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Content

Session on EAF modelling, simulation and efficiency I

Session chairs: Ville-Valtteri Visuri

Model Development about the Composition of Scrap in Electric Arc Furnace

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This article aims to reconstruct the composition of scrap in an Electric Arc Furnace (EAF) based on mass balance. The study develops two models to describe the behavior of elements in the EAF process. A linear state space model is used for elements transferring from scrap to steel, while a non-linear state space model is applied to elements moving into both steel and slag. The Kalman filter and unscented Kalman filter are employed to approximate these models, respectively. Importantly, the models leverage only data already collected as part of the standard production process, avoiding the need for additional measurements that are often costly or not used. This article outlines the formulation of both models, the algorithms used, and discusses the hyperparameters involved. We also provide practical suggestions on how to choose appropriate hyperparameters based on expert knowledge or historical data. The models are applied to real EAF data, and the results show that both models can reconstruct the composition of scrap. The findings provide valuable insights for improving process control and ensuring product quality in steelmaking.

Application of an artificial neural network to estimate the off-gas generation within an EAF under modified operating conditions

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By design the electric arc furnace (EAF) emits low carbon dioxide emissions when compared to other aggregates such as the blast furnace. This is due to electricity being the main source of energy while natural gas and coal are used only in auxiliary burners or to ensure beneficial process condition such as a foaming slag. For this reason, the electric steelmaking is at the focus of the current industrial transformation towards a CO2 neutral steel production. In this context, the furnace is subject to further optimization of the energy and resource efficiency.

Process models can be used in order to simulate and evaluate altered operating conditions within the EAF before conducting costly plant trails. With regards to these models, the off-gas generation plays a crucial role, as it directly affects the carbon footprint of the process. In addition, the off-gas generation determines the pressure within the furnace and therefore the leak air intake and oxygen availability. Unfortunately, an off-gas analysis is often unavailable. As the equipment is exposed to extreme conditions, it can also malfunction on a regular basis.

For this reason, a model of the off-gas generation was developed based on an artificial neural network. Furthermore, the model incorporates fundamental physical principles to ensure robust results. The discussed model is capable of predicting the total off-gas mass flow rate throughout the process as well as the mass fractions of relevant species such as CO, CO2, H2 and water vapor. The model utilizes only a-priori process data. This way the model can be used to complement an already installed off-gas analysis

in the event of a malfunction. It can also be integrated into an EAF process model in order to account for the variation in off-gas generation when optimizing the furnace operating chart. The model is trained and tested on an industrial scale EAF.

During the development of the off-gas model an emphasis was put on the data preparation to ensure training on a high-quality dataset. In addition, the original dataset is complemented by a customizable data generation module that can be utilized to adjust the timespan of process data used for prediction. This way, training of the model is more independent of plant characteristics such as delays in measurement or reaction time within the melt or gas phase. This method is intended to improve transferability of the results to different plants. Finally, a postprocessing step is implemented. During this multiple performance indicators are calculated and defiant results are labelled accordingly or corrected if applicable.

An Integrated CFD Modeling Approach Towards an Entire EAF Operation Process

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The electric arc furnace (EAF) is a process of growing importance in steel industry. Currently, more than 70% of U.S. steel is produced through the EAF route. The importance of EAF also relies on the low carbon emissions it produces, which can reduce up to 60% the carbon emissions of the blast furnace route. The EAF operation includes complex chemical-physical phenomena such as combustion, arc heating, phase change, chemical reactions, heat transfer, etc. The multiple (and concurrent) phenomena in the EAF process make proper understanding and accurate prediction of EAF operation difficult, which prevents further improvements and process efficiency.

Computational fluid dynamics (CFD) can provide significant insight into the EAF operation. In this study, a multi-physics CFD model is applied to simulate EAF processes of real operation scenarios. The CFD modeling includes a series of models developed specifically to address the complex phenomena of pre-heating, melting and refining stages of EAF operations. The CFD models include the coherent jet model, electrical arc model (both AC and DC modes), scrap melting model, oxidation model and the slag foaming model, which can be integrated to provide a 3D, transient description of EAF processes at the time and length scale of industrial operations. The CFD models have been validated against data provided by industrial partners. In particular, simulation of a complete tap-to-tap operation of AC EAF shows 10% difference in predicted melting rate, whereas the electrode position after bore-in differed less than 5%. Similar results were obtained when applying the scrap melting model to complete DC EAF operation. Moreover, validation of the refining model shows less than 2% error in co-jet velocity and ~8% difference in prediction of carbon content. The integrated EAF models have been applied to analyze and determine the impact of oxygen rate on refining efficiency, to study the burner efficiency during the scrap melting, and to assess the impact of charge layering on melting performance, providing guidance for troubleshooting and optimization of real EAF operations.

Foam-Arc Interaction in Electric arc Furnace: Insights into Flow, Stability, and Thermal Behaviour

Mohamad Al Nasser, Ebrahim Karimi Sibaki, Menghuai Wu, Anton Ishmurzin, Gernot Hackl , Nikolaus Voller, Christian Redl, Harald Holzgruber, Abdellah Kharicha, Montanuniversitat Leoben

Electric arc furnaces (EAF) are a leading technology in green steelmaking, offering a reduction in carbon emissions of over 75% compared to traditional methods. By 2050, EAF is conservatively projected to contribute 52% of global steel production. Unlike conventional approaches, EAF uses electrical energy to generate heat through an arc, eliminating the need for traditional fuels. The arc's dynamic and extreme nature makes numerical modelling an essential tool for optimizing EAF operations and understanding its behaviour, while avoiding the risks associated with experimental measurements. This approach supports industrial advancements and promotes more sustainable production methods.

This study presents a numerical model that simulates the behaviour of an industrial-scale furnace, including the arc plasma, molten steel bath and interaction at the level of the free surface at the interface. The study focuses on foam generation at the level of interface between the arc and molten pool. The foam generation rate influenced by slag properties is considered. Moreover, the effect of foam formation on arc stability, heat transfer, and the distribution of flow within the furnace is analyzed. The findings provide valuable insights into the complex dynamics of arc-foam interaction, highlighting how operational adjustments in foam control and material properties can significantly improve EAF performance.

Session on EAF modelling, simulation and efficiency II

Session chairs: Thomas Echterhof

From Air to Hydrogen: 3D Models of Electric Arcs in Sustainable Steelmaking

Mohamad Al Nasser, Ebrahim Karimi Sibaki, Menghuai Wu, Anton Ishmurzin, Gernot Hackl , Nikolaus Voller, Christian Redl, Harald Holzgruber, Abdellah Kharicha, Montanuniversitat Leoben

The electric arc in electric arc furnaces (EAF) is the central phenomenon upon which the operation of the furnace relies on. The arc provides and controls heat generation, mixing and chemical reactions inside the furnace. Thus, understanding and controlling the arc are crucial to improve furnace efficiency, steel quality and the extension of the furnace's life cycle. The arc's behavior and efficiency are influenced critically by the atmosphere of the furnace, power supply and magnetic field present in the furnace.

A 3D computational model of the arc and its environment is presented in this study which is under continuous development to capture the physics of the arc. The model captures the flow, thermodynamic, and electrical properties of the arc. The model accounts for different atmospheres such as air, argon and hydrogen. Moreover, the arc operates in both single-phase and multiphase modes, enabling the simulation of arc impingement on free surface liquid metal. The results obtained show the transient behavior of the arc and the noticeable difference in arc characteristics between air and hydrogen atmospheres. The analysis of these different dynamics provides a deeper understanding of the arc nature and the optimal integration of hydrogen into the steel industry, enabling greener steel processes and advancing low-carbon steel production.

Dissolved Oxygen Estimation in an Electric Arc Furnace Using a Soft Sensor Approach and Prediction Intervals

Aljaž Blažič, Igor Škrjanc, Vito Logar, Univerza v Ljubljani

This study presents a soft sensor modeling approach to address uncertainties in Electric Arc Furnace (EAF) steel production, focusing on the estimation of dissolved oxygen content in the steel bath. The approach combines Takagi-Sugeno (TS) fuzzy models with Prediction Intervals (PIs) to overcome the challenge of irregular and scarce output measurements, which are typically measured only a few times during the refining stage of EAF operations. Two methods are proposed: Instant TS (I-TS) and Input Integration TS (II-TS). In the I-TS method, the model is calculated for each individual indirect measurement, while in the II-TS method, multiple indirect measurements are integrated. By incorporating PIs, the models can provide a narrow range that contains a predefined percentage of data, even in the presence of heteroscedastic noise. This allows decision-makers to better understand variability and assess worst-case scenarios. Evaluation with real EAF data shows that both methods effectively address the challenges of scarce availability of measurement data. The I-TS approach is characterized by simplicity, interpretability and a strong alignment with operational realities. The II-TS approach achieves high performance across several metrics but shows theoretical inconsistencies under atypical operating conditions. The study has also shown that this approach can estimate the carbon content in the steel bath using the established equilibrium between dissolved oxygen and carbon, eliminating the need for direct carbon measurements. This underlines the potential of the proposed methods to improve the productivity and efficiency of the EAF steelmaking process.

AI-Driven Benchmarking for EAF Performance

Ensophea Toch, Pakrigna Long, Sokroeurn Ang, Amret PLC

Integrated steelmaking is incomplete without Electric arc furnaces commonly referred to as EAFs due to their flexibility and efficiency. Yet, the many mechanical processes that are involved call for constant attention so that the costs associated with system failure are minimized. Practical maintenance is, however, typically operational and entering periods of preventive maintenance to result in periodic interruptions and can take quite a long time. To overcome these challenges, the utilization of AI and the resulting application of ML are displaying potential to transform the strategies of maintenance with EAF in order to maximize equipment efficiency, minimize cost, and increase overall effectiveness of maintenance. For the predictive maintenance based on AI, an organization has to constantly generate volumes of data from operational sensors and records to identify potential failures. This information goes through analytical models to learn trends and prospection of corrosion; therefore, the maintenance crew can solve the problem before everything fails. By identifying problems like deteriorated electrodes, inefficient transformers or a faulty cooling system before they cause a shut down, AI achieves an optimised reduction of up to 40% of unscheduled loss of time of a key component. The third area for using AI and ML in EAF maintenance is inventory management. By using failure prediction and historical usage data to approximate spare parts demand activities, it is possible to optimize spare parts inventory without overburdening with stock. Such an approach is predictive in nature meaning that it helps to control unnecessary costs such as inventory expenses and optimize the usage of the resources available. Low-latency, hierarchical design, online learning capabilities, and other features have numerous applications in the real-world GP, which is discussed with reference to interfaces based on real-life case studies in EAF operation. For example, models for the prediction of maintenance costs have helped steel producers to reduce their maintenance costs by 30 per cent and, while maintaining the reliability of equipment and minimizing energy consumption. Further, AI systems provide sustainable development because they help to minimize wastage, emissions and energy consumption.

Session on EAF modelling, simulation and efficiency III

Session chairs: Vito Logar

A Data-Driven Approach to Scrap Charging Optimization in Electric Arc Furnaces

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The electric arc furnace (EAF), accounting for 28.9% of the total steel production worldwide, constitutes the main process in scrap-based steelmaking. Despite the reduction in energy consumption by up to 61% and the carbon emissions by up to 77% in comparison to the blast furnace and convertor route, there is a significant potential for optimization. The MultiSensEAF project was started with the aim of improved model-based process management and optimization. The project plans to achieve this goal with the help of new off-the-shelf sensors and existing measurement systems in industrial EAFs to create innovative multi-sensor systems and soft sensors.

One such sensor is the Optical Emission Spectrometry (OES) sensor installed in the EAF roof at Georgsmarienhütte GmbH which provides continuous data to the ArcSpec system provided by LuxMet. Using the data provided by the ArcSpec system, this study aims to create a soft sensor which will guide the EAF operator in charging a new scrap basket into the EAF. A machine learning based classification has been proposed to aid in the decision-making for changing the scrap basket during a charge. Additionally, the final decision of the classification algorithm would be supported by both the ArcSpec data and data provided by the existing sensors in the EAF at GMH. A threshold range for modified parameters has been defined which would provide the operator with more information in addition to the signal for changing the basket.

In conclusion, this study aims to provide first information into the meltdown evolution of a scrap basket and would provide the operator with a definite signal to point towards the complete melting of the charged scrap.

Improvement of EAF process management with new concepts of modelling monitoring and control of the process in order to improve process efficiency, source consumption and environmental impact

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In the frame of steel production, the EAF process is still playing a key role both for its flexibility to different production size and steel grades produced but also for the reduced impact in terms of CO2 emissions.

This flexibility and capability to maintain its adaptations to new scopes is increasing the application of this process also to new layouts and production scheme that in future years will include also the substitution of BF/BOF production routes in some production sites.

In this way looking at the interest of EAF applications also in different production cycles the necessity to improve the EAF process control and management is still a key factor in order to obtain improvement in process performances, reduction of energy consumptions, increase production rate of high-quality steels, improve capability of process management with low quality scrap and reduction of CO_2 emissions.

In this way Acciaierie di Calvisano (part of Feralpi Group) is working to improve this capability with application of process modelling, new concept of process control systems and new sensor as prosecution of a strategical route of improvement in this sector.

Activities included also in R&D projects as MultisensEAF are described realized with the support with R&D partners and with increasing internal skills in capability of process modelling and control.

Influence of thermodynamic and kinetic parameters on steel dephosphorization efficiency in electric arc furnace

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The aim of this study is to analyze the influence of electric arc furnace (EAF) process factors and thermodynamic parameters such as phosphate capacity (Cp), phosphorus partition (Lp), CaO and FeO activity, kinetic parameters such as viscosity and percentage of solid and liquid phases, on the efficiency of steel dephosphorization in the EAF process.

Different industrial heats with different slag compositions were analyzed.

Cp and Lp were calculated using classical models. The above mentioned slag properties and phases were determined by computational thermodynamics using FactSage 8.0 software, the results of all these analyses were related to the dephosphorization efficiency in order to identify which variables are most relevant for the dephosphorization process in an industrial plant.

The Dephosphorization Factor (FDeP) parameter, which measures the efficiency of a slag based on its properties, was used together with phosphate capacity and phosphorus partition to compare which industrial slag is best for dephosphorization.

It was found that FDeP presents a high correlation with dephosphorization efficiency, unlike thermodynamic models, and can therefore be used to predict which industrial slag will be more efficient and also assist the technical team in proposing improvements in the production process.

Optimizing Electric Arc in Electric Arc Furnace: An Arc Quality Index Based on Cassie-Mayr Modeling

Aljaž Blažič, Igor Škrjanc, Vito Logar, Univerza v Ljubljani

The optimization of electric arc furnaces (EAFs) is crucial for increasing efficiency and reducing costs in steel recycling. This study investigates the optimization of electric arcs, which have a significant impact on the energy consumption of EAFs. A three-phase equivalent circuit in combination with the Cassie-Mayr arc model is used to capture the complex, nonlinear dynamics of arcs, including the processes of arc ignition and arc breakage. Using real EAF data from current and voltage measurements, a particle swarm optimization technique is used to estimate the parameters of the Cassie-Mayr model. Based on these parameters, the study introduces an Arc Quality Index (AQI) that evaluates arc performance by highlighting deviations from optimal arc operating conditions. The AQI is a qualitative measure of the quality of the arc and complements traditional indices such as arc coverage and stability. The results show that the AQI is an effective tool for EAF operators, providing valuable insights to optimize arc performance and improve overall furnace efficiency. This approach underlines the importance of understanding the dynamics of the arc to improve the efficiency and sustainability of steel production.

Session on Slag and by-products engineering, processing and valorization

Session chairs: Davide Mombelli

Zinc Recovery from Flue Dust of Arc Furnace Plants in Pilot-Scale Waelz-Oxide Process

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Considering 2019, the world's crude steel production capacity has reached 2.4 billion/ton. When we look at the world, approximately three-quarters of the production is carried out through integrated facilities. However, when we look at our country, the situation is exactly the opposite. In our country, the share of arc furnace facilities in production in 2019 was 69.2%. The production amount in arc furnace facilities in our country has continued to increase every year. As of 2020, approximately 25 million of the 35 million tons of production were carried out in these facilities. The low initial installation costs of this situation are a very important factor.

The main factors for the increasing percentage of steel produced by Electric Arc Furnace (EAF) in total steel production are; low investment costs, structure of furnaces, developments in the sector, increasing demand for alloy steels and less labor requirement due to the ease of labor of machines.

In electric arc furnaces, a large amount of flue dust (10-15 kg for each ton of raw steel) is collected in furnace filters. The quality and composition of the scrap charged into the furnace during production generally affects the chemical composition of EAF flue dust. In previous years, flue dust was stored openly in the area where it was collected, but these dusts, which have very small grain sizes, bring many negative environmental effects. In addition, heavy metals found in their structures can mix with water. For this reason, these wastes have been considered dangerous wastes in the world for many years. On August 8, 1991, the United States Environmental Protection Agency (EPA) introduced the requirement that heavy metals in EAF dust containing 15% or more zinc be destroyed by high-temperature processing before being released into nature. For both environmental and economic reasons, it is very important to evaluate the precious metals in the composition of flue dust and to eliminate harmful elements.

While the primary raw material source in steel production is iron ore, the second raw material source is steel scrap. In our country, 80% of steel production is carried out in the Electric Arc Furnace (EAF) using raw material scrap. During steel production in electric arc furnaces, 10-15 kg of flue dust containing 25-45% Zn is formed per ton of steel, depending on the scrap composition. In this study, the pilot scale facility was established to protect the Zn in small amounts of flue dust from harming the environment and to separate it and turn it into a usable pure raw material. As a result of the experiments carried out in this study, 63% pure ZnO recovery was obtained. After the roasting process, this rate reached 84%. As a result of these studies, it was created by performing the waelz oxide (zinc separation) process in a pilot scale rotary kiln and then roasting in an electric oven. Afterwards, the studies were evaluated with XRF, XRD and SEM analyses. The highest ZnO yield was obtained as a result of the process by using 6000 g of coke from flue dust containing 27% ZnO. The lowest rate was obtained with anthracite coal and recorded as 49%. When 2500 g of coke was used, 56% ZnO percentage was reached. The results showed that coke is much more reactive than anthracite coal. The sulfur and chlorine content formed in the structure during the coals used and the precipitation process were eliminated by roasting. After roasting, the ZnO content reached up to 85%.

Upcycling pathway for Electric Arc Furnace slag: utilization as reinforcing fillers for polymers

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Steelmaking industry generates significant amount of waste every year, among which Electric Arc Furnace slags (EAF-slags) are particularly abundant, being their production in the range of 6-9 billion tons per year in the world. These slags are usually disposed in landfill, contributing to environmental pollution and wasting potentially valuable materials. In the last decades, the slags coming from Electric Arc Furnace have been considered as potential materials for future upcycling pathways, converting them into useful secondary products, such as additive for concrete, asphalt in road construction and fertilizers. One of the most promising upcycling routes is their utilization as reinforcing fillers in polymer composites, contributing to the circular economy by transforming industrial waste into valuable resources. The present research explored the application of EAF-slag as fillers in different polymeric matrices: polypropylene, polymethylmethacrylate and polystyrene. The slag was incorporated in different weight percentages (5% wt., 15% wt., 30% wt. and 40% wt. with respect to the polymer) to unveil the effect of its increasing concentration into the polymeric matrix on the final mechanical properties. A functionalization step on the slag surface was also performed with methacrylic acid to increase the slag-matrix compatibility by promoting chemical interactions between the slag surface and the polymeric chains through a free radical polymerization with methyl methacrylate. Different characterizations were employed to elucidate the final composites thermal stability (TGA analyses) followed by mechanical tests (tensile tests). Furthermore, X-ray tomography imaging during the tensile tests (ESRF synchrotron) was performed coupled with Raman mapping (LaserLab Europe, University of Coimbra) to evaluate the microstructure and the composition of the composites, along with Digital Image Correlation (DIC) to investigate the role of the slag inside the polymeric matrices, focusing on the stress propagation and cracking formation. Significant changes were observed at the highest slag concentration (40% wt.), in terms of enhanced Young’s modulus, brittleness, load at break and a decrease in the final elongation. Overall, increasing slag concentration consistently boosted rigidity, confirming EAF slag’s effectiveness as a sustainable polymer reinforcement.

Iron Recovery from Waelz Slag through Biogenic Carbothermic Reduction

Gianluca Dall'Osto, Davide Mombelli, Sara Scolari, Carlo Mapelli, Politecnico di Milano

Currently, more than 85%of the 1.2 million ton of electric furnace dust (EAFD) produced annually in Europe is sent to the Waelz process for zinc recovery. Nevertheless, the main drawback of the process is the generation of a significant amount of slag, known as Waelz slag (WS), which can still contain significant amounts of both zinc and iron oxides, approximately 10 wt.% and 40 wt.% respectively. Considering that for every ton of zinc oxide recovered, more than 2.000 kton of slag are produced, approximately 200-320 kton of iron oxide are removed from the steelmaking process each year, hence leaving a major open loop in the EAFD valorization pathway. Therefore, to propose a possible sustainable alternative to landfill disposal and following a waste-to-cradle philosophy, this study focuses on iron recovery by carbothermic reaction from WS using two biogenic carbon sources (digested biomass and biochar derived from olive pomace pyrolyzed at 750 °C) as reducing agents. Each reducing agent was individually agglomerated with the WS into self-reducing briquettes with increasing carbon-to-iron and zinc oxide ratio (C/FeO+ZnO), namely 0.262, 0.523 and 0.840. Prior to agglomeration, WS was chemically and mineralogically characterized by X-ray fluorescence and X-ray diffraction, while the total carbon content and the relative mass of each compound present in the biogenic carbon sources were evaluated by elemental analysis

and proximate analysis, respectively. The metallurgical performance (degree of reduction, recovered iron and swelling) of the briquettes was studied at three different temperatures (1000 °C, 1200 °C and 1400 °C) under inert atmosphere, and the mineralogical evolution was assessed by scanning electron microscopy and X-ray diffraction. Finally, the metallurgical behavior was compared with that observed when coke was used as a reducing agent to highlight the differences in the reducing capacity of biogenic and fossil carbon. The results showed the feasibility of iron recovery from WS regardless of the reducing agent used, hence providing a first indication of the possibility of recycling such a residue within the EAF cycle as an iron-bearing feedstock after its agglomeration. In particular, the 0.262 ratio and 1400 °C were found to be the best performing and economically feasible combination, with a degree of reduction up to 66.84, 82.86 and 80.28% and iron recovery up to 85, 92.08 and 96.77% obtained from biomass, biochar and coke, respectively. Finally, considering the swelling parameter, although all the briquettes treated at 1000 °C showed slightly positive swelling (<10%), they were subject to shrinkage after treatment at 1200 and 1400 °C.

Quantitative phase analysis in carbon steel EAF slag for the determination of phase-controlled leaching mechanism

Sara Scolari, Davide Mombelli, Gianluca Dall'Osto, Carlo Mapelli, Politecnico di Milano

The production of Electric Arc Furnace (EAF) slag is 120-170 kg per ton of steel, making its recycling essential for the steelmaking process's sustainability. Despite favourable mechanical properties as its good abrasion and fragmentation resistance, environmental challenges such as the leaching of harmful elements (e.g., Cr, V, Ba and Mo) limit its direct reuse in industries like cement production, road construction, and water filtration. The microstructure of the solidified slag is the key to address its leaching behaviour, as the hydration of specific phases (e.g., larnite and brownmillerite) can release these elements. Current regulations demand minimal environmental impact, thus the precise quantification of slag phases is a key to identify and mitigate the leaching mechanisms.

The slag is generally and rapidly characterized by means of X-Ray diffraction (XRD) and Scanning Electron Microscopy (SEM), however the quantitative analysis obtained by the Rietveld method is not always reliable because of the presence of preferential orientations common to several phases and the high sensitivity to the imposed background. Moreover, quinary diagrams specifically designed to study complex system like EAF slag are not always available or require intense computation efforts. Therefore, it is necessary to implement a methodology to refine the X-Ray analysis. Selective dissolution of larnite and brownmillerite, dangerous for Ba, V and Cr release, can be used for this purpose. In this work, different quantitative techniques (selective dissolution by Salicylic Acid Methanol (SAM) solution, KOH Sucrose (KOSH) solution and analytical calculation) were compared to tune-up the Rietveld analysis. These methods facilitated the accurate determination of critical phases within a slag sample coming from quality steel production: larnite, wustite, chromite and brownmillerite.

SEM and XRD analyses demonstrated the effectiveness of selective dissolution in quantifying phase contributions. In particular the identification of larnite amount showed an error of 4.3% respect to the Rietveld quantification, associated to the intrinsic slag heterogeneity. More criticality was instead encountered in the determination of brownmillerite (error 15.9%) where the residual presence of $Ca_4Al_2Fe_2O_{10}$peaks in XRD patter suggested only a partial dissolution. The difficulties encountered were associated to the formation of a viscous gel due to the hydration of silicates. Since a second dissolution by KOSH showed a reduced dissolution capacity with an error of 12.4% between the theoretical and experimental brownmillerite amount, a combined dissolution (KOSH + SAM) was performed reaching a final error of 1.8%. Moreover, the combined dissolution resulted more efficient if SAM is performed before KOSH.

Reduction and Smelting of Magnetic Fraction Obtained by Magnetic-Gravimetric-Separation of Electric Arc Furnace Dust

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The EIT RawMaterials RIS-DustRec-II project aims to transform Electric Arc Furnace Dust (EAFD) into a valuable resource by overcoming the challenges associated with traditional recycling approaches. Nevertheless, EAFD contains complex oxides such as franklinite ($ZnFe_2O_4$) which hinder the efficient extraction of zinc inside the traditional rotary Waelz kiln furnaces, while also loosing other valuables elements contained in EAFD (Fe, Ni, Cr, Cu, etc.) in the residual slag. The project aims to develop a multistage multidisciplinary approach to separate EAFD into two streams: a magnetic and non-magnetic one. In this paper the production of self-reducing briquettes made from the ferrous-magnetic stream of EAFD and several reducing agents was investigated, with the objective of recovering iron through carbothermal reduction, hence creating a viable secondary iron source to be introduced inside metallurgical furnaces. Research was focused on optimizing the magnetic and subsequent gravimetric separation processes, followed by high-temperature smelting to evaluate reduction efficiency and phase separation.

The characterization of two different raw EAFD samples and their magnetic and multi-gravity separation to isolate zinc- and iron-rich fractions was performed by X-ray diffraction and scanning electron microscope. The iron-enriched concentrates were then agglomerated into self-reducing briquettes by mixing them with either biochars (olive pomace pyrolyzed at 350 and 750 °C and wood chips pyrolyzed at 750 °C) or Cupola Furnace dust used as reducing agents and flux, whereas gelatinized corn starch was used as a binder. Smelting tests were carried out at 1400 °C in an inert argon atmosphere to assess the metallization efficiency and the separation between metal and slag phases. A carbon/oxides mass ratio of 0.262 ($C/(ZnO+Fe_2O_3)$) was used in these tests to maintain continuity with previous studies and to standardize reduction conditions.

The magnetic and multi-gravity separations effectively isolated zinc- and iron-enriched fractions, particularly for one of the two EAFD, where the concentration of Zn in the concentrated fraction was reduced to 8 wt.% while Fe reached 45 wt.%. The reduction tests conducted at 1400 °C showed that the chosen carbon/oxides ratio was sufficient for the smelting of the reducible oxides within the briquettes. However, an important limitation become apparent: the amount of carbon, exceeding the stochiometric value, proved to be excessive for the effective coalescence of metal droplets, hence preventing clear metal-slag separation. To address this, further smelting tests were carried out at 1500 °C, optimizing the $C/(ZnO+Fe_2O_3)$ to stoichiometric ratio and the basicity of the mixture. A metal recovery higher than 40% and the better separation of the metal and slag phases demonstrated that the controlled carbothermic reduction for EAFD is a promising alternative to traditional EAFD recycling methods.

Smelting of various steel-plant dusts to evaluate recovery of zinc and iron via the Enviroplas process

Sello Tsebe, Sanda Moloane, Habib Zughbi, Deside Chibwe, Peter Austin, Dursman Mchabe, Mukhethwa Netshia, Derek Hayman, Elias Matinde, Government of South Africa

Steelmaking plants are associated with generation of large quantities of dust streams from unit processes such as blast furnace, electric arc furnace, basic oxygen furnace, and argon-oxygen decarburisation furnace. The dust streams are commonly recycled to the smelting process several times until they are no longer suitable for recycling. The unsuitable dust is either discarded or stockpiled. Such recycling can result in dusts containing heavy metals such as lead, arsenic, and cadmium at hazardous levels. A cost-effective solution needs to be found to avoid long term stockpiling of these materials, taking into consideration the potential value of the zinc and iron units in these dust streams. Mintek developed the Enviroplas™ process to treat such hazardous technogenic materials, and extensively and successfully tested the process on numerous metallurgical solid waste streams such as steel-plant dusts, stainless steel slags, lead blast furnace slags, and some leach residues. Mintek recently completed a large pilot smelting campaign in a 3.2 MVA direct current electric arc furnace to demonstrate recovery of zinc-rich dust and pig iron metal streams, as well as an innocuous slag from processing of various steel-plant dusts via the Enviroplas process. The test work was undertaken as a feasibility study for Australian steelmaker, BlueScope Steel, to evaluate the Enviroplas process as a suitable technology for treating historical stockpiles and new arisings of dust from their steel plant in Port Kembla. The criteria for the suitability of the technology was based on the technical feasibility of the process to produce (i) a zinc-rich dust with >65% zinc oxide, (ii) pig iron metal with >96% iron, and (iii) a slag stream that was classified as non-hazardous solid waste by standards stipulated by the New South Wales State Environmental Protection Authority. The campaign processed a total of approximately 95 t of four different steel-dust streams with zinc oxide concentrations of 12% (OLD), 14.6% (NEW), 13.5% (BLEND), and 7% (MIXED), respectively. The test work demonstrated that zinc-rich dust with zinc oxide concentrations of 75%, 64%, 70%, and 63% can be recovered from the steel-dust streams, respectively. These percentages are likely to be higher if a couple of operational improvements are implemented, namely a better feed system to limit the carryover of feed dust into the gas stream and also a good control of the bag plant to better define the suction pressure at the gas offtake. The corresponding pig iron metal produced had iron contents of 98%, 94%, 97%, and 97%, respectively. Leach test results of slag generated from smelting each steel-dust stream showed that all the toxic metals (e.g. lead, arsenic, and cadmium) had leaching rates below 0.1 ppm (by mass), which classified the slags as non-hazardous solid waste and environmentally safe for disposal or usage in other applications. Therefore, the test work demonstrated that the OLD and BLEND steel-dust streams were suitable for processing via the Enviroplas process based on recovered zinc concentration in dust. All feed types are likely to be suitable for processing with minor improvements to the process. It was recommended that the NEW and MIXED steel-dust streams should be processed as a blend with the OLD dust stream to meet the suitability criteria for processing via the Enviroplas process.

Session on Fossil-free raw materials

Session chairs: Ville-Valtteri Visuri

Kinetic Modeling of Hematite Reduction by Hydrogen Plasma Smelting Reduction in laboratory scale

Areej Javed, Ilpo Mäkelä, Henri Pauna, Henna-Riikka Putaala, Ubaid Manzoor, Dennis Klapproth, Isnaldi R. Souza Filho, Ville-Valtteri Visuri, University of Oulu

The steel industry accounts for about 8% of global CO_2 emissions, primarily due to the use of carbon-based compounds like coke for iron ore reduction, making it essential for the development of sustainable alternatives to conventional steelmaking processes. Thus, hydrogen-based reduction has emerged as a promising alternative to reduce CO_2 emissions. In addition to hydrogen direct reduction, hydrogen plasma smelting reduction has been envisaged as a one-step process for melting, reduction and refining of steel from iron ore. In this study, a kinetic model for the reduction of hematite (Fe_2O_3) using hydrogen plasma is developed to explore the dynamic interactions and reaction mechanisms during the hydrogen plasma smelting reduction (HPSR) process. The gas-metal-slag model is used to calculate the reactions occurring between the molten metal, liquid slag and gas phase, using the effective equilibrium constant (EEC) approach, focusing on the stepwise reduction of hematite to magnetite (Fe_3O_4), wüstite (FeO), and metallic iron (Fe). The model can predict (1) the phase composition changes during the reduction process, (2) the relative reduction efficiencies of intermediate phases under specific plasma conditions. The implementation of the kinetic model has been found in good agreement with experimental results to predict phase transformation dynamics and reduction efficiency, providing better understanding of the HPSR process for environmentally sustainable iron production.

Mass and energy based modelling of EAF steelmaking scenarios using scrap and hydrogen reduced DRI as raw materials

Eetu-Pekka Heikkinen, Petri Sulasalmi, Ville-Valtteri Visuri, Seppo Ollila, Jarmo Lilja, University of Oulu

Pressure for radical reduction of CO_2 emission in steel industry favours EAF steelmaking using scrap and hydrogen reduced iron (H2DRI) as raw material over traditional blast furnace-based production. Increase in EAF-based production will undoubtedly affect on demand of raw materials. The availability of H2DRI will not allow 100% H2DRI-based production immediately. On the other hand, increasing share of EAF production in steelmaking yields increase in scrap demand. Therefore, different scenarios of steelmaking will appear where variable mixture of scrap and H2DRI will be used in EAF. The ratio of different raw materials (scrap and H2DRI) will affect various process parameters such as the quality of molten steel, energy consumption of the process, amount of slag, CO_2 emissions.

Mass and energy balance modelling provides a suitable way of studying possible future EAF steelmaking concepts. In this research, a set of scenarios were studied using a mass and energy balance based model with HSC Sim thermodynamic software. The model as well as the studied scenarios were constructed based on data available in the literature supported with industrial and experimental data. The main interest in the study was on energy consumption and CO_2 emissions when using scrap and H2DRI in multiple ratios and in different temperatures as a raw material.

Optimization Based Experimental Design of Metal-Slag Experiments in Hydrogen Plasma Smelting Reduction Process

Tero Vuolio, Ville-Valtteri Visuri, Michael Zarl, Iivari Lappeteläinen, University of Oulu

This study presents an optimization based experimental design scheme for design of metal-slag experiments in hydrogen plasma smelting reduction. The approach combines computational thermodynamics and machine learning techniques by making use of surrogate-modelling. The objective function for the optimization is formulated as a maximization problem, in which the reduction degree of iron oxides and the phosphate capacity are treated as the main objectives. The objective function is maximized with respect to slag composition in a CaO-SiO_2-FeO-Al_2O_3-MgO system. Additional constraints are introduced for maximum effective viscosity and slag/metal mass ratio to obtain results that are relevant for industrial operation.

The objective function uses the surrogate models for the evaluation of the objective function values. The surrogate-models are trained with data generated with FactSage by making use of full factorial design of computer experiments. Separate models are trained for the phosphorus partition ratio, dynamic viscosity and liquid fraction of the slag phase. The effective viscosity is computed using the Thomas' relation. The viscosity related models are implemented as shallow neural networks, whereas the phosphorus partition model is an ensemble of shallow neural networks, a multivariate regression model trained and validated against literature data and several simple regression models acquired from the literature. As the objective function is non-linear, multimodal and highly complex, a real-coded genetic algorithm (RCGA) is used for the maximization task. The RCGA is programmed in-house, and it is implemented using the hybrid selection, recombination and mutation operators.

The results of the study showed that the surrogate-models could be used as a fast alternative for computational thermodynamics in computationally complex optimization tasks. The results obtained with the approach are in good agreement with the literature. The modular structure of the algorithm allows the integration of more sophisticated models for example to describe the dynamic interaction of reduction dynamics and the slag composition. Nevertheless, the algorithm can be used as a decision support tool in the design of novel processes in several fields of metal producing industry.

A Novel Approach for Modeling the Thermal Properties of H-DRI during Melting in an Electric Arc Furnace

Ankur Agnihotri, Petri Sulasalmi, Ville-Valtteri Visuri, University of Oulu

Understanding the melting behavior of hydrogen direct-reduced iron (H-DRI) is essential for the further development of new ore-based steelmaking routes that utilize hydrogen reduction. This paper introduces a novel approach for deriving simple functions to predict the main thermochemical properties of DRI pellets—most notably the liquidus and solidus temperatures and enthalpy—which are critical for accurately predicting the energy balance of an electric arc furnace (EAF). The approach is demonstrated using a specific H-DRI grade as an example. First, the thermochemical properties of the selected H-DRI grade are experimentally determined through differential scanning calorimetry (DSC) from room temperature up to 1600 °C. The experimental results are then compared with computational thermodynamic simulations using FactSage software for the same temperature range. After validating the accuracy of the simulations, synthetic data is generated to derive regression equations for thermal properties using machine learning. The functions obtained from this regression analysis are directly applicable to various process models.

Session on Process control and sensors

Session chairs: Vito Logar

Implementation of an At-Line Slag Analyzer – Advantages and Challenges

Alexander Schlemminger, QuantoLux Innovation GmbH

Efficient control of steelmaking processes requires timely and precise data, particularly in the context of increasingly volatile input materials. Scrap with rising contamination levels, the use of residues like dust, the integration of secondary raw materials such as plastic granulates, and alternatives like DRI or HBI pose significant challenges to process stability. These factors can negatively impact refractory lifetime, yield, product quality, and other critical performance parameters.

The introduction of an At-Line Slag Analyzer based on Optical Emission Spectroscopy (OES) offers an innovative solution. This technology allows for the rapid analysis of granular slag samples, delivering results within 20–50 seconds compared to the 8–15 minutes typically required by conventional laboratory methods. Unlike traditional approaches that often need extensive sample preparation, Laser OES enables the direct measurement of unprepared granular samples. This significant reduction in analysis time enables faster process adjustments, improving efficiency and maintaining stability even under fluctuating input conditions. The ability to monitor slag composition in near real-time provides valuable insights for optimizing slag chemistry, reducing refractory wear, and enhancing the overall process yield and quality.

However, implementing OES technology comes with its challenges. The lack of suitable certified reference materials (CRMs) for granular slag samples complicates calibration and ensures consistent and comparable results. Additionally, maintaining long-term system stability requires the development and validation of robust standard samples and conducting round-robin tests for inter-laboratory comparisons.

This presentation highlights the advantages of OES technology, elaborates on the technical and organizational challenges involved in its implementation, and discusses prospects for standardization and further development. The work aims to contribute to the optimization of modern steelmaking processes in an evolving industrial landscape.

Development Of Measuring Technologies For Carbon-Lean Hydrogen-Plasma Smelting Reduction Process

Kunwar Shivam Pratap, Kendall Martin, Michael Zarl, Heraeus Holding GmbH

Steelmaking accounts for 7% of global CO_2 emissions; there is a strong commitment to reduce this figure significantly by replacing Carbon with Hydrogen as a reductant for Iron ore. The industry is exploring a number of alternative technologies of which Hydrogen Plasma Smelting Reduction (HPRS) furnaces have generated significant interest over the last few decades. The HPSR process utilizes electricity to create a plasma of Hydrogen which can directly reduce Iron ore to Iron and water vapour.

The fundamentals of the HPSR process are proven with the current pilot plant moving towards an industrial scale and advanced technology readiness. The utilization of Hydrogen as the reductant has serious implications regarding steel quality; it is well known that removal of Hydrogen dissolved in the steel to avoid Hydrogen Induced Cracking (HIC) for a large number of steel grades ranging from Aerospace to Rail steels is of utmost importance. Hydrogen can also cause cracking in slab shells in continuous casting leading to major production failures and significant avoidable costs, for these reasons measurement of Hydrogen dissolved in the steel becomes extremely important during the HPSR process. Measuring temperature and sampling for chemical analysis will also be a significant challenge due to the closed environment of the HPSR which excludes many state of the art technologies currently used in the steel industry.

This paper will highlight the measurement needs of the process as well as reviewing current technologies and the gaps that need to be filled to take the HPSR process from a Technology Readiness level (TRL) of between 5-6 to at least 7. The integration of continuous measurement technologies will allow closed loop control of the process to ensure optimal efficiency.

Interval Model Predictive Control of Bath Temperature in an Electric Arc Furnace

Aljaž Blažič, Igor Škrjanc, Vito Logar, Univerza v Ljubljani

In this paper, a novel approach for temperature control in Electric Arc Furnaces (EAFs) during the refining stage using Interval Model Predictive Control (IMPC) is presented. The proposed framework includes a soft sensor to estimate the bath temperature, which serves as the basis for implementing temperature control. The soft sensor integrates Prediction Intervals (PIs) to account for uncertainties in the temperature prediction and provide a more reliable basis for decision making. The IMPC framework uses particle swarm optimization to dynamically adjust transformer power to ensure robust and reliable performance throughout the process. A notable benefit of this approach is the ability to significantly reduce tapping times by minimizing dependence on frequent temperature measurements while optimizing tap power control. This reduction in measurement dependency not only enhances the production cycle but also improves operational consistency. The improved precision of control contributes to better energy utilization, reducing energy consumption and making the steel recycling process more efficient and cost-effective. The study highlights the potential of integrating predictive modeling and optimization techniques to reduce tap-to-tap times, improve energy efficiency and promote sustainable practices in steel production.

Session on CO_2 emission reduction and environmental impact I

Session chairs: Davide Mombelli

Scope 3 emissions in secondary steelmaking: relevance and impact on CFP

Luca Testini, Alessandro Misul, Vincenzo Morreale, Philippe Brocard, Livia Persico, Davide Mombelli, G Dotelli, Politecnico di Milano

Climate change represents a challenge for the steel sector, which is responsible for approximately 7% of global energy-related CO_2 emissions. Thus, as international regulations and stakeholder expectations tighten, transparency and accuracy have become increasingly important for GHG assessment and reporting.

Nevertheless, steelmaking companies struggle to incorporate Scope 3 emissions (i.e. indirect emissions from the industry value chain) in their reports due to the complexity of the supply chain, the limited control they can exert on suppliers and the lack of incentives or regulatory requirements pushing for more transparent reporting.

In particular, stainless-steel production is heavily impacted by Scope 3 emissions due to its high content of alloying elements (e.g. Cr, Ni and Mo), which leads to intense ferroalloy and raw materials consumption.

In this work a product carbon footprint (CFP) study for stainless-steel production via Electric Arc Furnace (EAF) was performed, incorporating both direct and indirect emissions along the value chain, adopting a cradle-to-gate boundary. Primary data for raw materials and energy consumption were gathered at facility level, while secondary data from ecoinvent 3.10 were used to characterize upstream processes such as raw materials extraction.

The steelworks under investigation featured three main areas: steel shop, forging line and rolling line. The steel shop direct CO_2 emissions were calculated via mass balance, considering carbon content in cast steel, raw materials, electrodes, EAF dust and EAF slag. Electric energy and methane consumption were directly measured for EAF and LF while other contributions were allocated based on the manufactured steel mass. Forging line and rolling line were subdivided into divisions, zones and working centres. Emissions were allocated using a top-down allocation model, linking data on electricity and methane consumption to specific products through a combination of mass, processing time and temperature-based allocation factors. Additional indirect emissions from goods and waste transport, waste disposal and other auxiliary operations were normalized by total steel production and distributed evenly across the product portfolio.

The results show that emissions distribution is heavily influenced by the product steel grade (i.e. chemical composition) as this parameter is the main driver for raw materials consumption (i.e. ferroalloys). In fact, Scope 3 emissions are always higher than 60% of total emissions for every analysed steel category (i.e. austenitic, ferritic, martensitic and duplex steel); in particular Ni, Cr and Mo are the most impactful elements. Finally, Scope 1 and Scope 2 emissions are driven by CH_4 and electricity consumption, which are both dependent on the steel grade (e.g. thermal treatments) and on the product format (i.e. product diameter and section). For instance, an austenitic bar with diameter ranging from 110 to 160 mm features a CFP difference equal to 11.5% mainly due to the different diameter.

Scope 3 emissions in secondary steelmaking: relevance and impact on organization carbon footprint

Luca Testini, Alessandro Misul, Vincenzo Morreale, Philippe Brocard, Livia Persico, Davide Mombelli, G Dotelli, Politecnico di Milano

Climate change represents a challenge for the steel sector, which is responsible for approximately 7% of global energy-related CO_2 emissions. Thus, as international regulations and stakeholder expectations tighten, transparency and accuracy have become increasingly important for GHG assessment and reporting.

However, steelmaking companies struggle to produce comprehensive GHG reporting incorporating Scope 3 emissions (i.e. indirect emissions due to the industry value chain). This is mainly due to the complexity of the supply chain, the limited control that can be exerted on suppliers and the lack of incentives or regulatory requirements pushing for more transparent reporting.

In particular, stainless-steel production is heavily impacted by Scope 3 emissions due to the relevant content of alloying elements (e.g. Cr, Ni and Mo), which leads to intense ferroalloy and raw materials consumption.

In this work an organization level carbon footprint study for stainless-steel production via Electric Arc Furnace (EAF) was performed according to ISO 14064:2019, incorporating both direct and indirect emissions along the value chain, adopting a cradle-to-gate boundary. Primary data for raw materials and energy consumption were gathered at facility level, while secondary data from ecoinvent 3.10 were used to characterize upstream processes such as raw materials extraction.

The steelworks under investigation featured three main areas—steel shop, forging line and rolling line. Direct CO_2 emissions from process operations were calculated via mass balance, considering carbon content in cast steel, raw materials, electrodes, EAF dust and EAF slag. Electric energy and methane consumption were calculated based on operational costs, by aggregating multiple cost-centres related to the same area (e.g. EAF and AOD considered as contributions to the steel shop). Additional indirect emissions from goods and internal transports, waste disposal, were calculated considering distances, vehicle’s type and waste disposal solutions.

The results show that the total emissions distribution is heavily influenced (> 65%) by Scope 3 emissions, of which the major contribution (>75%) is due to raw material consumption (e.g. ferroalloys, scrap and fluxes). In particular, it was determined that ferroalloys, Ni and Mo consumption alone accounts for more than 80% of total emissions associated with raw materials use. Scope 1 (i.e. direct emissions) is mainly driven by CH_4 use in heating furnaces (> 70% of total CH_4 consumption). Finally, Scope 2 (i.e. emissions related to energy production) is due to electricity use, as the main contributions are respectively the EAF and LF (around 32% and 4% of total electricity consumption).

Using a Novel Scaled Injector to Evaluate Biocarbon for Slag Foaming in EAF Steelmaking

Christopher DiGiovanni, Tiago Fernandes Lins, Michael Strelbisky, Majid Zamani, Allan Runstedtler, Colin Scott, Government of Canada

The steel industry faces increasing pressure to reduce carbon emissions, driving interest in sustainable alternatives to fossil-based carbon materials. Biocarbon, derived from renewable biomass, has shown promise as a charge carbon in electric steelmaking, but research into its application as an injection carbon for slag foaming is still ongoing. While studies have examined the reactivity and slag foaming behavior of biocarbon, its injectability has not been adequately evaluated due to the lack of a suitable experimental setups at the lab scale.

This study addresses this gap with a novel experimental setup using an induction furnace with a susceptor crucible and featuring a specially designed scaled-down industrial injector. Unlike previous experiments, which focused on evaluating slag foaming behaviour only, this equipment enables simultaneous assessment of biocarbon injectability and slag foaming behaviour under controlled laboratory conditions. This study measures the performance of biocarbon in comparison to a reference petcoke material, providing critical insights into biocarbon’s suitability as an injection carbon. By closely replicating industrial injection conditions, this setup facilitates a new understanding of biocarbon’s potential as a sustainable alternative in electric steelmaking.

Decarbonization and New Energy-Efficient Technologies for EAF Steelmaking

Hamzah Alshawarghi, Joachim von Schéele, Linde Plc

The CoJet® gas injection technology was developed and first introduced by Linde in 1996, and it has revolutionized Electric Arc Furnace (EAF) operation. Today there are more than 175 CoJet installations world-wide, and it has become the industry standard for chemical energy input into EAFs. To decarbonize the chemical energy input into EAFs and to optimize the furnace operation, recently Linde has developed the 3-in-1 Injector, the Fluidic burner, and OPTIVIEW®. The 3-in-1 Injector and the Fluidic burner can be operated with hydrogen as a fuel.

The OPTIVIEW image-based system analyses the flue gas composition, which provides online information to optimize the EAF post-combustion to obtain minimum energy losses.

The 3-in-1 Injector combines oxygen lancing, carbon injection and burner mode into one device. Using the momentum of the supersonic oxygen to fluidize the carbon jet, it generates and provides supersonic effective carbon injection into the molten bath and at the slag/steel interface from a fixed side wall position. This improves slag foaming and gives better control over steel refining. Additionally, it increases the solid injection efficiency for finer carbon materials – minimizes losses to the fume system and may be used to also inject DRI fines or lime. The transformation of ironmaking into DRI production to reduce the carbon footprint, makes efficient use of DRI fines becoming an increasingly important topic.

The Fluidic Burner uses a fluidic function to move the flame and melt a larger volume of scrap, found to be particularly beneficial when installed at the slag door or in the EBT area. The functionality of the Fluidic Burner has also been combined into a Fluidic CoJet, where the CoJet lancing capability is combined with a moving flame to cover a larger area in the burner mode.

This paper describes the OPTIVIEW and the new burner and injection technologies, the excellent operation results achieved, and how they can support decarbonization of the EAF. They are all operationally ready to use with hydrogen as a fuel.

Session on CO_2 emission reduction and environmental impact II

Session chairs: Thomas Echterhof

Results from the Experimental Campaigns with the H_2 Oxyfuel Burner for Electric Arc Furnaces

Eros Luciano Faraci, Irene Luzzo, Lilly Schulte, Jacopo Greguoldo, Fabio Vecchiet, Giulio Rinaldi, Fabiano Ferrari, Federico Nastro, Daniele Gaspardo, RINA Spa

In the modern EAF, the contribution of chemical energy for the scrap melting and refining is the range of 25-45% of the total energy required. The Natural Gas (NG) burners provide in the range of 40-80 kWh/t of energy. It means that the production of 100 tons of steel requires the combustion of 370-750 Nm^3 of NG with CO_2 emission of 0.75-1.5 tons. The substitution of NG with hydrogen in the EAF steel production will bring a remarkable reduction of CO_2 emission.

In this frame the RFCS project “Developing and enabling H_2 burner utilization to produce liquid steel in EAF“ DevH2forEAF is in line with the European roadmap toward achieving zero greenhouse gas emissions. The project focuses on the design and realization of burners, able to work with NG/H_2 mixture, up to 100% hydrogen.

The fuel mixing was performed by a dedicated mixing regulation system developed by Nippon Gases. These experimental trials represent a preliminary step to verify the functionality of the H_2 burner and to identify the optimal operating conditions for future industrial-scale tests at Ferriere Nord.

The pilot scale electric arc furnace (EAF) at RWTH-IOB was equipped with a burner down scaled to 50 kW able to burn natural gas and hydrogen as well as mixtures of these gases in order to analyze the influence of a H_2 burner on the EAF operation and especially the steel chemistry with regards to the hydrogen pick-up of the melt. During the trials multiple samples of steel and slag were taken for a throughout analysis of the chemistry and the hydrogen pick-up. The results show that the H_2 was only detected in the low ppm range in all steel samples.

A preliminary experimental campaign with an Oxyfuel burner was conducted, at the RINA-CSM combustion laboratory in Dalmine, to evaluate performance and feasibility of the burner with different fuels supplies: from 100% NG to 100% Hydrogen, including mixed configuration of NG-H_2. The burner was tested in the modular furnace pilot plant at RINA-CSM with a maximum thermal load capacity of 3 MW. The burner has been installed in the modular furnace and connected to the hydrogen line.

The industrial experimental campaign has been conducted at FENO EAF (155 ton capacity, for final rebar and wire rod production) replacing one of the existing burners (8 NG burners + 3 sidewall lances) with a new H_2 burner unit. The aim of these activities was to identify the feasibility of utilization of H_2 in EAF without impairing the quality of steel as well as ensuring the highest level of safety. The H_2 burner has been tested in different operating modes performing 20 heats.

Use of hydrogen as energy source in EAF

Pascal Kwaschny, Marianne Magnelöv, Erik Sandberg, Linde Sverige AB

The European steel industry is strongly committed to achieving climate neutrality by 2050. Processes need to adapt to new challenges where the transition from BF-BOF to EAF-based steelmaking plays an important role in the transition to green steel production. Some of the challenges are demonstrated in the EU-funded Horizon Europe project GreenHeatEAF.

GreenHeatEAF will demonstrates the integration of non-fossil fuels and renewable carbon sources into the EAF to reduce CO_2 emissions and dependence on fossil energy and carbon sources. The project will address the challenges associated with these applications by combining pilot, field and simulation studies.

The use of 100% hydrogen instead of natural gas as a chenicalenergy source has been investigated in Swerim's 10-ton pilot EAF where the hydrogen was produced in an electrolyzer. A CoJet burner adapted to Swerim's EAF has been designed and manufactured by Linde. Experiments with the burner have also been carried out on laboratory scale. During the trials in the pilot EAF, different iron carriers as well as different processes such as scrap charging and feeding of HBI, DRI and scrap have been studied.

The trials have been carried out with successful results and the paper presents the outcome during different process steps regarding energy, EAF-gas, steel and slag chemistry.

Numerical Investigation of Hydrogen Blending on the Impinging Flame Structure in Non-Premixed CH_4/H_2/Air combustion for Scrap Metal Heating

Gopal Pandey, Geoffrey Brooks, Jamal Naser, Daniel Liang, Swinburne University of Technology

Gas burners play a crucial role in various ironmaking and steelmaking processes, particularly for heating and cutting operations. In Electric Arc Furnaces (EAF), high-speed gas burners are widely used to enhance thermal efficiency. While the majority of heat in EAF is generated by electric arcs, gas burners help distribute heat more uniformly, improving overall energy efficiency. Currently, most of these burners operate with natural gas (primarily methane, CH_4) as fuel and oxygen (O_2) as the oxidizer. The gases are supplied through separate ports, forming non-premixed flames. As these flames impinge on scrap metal inside the furnace, heat is transferred primarily through convection and radiation to the scrap metal. However, despite their efficiency, these flames contribute to carbon dioxide (CO_2) emissions, increasing the furnace's overall carbon footprint.

With the steel industry striving to reduce carbon emissions, hydrogen is emerging as a promising alternative fuel—particularly green hydrogen, which is produced with zero carbon emissions. Due to challenges associated with hydrogen transportation and storage, blending hydrogen with natural gas is becoming an economical transition strategy in the early stages of decarbonisation. However, before implementing this approach, it is essential to understand the combustion and heat transfer characteristics of hydrogen-enriched non-premixed impinging flames. Despite its significance, research in this area remains limited.

This study aims to investigate the combustion and heat transfer behavior of non-premixed flames impinging on a steel plate. A numerical approach using computational fluid dynamics (CFD) modeling, coupled with a thermodynamic combustion mechanism, is employed to analyze the flow field, combustion zone, and heat transfer characteristics. Large Eddy Simulation (LES) with the GRIMech3.0 combustion mechanism is applied to study cases with 5%, 10%, 25%, 50%, and 100% hydrogen blending. Heat flux and temperature profiles on the scrap metal plate are analysed to provide insights for designing more efficient burners and integrating hydrogen blending technology into steelmaking furnaces.

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