Model-based process control of the EAF

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The Electric Arc Furnace process is very complex and shows high fluctuations in process behaviour as well as a significant scatter in process variables, especially regarding the charge materials.

Thus one important topic of R&D work on the EAF process has been and is still process modelling and control.

Discussed topics within this presentation are:

- Modelling of energy and mass balances of the EAF process for end point control
- Process control of chemical energy input using EAF off-gas analysis
- Through process control of the complete electric steelmaking route
The energy and mass balance of the EAF comprises a large number of energy and material inputs and losses.

For optimisation of the energy and resource efficiency of the EAF process, a continuous and as far as possible complete data acquisition and on-line dynamic modeling is required.

- Development of a dynamic energy and mass balance model:
  - for on-line observation and validation of the energetic EAF performance
  - for online calculation of the actual melt temperature and chemical composition, especially the carbon and oxygen content
  - for a precise determination of the process end-point
  - for model-based process control, e.g. regarding the chemical energy inputs
ECSC project “Improved Control of EAF Operations by Process Modelling”: Fully dynamic EAF model

**Description**
- Dynamic metallurgical model
- Continuously solves mass and thermal balances for scrap, liquid steel, slag
- Calculates scrap melting evolution
- Based on dynamic process information

**Objectives**
- Assessment of the end of heating and refining point
- Scrap melting evolution (best moment to charge second basket, …)

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**Layering of different scrap types in the scrap basket**

EAF discretisation in different zones

- Mass and thermal balance (temperature, composition, weight) for different phases

- Solidified metal skull
- Scrap immersed in liquid steel
- Scrap immersed in slag
- Scrap input from the basket
- Free scrap
- Arc
- Solidified metal skull
Structure and input parameters of the dynamic EAF model of CRM

- Exhaust gas collection
- Scrap charging
- DRI charging

Preheating shaft

- Furnace roof
- Cooling panels
- Scrap
- DRI
- Slag
- Liquid metal
- Metal skull

Furnace

- PC O₂ lances
- Air ingress
- Burners
- HBI, DRI
- Lime
- Hot metal pouring

- Mass flux
- Thermal flux
- Thermal & Massflux

- Liquid steel
- Slag
Calculated evolution of melt temperature and carbon content

Evolution of melt temperature and validation of model accuracy by comparison with dip measurements

Evolution of carbon content and validation of model accuracy by comparison with Celox measurements
Set-up of a dynamic model to cover effects of N pick-up and removal

- Nitrogen pick-up during meltdown increases with time of non-submerged scrap.
- Nitrogen pick-up in the refining phase depends on the quality of foamy slag.
- Nitrogen removal is induced via CO bubbles created by decarburisation.

- Model accuracy is not as good as for C content ⇒ dynamic control of N content is difficult.

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**Graph:**
- Measured EAF N values vs. N values from Dynamic Model.
- EAF sample: C: 0.027 %, N: 73 ppm.
On-line energy and mass balance for observation of the EAF process state with respect to melt temperature and composition (mainly Carbon and Oxygen content)
Completion of the energy balance with the use of continuously measured off-gas composition

- Continuous off-gas sampling at the roof elbow
- Off-gas analysis by a mass spectrometer (all relevant off-gas components are assessable)
- Determination of the off-gas and leakage air flow rate by argon and nitrogen balances
- Off-gas temperature measurement by a pyrometer
- Calculation of the off-gas losses
- Sensible heat losses via flow rate and temperature
- Chemical energy via flow rate and CO- / H₂-content
Input data of the energy balance for an example heat

Energy inputs
- Electrical energy
- Natural gas burners
- Oxygen input via jet injectors and door lances
- Post combustion oxygen, e.g. via over-stoechiometric burner oxygen or special PC tuyeres

Energy losses
- Sensible heat and chemical energy content of the off-gas
- Water cooling of furnace wall and roof
- Radiation and convection
Temperature calculation for an example heat

- Continuous real-time calculation of the melt temperature and comparison with temperature measurements
- Adaption to the first plausible temperature measurement increases the accuracy of the model for the further treatment
- Meltdown degree is calculated from the current energy content of the melt related to the meltdown energy requirement of the charged materials
  - optimal time to charge the next scrap basket can be derived
Model accuracy regarding the calculation of the melt temperature

- Standard deviation of the model error for the first temperature measurement is about 25 K (blue)
- After adaption to the first measurement the model error for further measurements is decreased to ca. 21 K (red)
- Error of the energy balance is about 7 kWh/t
- For a total energy input of about 690 kWh/t this means a relative error of the energy balance of about 1 %
- On-line calculation of the melt temperature allows a more accurate adjustment of the aim tapping temperature
  → Over-heating of the melt can be avoided
RFCS project “LOWCNEAF”: Extension of the dynamic EAF model to calculation of carbon content

Besides energetic aspects, the improvement of the resource efficiency of the EAF process is important:

- Oxygen inputs for decarburisation and dephosphorisation cause undesirable losses of iron by oxidation.
- The amount of iron losses strongly depends on the carbon content of the melt.

→ Extension of the dynamic process model by a detailed carbon balance calculation to determine continuously the current carbon content and the oxidation status of the steel melt.

→ Based on the modelling results a dynamic control of the oxygen input depending on the aim oxygen and carbon content can be developed, to avoid iron losses and over-oxidation of the melt.
Dynamic calculation of the Carbon and Oxygen content

- Dynamic energy and mass balance model was extended by a detailed carbon balance.
- Input data for the carbon balance:
  - charged scrap types and carbon materials with information regarding C content
  - injected carbon for slag foaming
  - lance and injector oxygen
- C content is calculated cyclically from the carbon input and the decarburisation effect by oxygen input.
- Decarburisation efficiency of the oxygen input depends on the process phase (melting / refining) and the current C content of the melt.
- O content can be calculated from equilibrium relations.
- Model adaption to steel analyses and Celox measurements.
Model accuracy regarding carbon content

First plausible Celox measurement respectively sample analysis

Further measurements after adaption to previous measurements
Model accuracy regarding oxygen content

First plausible Celox measurement

Further measurements after adaption to previous measurements

![Graph showing model accuracy](image)
Dynamic model and offgas analysis for control of chemical energy inputs at the EAF

- Application of the dynamic model for process control
- Optimisation and control of chemical energy inputs for e.g. post-combustion based on the continuous off-gas analysis
Closed-loop control of oxygen supply for CO post combustion inside the furnace

- Off-gas composition: CO, CO₂, O₂, H₂
- Offgas analysis with mass spectrometer or other equipment
- Offgas sampling at the elbow
- Oxygen supply for post combustion with sufficient CO amount in the offgas
- Dedicated injectors for well distributed oxygen supply
- EAF

The more efficient input of post-combustion oxygen leads to an energetic benefit of about 20 kWh/t
Dynamic control of post-combustion oxygen supply based on in-situ off-gas analysis

- Laser based, nearly delay-free in-situ off-gas analysis of CO and O₂
- Linear control strategy of post combustion oxygen input depending on CO / O₂ ratio
- Required oxygen input for post combustion strongly varies from heat to heat
- Efficiency of post combustion oxygen is increased by dynamic control
- Slightly reduced electrical energy consumption with less oxygen consumption
  - Net energy saving of about 8 kWh/t
- No negative impact on metallic yield
Combination of different dynamic process models and regression / statistical models to a through process control approach for the complete electric steelmaking route

- EAF charge material selection with a cost optimal charge input calculation
- Control of decarburisation in the EAF based on a dynamic carbon balance model down to the required C content at tapping
- Selection of alloys by a cost optimal alloy calculation with restriction of C and N pick-up
- Control of denitrogenation during vacuum degassing with monitoring of the achievement of the required Nitrogen end-point via a dynamic degassing model
Through-process temperature and quality control along the electric steelmaking route

Charge and alloy material additions
- Slag former additions
- Energy input

Stirring patterns
- Vacuum patterns

Dynamic set-points to achieve target steel quality and temperature throughout the process route

Optimisation of treatment practices

Evaluation of quality relevant parameters

EAF treatment → EAF tapping → LF treatment → VD treatment → Continuous casting

Dynamic on-line monitoring and prediction of steel temperature and analysis evolution based on measured data and process models

Graph showing C-content in % and N-content in ppm over the process stages:
- C-content decreases from scrap mix to EAF treatment, then stabilises until EAF tapping.
- N-content increases from scrap mix to EAF treatment, peaks at EAF tapping, then decreases to VD treatment.

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Conclusions regarding dynamic modelling for on-line control of the EAF process

- Dynamic energy and mass balance model describes EAF process with good accuracy
- Model deviations for the 1. temperature measurement below 30 K and for the following measurements of about 20 K were achieved
  - Error of the energy balance of about 7 kWh/t, relative error of about 1%
- Model accuracy regarding calculated C and O content of about 15 – 20 % of the aim contents
- Dynamic models can be used to monitor on-line the process behaviour and to control the EAF process with regard to end-point control, as well as energy and oxygen input
- Number of temperature and Celox measurements can be reduced
- Aim temperature can be adjusted more precisely
  - Energy savings by avoiding melt over-heating
- Aim carbon content can be adjusted more precisely
  - Improving the metallic yield by avoiding over-oxidation
- For closed-loop control, strategies and model-based set point calculations for on-line determination of control parameters are required
- Dynamic model calculations can be supported by continuous measurements
  - Monitoring the liquid steel temperature during the refining phase by means of optical measurement systems (contactless or optical fibre based)
  - Continuous measurement of liquid steel and slag composition (LIBS)
Conclusions regarding off-gas analysis for EAF process control

- Off-gas analysis is an important tool
  - to close the energy balance of the EAF
  - to provide information for online control of the chemical energy input, e.g. of post-combustion oxygen

→ The control of oxygen input for post-combustion based on a continuous off-gas analysis already proved to lead to a reduction of the electrical energy consumption of up to 20 kWh/t

→ Future developments should lead to a fully dynamic closed loop control of all sources of chemical energy input as oxygen and carbon injection

- In application of the different off-gas analysis systems for process control it has to be considered that a short response time today means also that not all off-gas components can be analysed
Future developments and prospects

- Utilisation of further sensor information as input for dynamic model calculations for an extended on-line process monitoring and control
  - in “MeltCon” project regarding melt temperature control
  - in “AdaptEAF” and “OptiScrapManage” projects regarding monitoring of meltdown behaviour of scrap with adaption of operating practices and control parameters for chemical energy input

- Further extension of dynamic EAF process models for on-line control in the refining phase
  - for dephosphorisation to reliably achieve lowest phosphorus contents
  - for slag reduction in high-alloyed steel production and for control of EAF slag properties

- Inaccuracies and variations in the charge material properties shall be detected by statistical methods, to reduce their impact on performance of process models and operation practices

- Adaptive control of electrical parameters depending on the charge material mix required?

- Through process control of the complete process chain of electric steelmaking becomes more and more important
  - to allow a multi-criterial optimisation of all quality relevant process parameters
  - to consider the interdependencies between EAF process and following ladle metallurgy
  - to provide control of electrical energy demand due to fluctuating energy supply
Thank you very much for your attention!

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