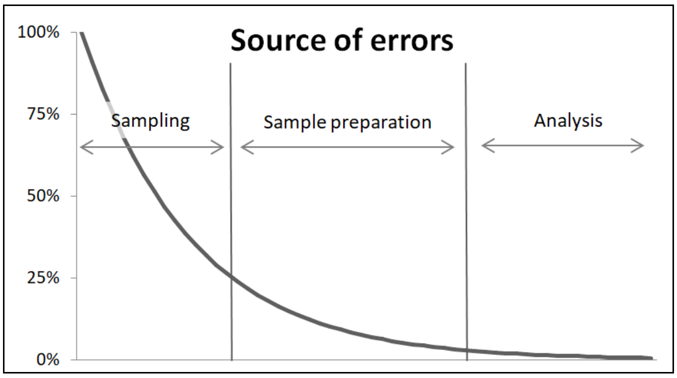

Fig. 1 Impact of single errors to the representativeness of the analysis results

Due to that complexity steel making slags have been analyzed mostly in central laboratories somewhere on the steel mill site rather than near the furnace. In contrast to that, steel samples for example are increasingly analyzed in the control room close to the melt shop. Thus, in addition to the analysis time, time must be calculated in for cooling, packing and shipping the sample, usually by pneumatic tube.

Only a few steel mills can wait that long for LF and EAF slag analysis results. Therefore, in most of the cases the steel further treated and transferred to the following treatment stages without having the slag composition on hand. The results of the analysis can then only be used for post-mortem evaluation and, if necessary, for adjusting subsequent melts. Thus, further optimization of the process control is very limited.

2ND SECTION

Laser-based optical emission spectroscopy (laser OES) is becoming increasingly established as an alternative to existing analysis approaches. It works equivalent to spark spectrometry but with the essential difference that the plasma is not ignited by an electric spark but by a laser. The energy pulse created by the laser transforms minimal amounts of the sample material into a plasma, which emits a light during degeneration which is specific to the elemental composition of the sample at that point.

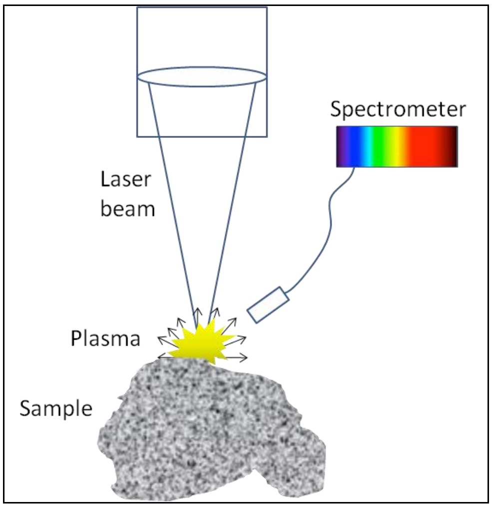

Fig. 2 Laser OES principle on heterogeneous sample

The light is then detected by a spectrometer and converted into a digital signal. Since the laser OES is capable of generating thousands of measurements in a few seconds, the tremendous amount of data can be evaluated on the basis of an appropriate calibration. In addition to its speed, the laser as a plasma excitation source is also particularly stable and hence far more durable than the available radiation sources for X-ray-based analysis. Furthermore, the non-contact measurement minimizes negative effects on the measurement such as dust and dirt contamination or high temperatures.

RESULTS

In this way, it is possible to analyze the heterogeneous slag at many thousands of individual points and to digitally homogenize these measured values to one stable analysis result.

Physical homogenization of the sample is no longer necessary. This is not only efficient but also smart in regards to Industry 4.0. Thus, an overall measurement time of less than 2 minutes is achieved, which enables direct and precise process adaption in the EAF.

Another advantage of Laser OES is that light elements or halogens such as fluorine can also be analyzed. Thus, the CaF content can be adjusted more precisely, which is due to more and more strict environmental requirements relevant. Thereby slag can reliably sold as a byproduct instead of costly disposals in land filling

CONCLUSION AND OUTLOOK

Summarizing, steel mills do have the opportunity now to use their resources even more efficiently. They can produce higher quality, increase the operating life of their equipment and minimize the disposal costs of slag. All this can be achieved without significant changes to the production facilities, simply by adapting the analysis strategy and to adjust their melt shop process control. In line with the motto "those who know a lot can optimize a lot", savings of over €1 per ton of steel produced can be achieved. With production volumes of over 1 million t / year, savings in the mid seven-digit € range can be targeted in this way. This increase in efficiency is an important factor for the competitiveness of steel mills worldwide.

Optical emission spectroscopy in electric arc furnaces and ladle furnaces – from laboratory to industrial applications

H.Pauna[a)], M. Aula[a)], M. Huttula[b)], and T. Fabritius[a)]

a) Process Metallurgy Research Unit, University of Oulu, P.O. Box 4300, FI-90014 Oulu, Finland
b) Nano and Molecular Systems Research Unit, University of Oulu, P.O. Box 3000, FI-90014 Oulu, Finland

Contact email: henri.pauna@oulu.fi

INTRODUCTION

Steel is one of the most recycled materials in the world, and electric arc furnaces (EAFs) together with ladle furnaces (LFs) are the main units to process the recycled scrap metal [1]. As the steel recycling rate, furnace capacities, and the electricity-based steelmaking overall are expected to increase, the real-time response of the analysis system becomes more and more important. One promising on-line measurement tool for EAFs and LFs that can withstand the furnace conditions is optical emission spectroscopy (OES). In this paper, the recent experimental OES research for EAFs and LFs is reviewed. The research includes a small-scale furnace (University of Oulu, Finland), a pilot-scale furnace (RWTH Aachen University, IOB, Germany), and industrial furnaces (Deutsche Edelstahlwerke, Germany).

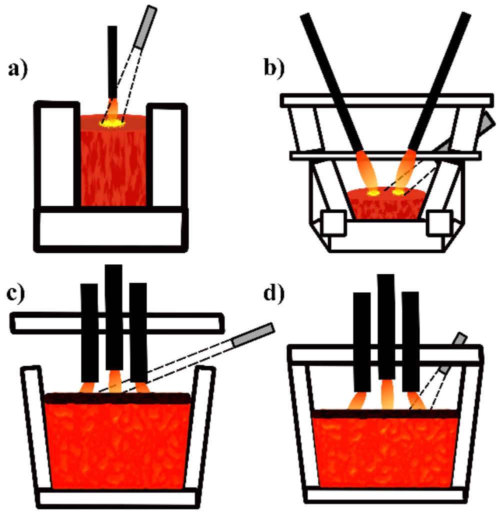

Fig. 1. Example view cones into the arc for a) laboratory, b) pilot-scale, c) industrial ladle furnace, and d) industrial electric arc furnace. The OES measurement head has been indicated with a gray bar and the view cone into the furnace with dashed lines.

EXPERIMENTAL

Schematic illustrations of the measurement setups for small-scale, pilot-scale, and industrial furnaces have been presented in Fig. 1. The capacity of the pilot-scale EAF was 200 kg of liquid steel. The capacities of the industrial EAFs were 120 and 140 t depending on the steel grade, whereas the capacity of the industrial LF was 140 t. The spectrometers were Czerny-Turner Avaspec-ULS2048 provided by Luxmet Oy. The spectrometers covered ultra-violet (UV), visible (VIS), and near-infrared (NIR) regions of the spectrum of light.

THEORETICAL

Plasma temperature and electron density are the fundamental parameters that describe the plasma. The plasma equations that have been used are

$$N_e = C\sqrt{T^3}\frac{I_{mn}^z \lambda_{mn}^z A_{ij}^{z+1} g_i^{z+1}}{I_{ij}^{z+1}\lambda_{ij}^{z+1}A_{mn}^z g_m^z} exp\left(\frac{E_m^z - E_{ion} - E_i^{z+1}}{kT}\right) \quad (1)$$

$$ln\left(\frac{\varepsilon^z \lambda_{mn}}{g_m A_{mn}}\right) = -\frac{1}{kT}E_m^z + ln\left(\frac{hcN^z}{4\pi U^z(T)}\right) \quad (2)$$

$$N_e \geq 1.6 \times 10^{12}\sqrt{T}(\Delta E)^3\ cm^{-3} \quad (3)$$

where Eq. (1) is the Saha-Boltzmann equation for electron density, Eq. (2) is the Boltzmann equation for plasma temperature, and Eq. (3) is the McWhirter criterion for the fulfilment of local thermodynamic equilibrium (LTE). Full description of these equations can be found elsewhere [2,3]. The electrons are the main particles that distribute the heat energy inside the plasma [4], and thus exceeding the McWhirter electron density criterion means also that the heat in the plasma is more uniformly distributed.

RESULTS AND DISCUSSION

Example spectra for pilot-scale furnace, industrial ladle furnace, and industrial electric arc furnace have been presented in Fig. 2. In comparison to the industrial spectra, finer details can be observed in the IOB

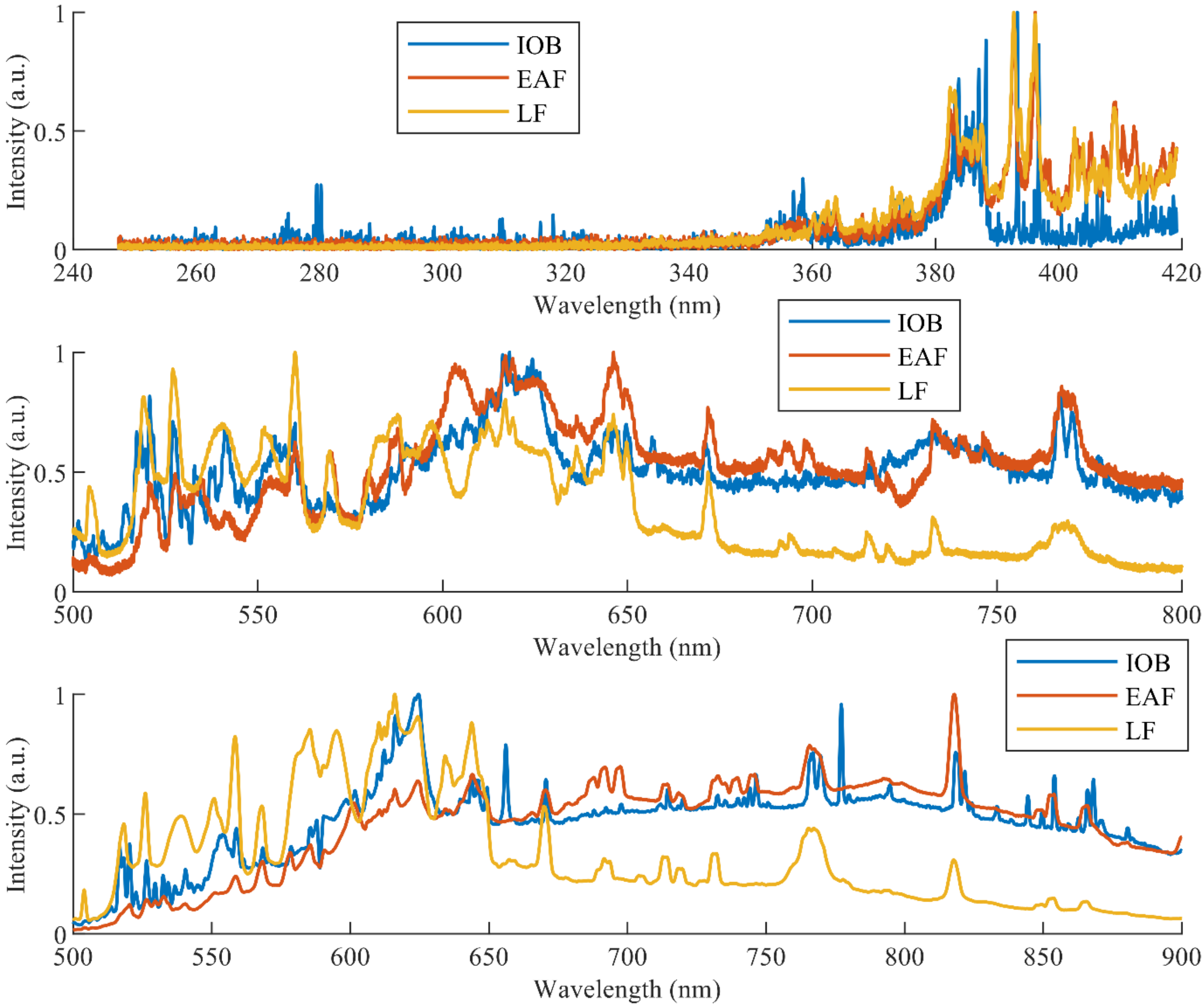

Fig 2. Spectra from pilot-scale furnace (IOB), industrial electric arc furnace (EAF), and industrial ladle furnace (LF). The intensities have been normalized for comparison purposes.

spectra. This is caused by several factors since e.g. the furnace atmosphere and heat radiation are not as extreme in the pilot-scale furnace as in industrial furnaces. The light, especially in the UV range, is effectively absorbed by the gases in the furnace atmosphere, and thus the harsh environment may lead to absorption of light. Weaker emission lines, on the other hand, might not be distinguishable if the emission lines are overwhelmed by the intensive heat radiation or other intensive emission lines.

All of the spectra in Fig. 2 have many intensive emission lines from the atomic slag components and molecular sources. The atomic optical emissions originate mainly from Cr I, Fe I, Ca I, Ca II, Mg I, and Mn I with few lines also from Al I and Si I. The Roman numeral refers to the ionization degree of the atom (I = neutral, II = singly ionized). Atmospheric components, such as N I, C I, H I, and O I, are also observed together with K I, Na I, Li I, and Rb I. The most intensive molecular optical emission comes from cyanide (CN) with intensive emission bands at 355 and 385 nm [5].

The preliminary OES tests were conducted in the University of Oulu on a small-scale furnace by Mäkinen et al. [6] already in 2013. Afterwards, Aula et al. [7] identified emission lines of various components that are usually present in slags. They found several suitable lines for the evaluation of Cr_xO_y/Fe_xO_y and MnO/SiO_2 slag components. Another laboratory EAF was used for OES measurements at The Royal Institute of Technology (Sweden), where image analysis was combined with OES plasma analysis and used to study the foaming conditions [8].

The OES measurements in the pilot-scale EAF have included studies on the on-line analysis of Cr_2O_3 content [9] and arc plasma characterization [10]. These studies have brought new insight into the on-line applicability of the OES and how the quality of the spectra can be evaluated with plasma diagnostics. An example of plasma diagnostics for a pilot-scale measurement is presented in Fig. 3. The electron density (Eq. (1)) is usually several magnitudes above the LTE criterion density (Eq. (3)). Plasma temperatures (Eq. (2)) that are derived from different atomic species, on the other hand, have been observed to deviate from one another and range from 4000 to 12000 K. Differences in plasma temperature can be attributed to non-satisfactory LTE conditions [2].

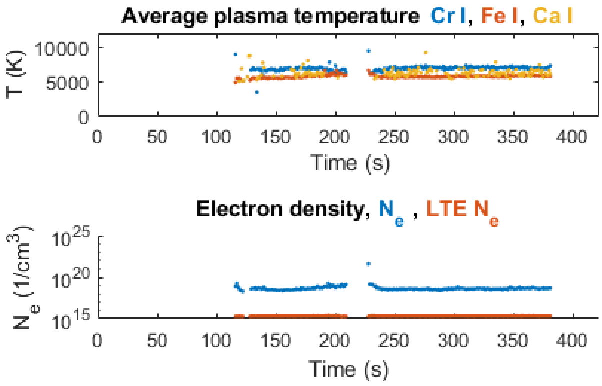

Fig. 3. Example plasma diagnostics in an IOB measurement.

In the industrial EAF campaigns, the focus has been on the process condition characterization [11], monitoring of the slag surface conditions and furnace atmosphere [12], plasma analysis as a tool to evaluate the spectrum quality for slag composition analysis [13], and OES as a process monitoring tool [14]. The equipment withstands the EAF process conditions even if the measurement head is attached to the EAF roof. A recent study on the industrial LFs has focused on the slag composition analysis for CaF_2, MgO, and MnO together with plasma diagnostics [15].

CONCLUSIONS AND FUTURE WORK

OES has proven to be a valid option for the development of on-line method for slag composition analysis and process control in industrial EAFs and LFs. In addition to the on-line applicability of OES, the measurement equipment is simple, withstands the harsh process environment, and requires only minimal maintenance when installed properly. The data validation and quality control can be made with plasma diagnostics.

The on-line slag composition analysis tool is probably the most prominent application of the OES in the EAFs and LFs, but the method has the potential to be used also to observe radiative heat transfer, molten bath surface temperature, process conditions, and melting of the charge material. Furthermore, OES can be used to study flames and practically any other sources of light, making e.g. burner studies with OES viable. Potential and promising OES research in the future, just to name a few, include the development of on-line process control for EAFs and LFs, flame studies, and coupling OES with models.

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Session V

Digital transformation of the steelmaking industry: An EAF case study

V. Logar, S. Tomažič, G. Andonovski, A. Blažič, I. Škrjanc
Faculty of electrical engineering, University of Ljubljana, Tržaška 25, SI-1000 Ljubljana, Slovenia
vito.logar@fe.uni-lj.si

INTRODUCTION

In the past decade, steelmaking industry has been a subject of increasing importance in terms of its digitalization and informatization. The reason for this lies in increased market competition, higher consumer demands for the final products, stricter environmental regulations, as well as in a strive for lower energy and raw material use. Even today, many of the steelmaking plants still manufacture their products in a very similar manner as they did twenty or more years ago, meaning that very few software-support systems exist that give the opportunity for a potentially higher plant efficiency. Nevertheless, there were already many attempts to enhance several steelmaking systems by introducing advanced software support systems. Since the introduction of process monitoring and data acquisition systems, also known as SCADAs, most steelmaking plants acquire large amounts of process data, which is mainly used for process monitoring and fault detection; however, it also facilitates the development of advanced digitalization and informatization of plant processes.

BACKGROUND

Faculty of electrical engineering, University of Ljubljana cooperates in an ongoing EU Horizon 2020, SPIRE initiative project INEVITABLE (Optimization and performance improving in metal industry by digital technologies), primarily focusing on the introduction of advanced software methods for improving the performance of the steelmaking industry. In the scope of the project, several steelmaking processes are being addressed as subjects of digital transformation, such as the electric arc furnace (EAF), ladle furnace (LD), vacuum degassing (VD), cold-rolling mill (ZRM), and metal casting. All these processes will be a subject to full digitalization and upgrade to different levels of advanced software support, which will consist of mathematical process models, data-based process models, as well as mathematical and data-driven process optimization. The main goals of the project are focusing on decreased resource use (energy and materials) and green-house-gas (GHG) emissions. One of the three proposed use cases is led by the Faculty of electrical engineering and is devoted solely to the digitalization, optimization and advanced software support of the EAF.

EAF DIGITALIZATION CONCEPT

The concept of EAF digitalization and advanced software support can schematically be represented in Figure 1. The idea of EAF digitalization is to use the appropriate data acquisition systems to obtain all necessary EAF measurements, use them in either an online or an offline manner in different software tools intended for enhanced process monitoring, advanced operator decision support, or advanced process optimization, and finally, to use the outputs of these tools for process improvement. The tools developed, integrated into the industrial environment, and used to increase the process efficiency in the scope of the INEVITABLE project (EAF use case) comprise of two main solutions, i.e. the mathematical models of the EAF (used for offline simulation and online process monitoring), and the EAF optimization framework (used for offline EAF profile optimization).

MATHEMATICAL EAF MODELS

As already mentioned, the first proposed solution are the mathematical EAF models. These models represent the foundation to all other implemented methods. The idea behind the models is to describe certain parts or subprocesses of the EAF with sufficient accuracy and thus, use them as a basis for process monitoring, estimation of the unmeasured process values, process simulation, and EAF profile optimization. In the scope of the project, two different approaches regarding the process modelling are taken.

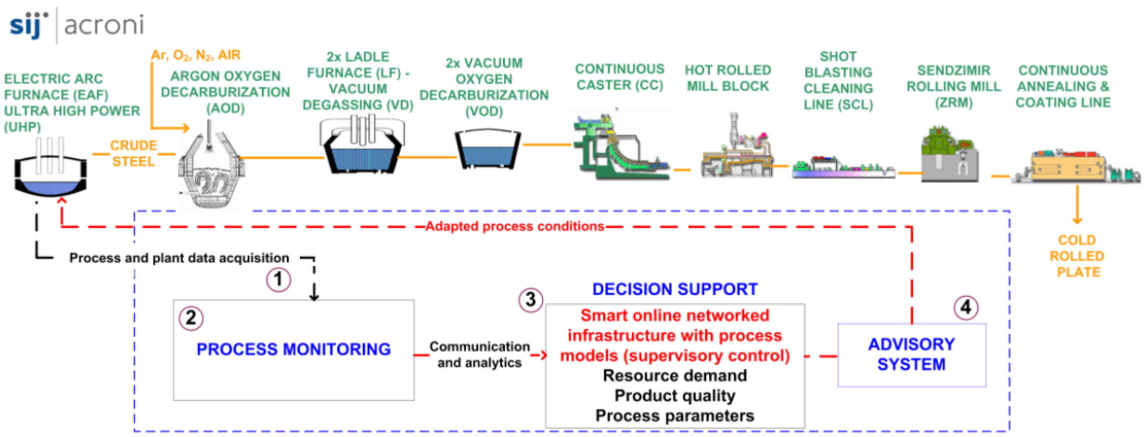

Figure 1: schematic representation of the EAF use case

The first approach is based on theoretical background, meaning that the developed EAF models are designed on known theoretical and physical laws and parameterized using the available EAF measurements. The aim of these models is twofold. First, these models will be used in an online manner for process monitoring and estimation of the unmeasured process values, such as the furnace temperatures, energy balance, and the stage of melting. Second, the models will also be used in an offline manner for testing different EAF operation scenarios, aiming to give additional information to the technologists. In this regard, the users will have a possibility to simulate different melting programs, and different charging patterns and simultaneously observe their influence on the overall EAF performance. Theoretical EAF models have been developed by our group in the past and modified several times [1-6]. Existent models were simplified (simpler geometry and chemistry), parameterized using actual EAF measurements, and modified in terms of proper data handling, error handling etc. to insure proper online processing.

The second approach is based on data-driven background, meaning that the developed EAF models are designed without any physical background and rely solely on the input-output data mapping. In this case, fuzzy-based nonlinear modelling is implemented. The aim of these models is to obtain a dynamic relation between the influential EAF inputs and the desired output, using a simpler model structure in comparison to theoretical models, as well as to use as few data inputs as possible. Two fuzzy-based models were designed and trained using the EAF data, i.e. fuzzy-based bath temperature estimation and fuzzy-based dissolved oxygen estimation. Since the design and parameterization of the fuzzy models highly relies on the measured data, these two models are designed to be used in an online manner only for the refining stage of the EAF process. The reason for this lies in the deficient measurements in the main EAF melting stage, i.e. temperature, dissolved oxygen, which disables the training and validation of the models. The study has shown that fuzzy-based approach yields even slightly better results in terms of estimation errors in comparison to the theoretical models, which is the main reason to include them as one of the solutions for the industrial environment.

EAF OPTIMIZATION FRAMEWORK

The second proposed solution is represented by the EAF optimization framework. The idea behind it is to obtain new operational strategies for the EAF, which lead to increased EAF efficiency, either in terms of energy use, production times, or steel yield. The framework is intended to be used in an offline manner for optimizing the profiles of influential EAF inputs (transformer tap, oxygen lancing, carbon injection, slag formers addition) and scrap charging patterns. The methodology driving the optimization framework is based on historical EAF data and comprises of different statistical methods, clustering, classification, as well as data-based modelling. All proposed solutions are schematically shown in Figure 2.

CONCLUSION

The idea behind the ongoing EU project is to introduce and put into the operation advanced software-support solutions, facilitated by the digital infrastructure, aiming to improve the performance of the EAF. To follow the current state-of-the-art, all developed solutions will be based on Edge and Cloud Computing technology (Siemens Mindsphere).

ACKNOWLEDGEMENT

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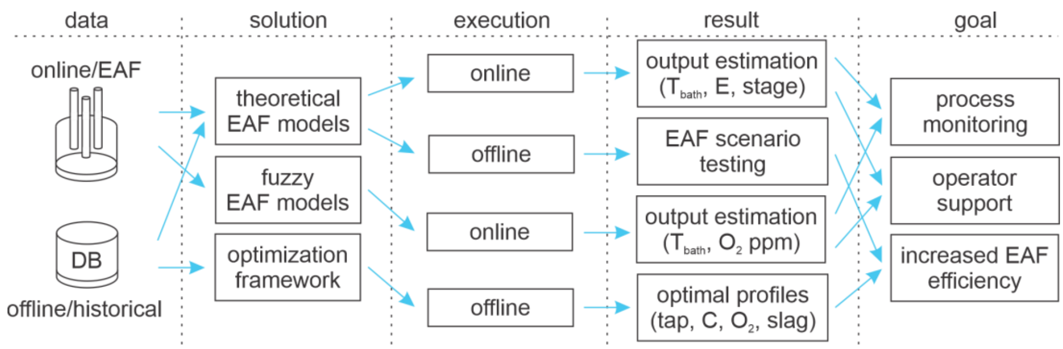

Figure 2: schematic representation of the solutions in the scope of the INEVITABLE project

Study of the influence of the charging materials on the metallic loss of a continuous charging electric arc furnace by multiple linear regression

D. M belli [a)], G. Dall'Osto [a)], C. Mapelli [a)], A. Gruttadauria [a)], S. Barella [a)]

a) Politecnico di Milano, Dipartimento di Meccanica, Via La Masa 1, 20156 Milano, Italy
gianluca.dallosto@polimi.it

INTRODUCTION

Steelmaking is a fundamental part of the base European and global industry. In Italy, the scrap-based route covers a crucial role with 37 electric arc furnace (EAF) production sites and a crude steel production share of 82% (global share is about 27%) [1, 2]. Furthermore, the principle of CO_2 and dust emission reduction to achieve the sustainable development scenario (SDS) is highly encouraging the use of electric arc furnaces (EAFs) as production process worldwide [3].

Scraps provide most of the metallic needs of the EAF. Based on several factors such as origin, chemical composition, sizes, and density, the scraps can be generally divided in three categories: obsolete, industrial and internal [4].

By a thermodynamic point of view, all the phenomena that are present during the scrap melting can be related to their surface over volume (S/V) [5]. From a theoretical point of view, to achieve faster and less energetically expensive scrap melting, it is necessary to use high S/V (light) scrap; however, a higher oxidation of the charging materials will be achieved [5]. Therefore, based on the type of steel that has to be produced, a scrap blend will be selected in order to minimize both the electrical demand and the metallic loss of the heat [6].

In the latest years, the optimization of the charge mix by empirical mathematical models, has become a fundamental practice aimed at decreasing the metallic losses, increasing the furnace performances and obtaining a proper melt chemistry.

Due to the complexity of modeling the EAF process a high number of approaches are possible, from linear regression [7 - 10] to genetic programming with long computational times [11]. However, in all these studies the different scraps are usually grouped in one variable.

The aim of this work is the development of two multiple linear regression (MLR) models for the investigation on the influence of eight charging materials on the metallic losses. More precisely: industrial demolition scrap, light and heavy metal sheets, internal scrap, shredded scrap, pig iron, bales and hot briquetted iron (HBI).

For the calibration and subsequent validation of the models, the data regarding 56 monthly heats performed by a Consteel EAF (nominal charging capacity of 250 tonnes and used for the production of mild steel) were used.

In particular, the first MLR model considered the output (metallic loss) depending to the predictors (charging materials) taken as non-interactive variables, whereas second-order interactions between the charging materials were added in the second one.

RESULTS

MLR Model Without Variable Interactions

The work started with the selection of the calibration heats, so as to obtain the most heterogeneous set possible and increase therefore the model adaptability. Then, for the model reduction, the p-value analysis was performed (significant level α was set to 0.050). The final regression analysis highlighted that light sheets, shredded and internal scraps are three of the four statistically significant charging material; whereas HBI, even if characterized by a p-value higher than α, was kept in model due to its known influence on the melting process [12,13] The model was characterized by an R^2 and R^2_{adj} of 98.20% and 97.75%, respectively.

In particular, sheet and shredded scraps due to their high S/V ratio (high oxidation tendency) increases the metallic loss value. On the other hand, the introduction of heavy internal scrap has a positive effect on the metallic loss, decreasing its value, consistently with its low S/V ratio.

MLR Model with Variable Interactions

The same heats used in the first MLR model and significance level were also used for the MLR model with variable interactions.

The results showed that each charging material interacts at least once with another one, with the main interactive material being the HBI.

In particular, thanks to the high amount of C introduced by the pig iron in the melt [28], the iron oxide present in the HBI can be reduced, and the metallic loss decreased. This interaction is correctly described by the term contained in the model.

MLR Models Validation

The MLR models were used in order to foresee the metallic losses of a set of heats, not used during the calibration, in order to validate their effectiveness.

The comparison between the calculated values of metallic loss obtained by using the non-interactive and interactive MLR model and the observed metallic loss values are shown in Fig. 1 and Fig. 2, respectively.

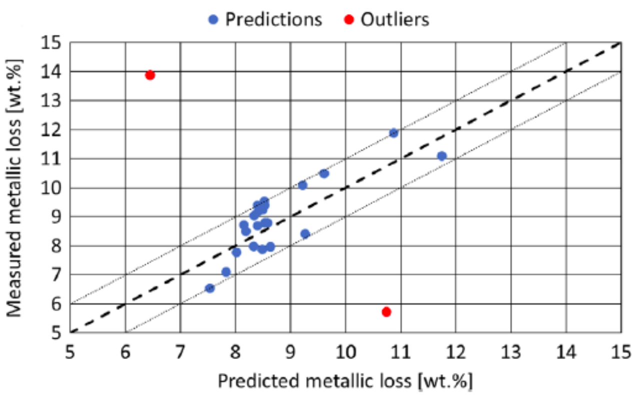

Fig. 1 Measure and predicted metallic loss plot (red dots are outliers) by MLR without variable interactions.

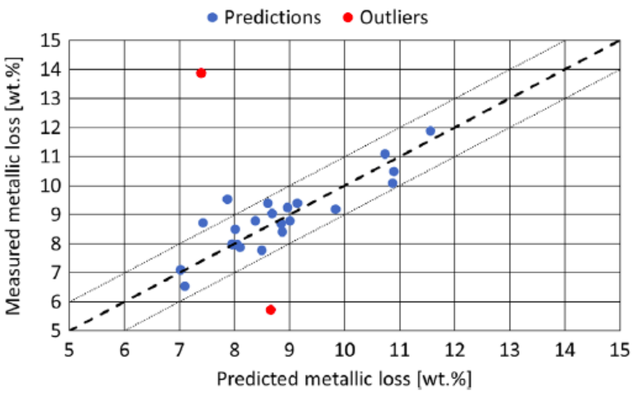

Fig. 2 Measure and predicted metallic loss plot (red dots are outliers) by MLR with variable interactions.

For most of the heats, both the model well approximates the actual value of the metallic loss with an accuracy of less than 10%. Therefore, it is possible to confirm the reliability and prediction ability of them, in particular for metallic loss values between 7% and 12%.

CONCLUSION AND OUTLOOK

Being able to know in advance, the metallic loss of a specific heat allows to carry out the necessary variations to the charge mix to increase the furnace productivity, minimize the economic losses and, most importantly, the environmental impact of the process.

The aim of this work was to analyze and describe how eight of the most common charging materials influence the metallic loss of an EAF Consteel by the development of two multiple linear regression models of increasing complexity.

The results obtained were physically coherent and the predicted metallic losses of the regression models were close to the actual ones. In addition to the aforementioned, the most important result of this study may be the need to rethink the way charging materials are considered when creating a statistical model for EAF.

The use of the various types of scrap as single variables and not enclosed in a single one, as mainly done so far, leads to an increase in the predictive capabilities of the statistical model, as well as an investigation into the relationships between the various charging materials during the heat

The MLR model without variable interactions highlighted how only some of the charging materials have a strong statistical significance on the metallic loss. The second MLR model (with variable interactions addition) highlighted how the metallic loss is influenced by the interaction among the charging materials, too.

The validation of the MLR models allowed to state the reliability of their predicted values. In particular, the second model predictions are more accurate than the first model ones, due to the presence of the second-order predictors which are also able to provide a good insight of the main interaction that occurs among the several charging materials during the heat. Therefore, the hypothesis of the correlation between the charging materials fraction inside the charge mix and the metallic loss should be essential for the performance enhancement of the furnace.

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IDEAS: Intelligent Dynamic EAF Advisory System for Improving Operating Efficiency

Z.   oss[a)], J. Jones[a)], R. O'Malley[b)], S. Sridhar[c)]

a) Continuous Improvement Experts, Inc.
b) Missouri University of Science & Technology
c) A zona State University
Zane.Voss@CIXLLC.com

INTRODUCTION

In recent years there has been an effort to integrate tools such as Artificial Intelligence (AI) into Electric Arc Furnace (EAF) manufacturing operations. In heavily automated operations with repetitive, similar operating cycles this may be possible. However, processes such as EAFsteelmaking experience a large number of variations from cycle to cycle, making it difficult to apply AI effectively. A more effective solution is the use of effective tools based on a sound understanding of process fundamentals. A recent program proposed by the Missouri University of Science and Technology, Arizona State University, Continuous Improvement Experts, Inc., several industrial partners and Linde with funding from the US Department of Energy's Advanced Manufacturing Office aims to develop and integrate a series of process models coupled with novel instrumentation. When operated in tandem, this will allow for the creation of an effective digital twin for the EAF.

BACKGROUND & DESCRIPTION

Over the previous two decades, few major changes in EAF technology have been adopted. Instead, equipment suppliers and plant operators turned their focus to improving safety, reliability, and consistency of technologies that are already employed. Concurrently, less focus has been placed on process analysis due to lower staffing levels, reduced training for operators and engineers, and the desire to heavily automate the EAF process at the expense of removing the operators from the decision loop.

Modern EAF operations collect millions of data points daily. However, little of this data is processed and filtered to provide actionable information due to lack of trained resources in analytical process metallurgy and appropriate process tools.

The goal of the current research will be to develop an expert system comprizing several modules functioning as a digital twin tied to fundamentals-based process modules. The expert system will feed information forwards and backwards between system modules to accurately synchronize the system and allow for tuning and customization at different steelmaking sites. This system will aid in EAF optimization, diagnosis of operational problems, and assist in raw materials optimization.

APPLICATION OF PROCESS MODELS

Models based on a detailed understanding of process fundaments are key to EAF optimization. As the EAF is an extremely high-temperature, highly oxidizing, and dynamic environment, direct measurement of the process is limited in scope. Measurements tend to be single-use disposable items like temperature and oxygen readings taken at the end of a heat. Others are taken after the heat cycle is completed, like offline chemical analysis of steelmaking slag.

Therefore, opportunities to carefully measure inputs to and outputs from the process must be taken in order to illustrate a complete picture of the process. IDEAS couples novel optical fiber sensor technology with process models to develop a real-time mass & energy balance of the EAF. The process models will take into account the scrap, iron, and non-metallic inputs to the EAF, measure energy losses, and display analytical statistics to the operator and process engineer.

THE ROLE OF THE OPERATOR AND PROCESS ENGINEER

With enhanced process analysis tools, it might be easy for one to believe that the roles of the EAF operator and process engineer might become obsolete. Nothing could be further from the truth. The EAF is one of the most complex process reactors encountered in heavy industry, requiring constant adjustment and optimization. In the future, the process engineer's role will be one of macro-optimization; tying together the results of mutiple tools to inform and drive high level optimization of the process. The operator will adopt the role of micro-optimzation; making small adjustments to the process based on actionable intelligence generated by the process tools and process engineer.

CONCLUSION AND OUTLOOK

With proper tools combined with an improved understanding of process fundamentals, the IDEAS project will provide a greater understanding of the EAF and allow for enhanced optimization of this very challenging production process.

Preliminary experiences from the application of model predictive control for the EAF process in stainless steelmaking

V.-V. Visuri[a)], S. Jawahery[b)], N. Hyttinen[a)], S. O. Wasbø[b)], M. Schlautmann[c)]

a) Outokumpu Stainless Oy, Terästie, 95490 Tornio, Finland
b) Cybernetica AS, Leirfossvegen 27, 7038 Trondheim, Norway
c) VDEh-Betriebsforschungsinstitut GmbH, Sohnstraße 69, 40237 Düsseldorf, Germany
ville-valtteri.visuri@outokumpu.com

INTRODUCTION

Electric arc furnace (EAF) is a unit process for melting steel scrap and forms the second most common process route for producing steel after the blast furnace-converter route. Many of the parameters required for analysis and optimization cannot be measured directly due to the harsh conditions in the furnace. Mathematical models are thus a valuable tool for optimizing and controlling the EAF process. An exhaustive review of the available process models has been published recently by Hay et al. [1].

In recent decades, also fundamental process models have been applied for online control of the EAF process. The model by Bekker et al. [2] is intended for controlling the off-gas system and manipulates two variables (fan force and slip-gap) to adjust three outputs: the relative furnace pressure is regulated, while the off-gas temperature and off-gas CO mass fraction are only limited. Building on this model, Oosthuizen et al. [3] added a slag foaming model and used the rate of directly reduced iron (DRI) addition as an additional manipulated input variable. In later work, Oosthuizen et al. [4] proposed an MPC controller based on economic objectives, which were implemented as weights in a quadratic objective function. The model by MacRosty and Swartz [5] is formulated in terms of an economic performance objective and adjusts the arc power, oxygen flow from the burner, natural gas flow from the burner, oxygen injection, carbon injection, and mass of the second charge to minimize the total costs. The model by Oosthuizen et al. [3–4] employs a linear model predictive control (MPC) algorithm, while the models by Bekker et al. [2] and MacRosty and Swartz [5] employ a non-linear model predictive control (NMPC) algorithm.

In this work, an earlier-developed model by Pierre et al. [6–8] was used as a basis for a new model development, which was tested for model predictive control of the EAF process in stainless steelmaking.

MATERIALS AND METHODS

The extended model is formulated in terms of state variables (see Fig. 1) and ordinary differential equations. The model accounts for the reaction of oxygen with Fe to FeO, C to CO or CO_2, Cr to Cr_2O_3, Mn to MnO, Al to Al_2O_3, and Si to SiO_2. The oxidized components can be reduced by C or metallic species. The energy generated is distributed between different masses. The treatment of chemical reactions, phase changes, and heat transfer will be described in more detail in an upcoming publication.

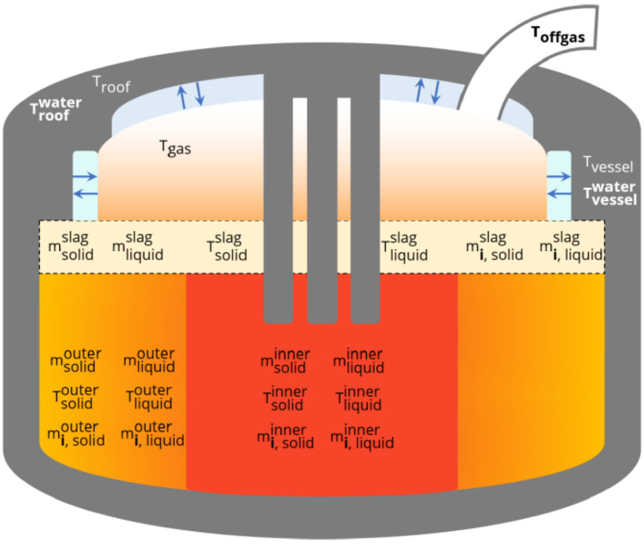

Fig. 1 Schematic illustration of the state variables employed in the model.

The model is adapted to process data using recursive parameter estimation. The real-time optimization of the process is based on the NMPC framework. The model predictions are compared with actual measurements and the resulting residuals are used by a Kalman filter, which updates the state variables and selected parameters for estimation.

Two different NMPC applications were developed: time priority and energy priority. The underlying optimization scheme for both applications is the same and seeks to minimize two Key Performance Indicators (KPIs): (1) batch time and (2) energy consumption. The applications differ by the relative weight of each of these KPIs in the optimization cost function – the time priority strategy adjusts power input to attain a minimum processing time, while the energy priority focuses on minimizing the projected energy consumption.

The model was tested at a 140-tonne EAF in operation at Outokumpu Stainless Oy in Tornio, Finland. This furnace has a transformer capacity of 140 MVA and is equipped with an auxiliary burner and an oxygen manipulator with a consumable lance including carbon powder injection [9].

RESULTS AND DISCUSSION

Fig. 2 shows the comparison of predicted and measured temperature and weight of the metal bath after tapping for offline simulation of 247 heats. The predictions are scattered approximately evenly on both sides of the diagonal. The standard deviations of the predicted temperature and weight of the metal bath from the measured ones were approximately 27 °C and 7 tonnes, respectively.

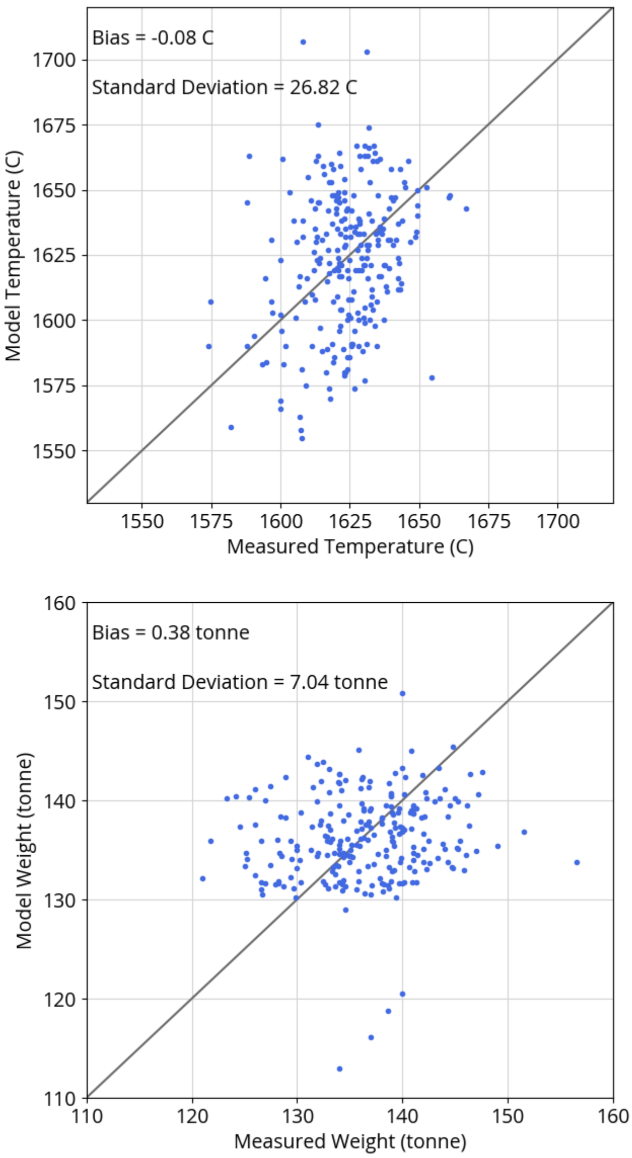

Fig. 2 Comparison of predictions for temperature and weight of the metal bath with process measurements from 247 heats.

The NMPC applications continuously produce optimized electric power profiles, where the allowed power outputs are constrained to not deviate beyond a given interval from a pre-defined recipe profile. The optimized electric power is then converted to a voltage tap recommendation that can be used by operators. A setpoint deadband solution is employed to avoid oscillations or sudden changes in the voltage taps during the online testing period.

In a preliminary online testing campaign, the time priority NMPC was applied for providing suggestions to the operators, who would then execute the recommended voltage tap changes manually. The application also generates a prediction for the time point at which the scrap charge will be fully melted, which the operators can choose to consider. The results of this campaign will be reported in further work.

CONCLUSIONS AND OUTLOOK

This work aimed to test the applicability of model predictive control for an industrial-scale EAF in stainless steelmaking. The results of the offline simulations were conducted for a 140-tonne EAF in operation at Outokumpu Stainless Oy in Tornio, Finland. The results indicate that the model can predict the final temperature and weight of the metal bath with good accuracy and provide suggestions to the operator regarding optimized electrical power input.

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RWTH Aachen University
Department for Industrial Furnaces and Heat Engineering
Kopernikusstr. 10
52074 Aachen, Germany

For questions and additional information contact:
Dr.-Ing. Thomas Echterhof
Phone: +49 241 80-25958
mail: seminar@iob.rwth-aachen.de

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