Seminar: Advanced EAF Modelling

Dynamic EAF process models for on-line monitoring and end point determination

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Private research institute
Founded in 1968
Non-profit limited liability company
Sole stockholder: Steel Institute VDEh
Staff: 130 people, 75 % with academic degree
Budget: about 15 Mio €
  6 % from VDEh (basis financing)
  94 % Industry, EU, BMBF, …
Working fields of applied research at BFI

- Quality Assurance and Information Technology
- Material and Surface Finishing
- Process Fluids and Water Management
- Environmental Engineering
- Chemistry and Fluid Mechanics
- Energy and Heat Engineering
- Automation and Process Simulation
- Analysis, Measuring and Testing Techniques
- Process and Plant Technology

BFI
Process Automation Steelmaking

Optimisation of process control through:

- Model based on-line process monitoring
- Dynamic process control
- Off-line process analysis

With the objectives of:

- Reduced consumption of energy, material and media ressources
- Reduced number of samples and measurements
- Increased productivity
- Reliable and reproducible process operation
- Improved transparency of the production process
- Improved quality of liquid steel regarding
  - Adjustment of aim temperature
  - Achievement of target analysis
  - Steel cleanness
Main working fields for EAF steelmaking

Electric Steelmaking

- On-line process observation based on dynamic energy and mass balance models and thermodynamic models for monitoring and end point control of
  - steel and slag weight
  - steel temperature
  - decarburisation
  - metal oxidation
  - dephosphorisation
  - slag composition

- Model-based dynamic control of electrical and chemical energy input

- Model-based dynamic control of oxygen input for decarburisation and dephosphorisation

- Through process modelling, control and optimisation of the complete route of EAF steelmaking

- Regression calculation for determination of composition of the charged scrap types, and optimisation calculation for cost minimal charge mix determination

- Implementation of process models within Level-2 process control systems
### History of EAF model development of BFI within European ECSC and RFCS research projects

#### ECSC projects

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<tr>
<th>Contract Report</th>
<th>Title</th>
<th>Participants</th>
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<td>7210-PR/132 EUR 20803</td>
<td>Improving the productivity of EAFs</td>
<td>BFI, Profilarbed, CRM, FERALPI</td>
<td>1999-07-01 to 2002-06-30</td>
<td>Extension and application of a statistical model for electrical energy demand</td>
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<td>7210-PR/328 EUR 22973</td>
<td>Development of operating conditions to improve chemical energy yield and performance of dedusting in airtight EAF</td>
<td>CSM, BFI, RWTH-IOB, ORI, GMH, TKN</td>
<td>2002-07-01 to 2005-06-30</td>
<td>First version of dynamic energy and mass balance model for the EAF</td>
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#### RFCS projects

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<td>RFSR-CT-2003-00031 EUR 23920</td>
<td>Dynamic control of EAF burners and injectors for oxygen and carbon for improved and reproducible furnace operation and slag foaming (EAFDYNCON)</td>
<td>BFI, Profilarbed, CRM, FERALPI</td>
<td>1999-07-01 to 2002-06-30</td>
<td>Improvement of dynamic energy and mass balance model for the EAF to calculate melt temperature</td>
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<td>RFSR-CT-2006-00004 EUR 25048</td>
<td>Improved EAF process control using on-line offgas analysis (OFFGAS)</td>
<td>RWTH-IOB, CRM, CSM, DEW, Marienhütte, ORI, TENOVA, TKN</td>
<td>2006-07-01 to 2009-06-30</td>
<td>Application of dynamic energy and mass balance model at AC furnace</td>
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<td>RFCS-CT-2008-00003 EUR 25968</td>
<td>Optimised production of low C and N steel grades via the steelmaking route (LOWCNEAF)</td>
<td>BFI, AM Olaberria, CRM, GERDAU, Peiner Träger, RIVA Verona</td>
<td>2008-07-01 to 2011-12-31</td>
<td>Model extension to calculation of carbon and oxygen content</td>
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<td>RFSP-CT-2014-00004</td>
<td>Adaptive EAF online control based on innovative sensors and comprehensive models for improved yield and energy efficiency (AdaptEAF)</td>
<td>BFI, HSU, GMH</td>
<td>2014-07-01 to 2017-06-30</td>
<td>Model extension to calculation of slag weight and composition</td>
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The energetic performance of an Electric Arc Furnace can not be judged only from the electrical energy consumption, as:

- More and more chemical energy inputs as natural gas and oxygen are used
- Quality and specific meltdown energy requirements of the different charge materials (different scrap types, solid pig iron or liquid hot metal) are strongly varying
- The operating practices are differing a lot from plant to plant (e.g. tapping temperature, tap-to-tap time, scrap preheating)

Development of an objective calculation of the electrical energy demand based on the most relevant consumption figures of the Electric Arc Furnace [1-5]

The model shall allow:

- An objective comparison of the energetic performance of an EAF with other furnaces
- The judgement of measures for improvement of the furnace operation regarding energy consumption by evaluation for a single furnace
Statistical regression model for calculation of the EAF electrical energy demand

\[
\frac{W_R}{\text{kWh} / \text{t}} = 375 + 400 \left[ \frac{G_E}{G_A} - 1 \right] + 80 \cdot \frac{G_{\text{DRI/HBI}}}{G_A} - 50 \cdot \frac{G_{\text{Shr}}}{G_A} - 350 \cdot \frac{G_{\text{HM}}}{G_A} + 1000 \cdot \frac{G_Z}{G_A} \\
+ 0.3 \left[ \frac{T_A}{\text{°C}} - 1600 \right] + 1 \cdot \frac{t_S + t_N}{\text{min}} - 8 \cdot \frac{M_G}{\text{m}^3/\text{t}} - 4.3 \cdot \frac{M_L}{\text{m}^3/\text{t}} - 2.8 \cdot \frac{M_N}{\text{m}^3/\text{t}} + NV \cdot \frac{W_V - W_{Vm}}{\text{kWh} / \text{t}}
\]

- \( G_A \): Tap weight
- \( G_E \): Metallic charge weight
- \( G_{\text{DRI}} \): DRI
- \( G_{\text{HBI}} \): HBI
- \( G_{\text{Shr}} \): Shredder-Scrap
- \( G_{\text{HM}} \): Hot metal
- \( G_Z \): Slag formers
- \( T_A \): Tapping temperature
- \( t_S \): Power-on time
- \( t_N \): Power-off time
- \( M_G \): Burner gas
- \( M_L \): Injected oxygen
- \( M_N \): PC oxygen
- \( W_V \): Energy losses
- \( NV \): Factor 0.2 - 0.4

- Electrical energy consumption of a furnace can be judged in comparison to other furnaces
- Changes in the electrical energy consumption of one furnace as result of a modified operation practice can be analysed
Energy consumption of an conventional AC furnace was evaluated over 35 months:

- Tapping weight increased: 77 → 84 t
- Active power increased: 43 → 51 MW
- Percentage shredder scrap increased: 0 → 400 kg/t
- Consumption slag formers decreased: 44 → 35 kg / t

With the formula the development of the electrical energy consumption from 380 down to 330 kWh/t was tracked with good accuracy:

\[ dW_R = W_R - W_E \]

Mean deviation \( dW_R \): 2 kWh/t, standard deviation of \( dW_R \): 7 kWh/t
Dynamic energy and mass balance model for the EAF process: Motivation

- 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
Chemical energy input at a typical DC Electric Arc Furnace
Structure of a dynamic energy and mass balance model for the Electric Arc Furnace
Components of the dynamic balance model for the EAF: 
1. Mass balance

Mass balance and meltdown energy requirement

- Weight of steel and slag are calculated in a mass balance from weight and composition of all charged materials (scrap, alternative iron materials like pig iron or DRI, slag formers, carbon materials, injected recycling dust etc.)
- With the specific meltdown energy in kWh/t of the different materials, the total energy demand is calculated, which is needed to melt the charged materials and to heat up the melt to a reference temperature (e.g. 1600 °C)
- The influence of the hot heel in the furnace is considered according to its state (weight, temperature, analysis) after tapping of the preceding heat
Components of the dynamic balance model for the EAF: 2. Energy input

Energy input

- The energy input comprises the electrical energy input via the arcs and the chemical energy input via natural gas burners, oxygen input via door lances, injectors (coherent jets) mounted in the furnace wall, as well as special post combustion injectors.

- The flow rates of natural gas and oxygen are converted into a power input via efficiency factors (in kWh / Nm³).

- The oxygen input is used for different chemical reactions like decarburisation, metal oxidation, combustion of carbon compounds which are introduced via the scrap etc. Thus an average efficiency factor has to be chosen, as the distribution of oxygen to the different reactions can not be exactly determined.

![Diagram of energy input components]

- Electrical energy
- Burner natural gas
- Lance and jet burner oxygen
- Post-combustion oxygen

Energy input
Electrical energy input for an example heat

- For long periods during meltdown of the two scrap baskets the active power is nearly constant.
- Step down of active power in case of thermal overload of the water-cooled panels, and in the final phase of superheating.
Control of the burners via fixed operating patterns, where set-points for flow rates of natural gas and oxygen are defined for different steps, which are e.g. switched according to the electrical energy input.

The natural gas burners are operated for longer periods in an over-stoechiometric mode, to provide oxygen for post combustion in the furnace vessel.
Chemical energy input via door lances and jets for an example heat

- Oxygen input via door lances, e.g. for meltdown of scrap at the furnace door
- Oxygen input via jet burners together with carbon injection to create and maintain a foamy slag and to decarburise the melt
Components of the dynamic balance model for the EAF:
3. Energy losses

Post combustion and energy losses

- Energy input via post combustion of CO and H₂ via oxygen of leakage air
- Energy losses via not completely combusted off-gas components CO and H₂ are determined from the measured values of off-gas flow rate and composition
- Energy losses furthermore consist of the sensible heat of the off-gas and of the thermal losses via water-cooled furnace panels and roof
- Radiation losses during open furnace roof are calculated in dependence of the current melt temperature
- Convection losses via the furnace hearth are considered with a constant loss rate
Thermal losses via water-cooled panels of the furnace wall and via the water-cooled furnace roof

Power loss rate is calculated from cooling water flow rate and difference between input and output temperature
Extractive off-gas analysis with mass spectrometer

- Analysis of all relevant off-gas components via a mass spectrometer [6]
- Determination of off-gas and leakage air flow rate via Argon and Nitrogen balance
- Delay time of about 20-30 seconds due to probe gas sampling and analysis
Off-gas measurement via mass spectrometer

- Extractive measurement with probe gas sampling at the furnace roof
- Off-gas analysis via mass spectrometer, all relevant off-gas components can be measured
- Determination of off-gas and leakage air flow rate via Argon and Nitrogen balance
- Measurement of off-gas temperature via pyrometer
- Calculation of the losses via the off-gas
  - Sensible heat from flow rate and temperature
  - Chemical energy content from flow rate and CO / H$_2$ content
Current energy content and calculation of the melt temperature

- The difference between energy input and energy losses determines the current energy content of the melt
- The energy content is related to the meltdown energy requirement of the charged materials to calculate the melt temperature
- The energy requirement for superheating of the melt beyond the reference temperature of 1600°C is calculated from the specific heat capacity of steel and slag
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: Example DC furnace

- 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
Model accuracy regarding the calculation of the melt temperature: Example AC furnace with bottom stirring

Accuracy of the first measurements

Accuracy of further measurements after adaption to the previous ones

- Standard deviation: 28.6 K
- Standard deviation: 19.3 K
Example for on-line implementation of the dynamic process model for temperature calculation
Optimisation of oxygen input for decarburisation

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 model for process control of the Electric Arc Furnace: Extension to calculation of C and O content

- On-line energy and mass balance for observation of the EAF process state with respect to melt temperature and composition
Dynamic energy and mass balance model was extended by a detailed carbon balance [7, 8]

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: Example DC furnace

First plausible Celox measurement respectively sample analysis

Further measurements after adaption to previous measurements
Model accuracy regarding oxygen content: Example DC EAF

First plausible Celox measurement

Further measurements after adaption to previous measurements

stand. dev.: 216 ppm
stand. dev.: 157 ppm

0 500 1000 1500
calculated oxygen content in ppm
measured oxygen content in ppm
stand. dev.: 216 ppm
stand. dev.: 157 ppm
Model accuracy regarding carbon content: Example AC EAF

Accuracy of the first Celox measurements

Accuracy of further Celox measurements after adaption

standard deviation: 0.009%

standard deviation: 0.006%
Conclusions and prospects

- The dynamic energy and mass balance model describes the energetic process at the EAF with very good accuracy.

- Model deviations for the first temperature measurement well below 30 K and for the following measurements of about 20 K were achieved.
  → Error of the energy balance of about 7 kWh/t.
  → With respect to the total energy input of around 690 kWh/t, the relative error is about 1%.

- Model accuracy regarding calculated carbon and oxygen content of about 15 – 20% of the aim values.

- The process model is robust and easily adaptable to further EAFs (so far in use at 6 EAFs).

- Tools for validation and model parameter optimisation exist.

Benefits of the on-line application of the dynamic model:

- Number of temperature and Celox measurements can be reduced.

- Aim temperature can be adjusted more precisely → Energy savings by avoiding over-heating.

- Aim carbon content can be adjusted more precisely → Improved metallic yield by avoiding over-oxidation.

- The model can be used to optimize and to control the melting process.

- Extension of the model regarding dephosphorisation and slag control has been started.
Thank you very much for your attention!

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References

[1] Köhle, S.: Variables influencing electric energy and electrode consumption in electric arc furnaces. MPT International (1992), Nr. 6, S. 48-53


