Seminar: EAF energy and resource efficiency

Erhöhung der Energie- und Ressourceneffizienz des Lichtbogenofen-Prozesses durch dynamische Steuerung der Sauerstoffzufuhr

*Increased energy and resource efficiency of EAF process by dynamic control of oxygen input*

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Topics of EAF energy and resource efficiency

- Modelling of the EAF process for evaluation of the energetic performance and for dynamic online observation and control
- Process monitoring and control based on EAF off-gas analysis
- Dynamic control of oxygen input for post-combustion purposes
### Selected ECSC and RFCS research projects dealing with aspects of EAF energy and resource efficiency

<table>
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<tr>
<th>Contract Report</th>
<th>Title</th>
<th>Participants</th>
<th>Start / End</th>
<th>Topic regarding process models</th>
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<td>7210-PR/132 EUR 20803</td>
<td>Improving the productivity of Electric Arc Furnaces</td>
<td>BFI, Profilarbed, CRM, FERALPI</td>
<td>1999-07-01 to 2002-06-30</td>
<td>Application of a statistical model for the 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>Dynamic energy and mass balance model EAF off-gas analysis with mass spectrometer</td>
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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, CRM, AM Long Carbon, GERDAU I&amp;D, GMH</td>
<td>2003-09-01 to 2007-02-28</td>
<td>Dynamic energy and mass balance model for the EAF to calculate melt temperature and to control oxygen input</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>EAF off-gas analysis with in-situ laser based measurement Control of PC oxygen input</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>Extension of models to calculate Carbon content as basis for control of decarburisation</td>
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Motivation for development of a statistical model for calculation of the electrical energy demand

- 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

- The statistical model allows:
  - an objective comparison of the energetic performance of an EAF with other furnaces
  - to identify reasons for non-optimal energetic performance
  - to judge 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

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

\(G_A\) Tap weight  \(t_S\) Power-on time
\(G_E\) Metallic charge weight  \(t_N\) Power-off time
\(G_{\text{DRI}}\) DRI  \(M_G\) Burner gas
\(G_{\text{HBI}}\) HBI  \(M_L\) Injected oxygen
\(G_{\text{Shr}}\) Shredder-Scrap  \(M_N\) PC oxygen
\(G_{\text{HM}}\) Hot metal  \(W_V\) Energy losses
\(G_Z\) Slag formers  \(T_A\) Tapping temperature
Average electrical energy demand of different EAFs: Comparison of energy savings by post combustion

- Comparison between 14 AC furnaces without and 8 furnaces with post combustion
- For 7 furnaces comparison between operation without / with post combustion possible
- Average energetic efficiency of post combustion oxygen was determined with 2.8 kWh / Nm³ (theoretical value for reaction CO + \( \frac{1}{2} \) O₂ → CO₂ is 5.8 kWh / Nm³)
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:

Mean deviation \( dW_R = W_R - W_E \): 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
Dynamic EAF process model of BFI

- 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)
Input data of the energy balance for an example heat

- **Energy inputs**
  - Electrical energy
  - Gas burners
  - Oxygen injection via jets and door lances
  - Oxygen for post-combustion of CO inside the furnace

- **Energy losses**
  - Sensible heat and chemical energy content of the off-gas
  - Cooling water losses of furnace walls and roof
  - Radiation and convection
Extractive off-gas analysis with mass spectrometer

- Analysis of all relevant off-gas components via a mass spectrometer
- Determination of off-gas and leakage air flow rate via Argon and Nitrogen balance
- Delay time of about 30-40 seconds due to probe gas sampling and analysis
Off-gas measurement by mass spectrometer

- 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
- Real-time calculation of melt temperature and comparison with measurements
- Adaption to plausible temperature measurements increases the accuracy of the model for further treatment
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.
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
Configuration of the EAF of GMH with locations of chemical energy input

- 4 natural gas-oxygen-burners (max. 4MW each), 3 of them with lances (jet) (max. 2000 m³/h each)
- 3 lines oxygen diffusors (5 nozzles, max. 900 m³/h each line)
- 2 oxygen lances on manipulator (max. 2500 m³/h each line)
- 3 carbon injection bins for 4 carbon lances (burner 5 and manipulator = same bin)

Dust injection

Burner 3 (+jet) carbon injection

Burner 4 (+jet) diffusor 2 carbon injection

Diffusor 3

Burner 5 (+jet) diffusor 1 carbon injection

Burner 6

Lance manipulator
Lance 4: carbon
Lance 3: stand by
Lance 2: oxygen
Lance 1: oxygen
Control of the post-combustion reaction in the EAF based on off-gas analysis

- Development and implementation of an automatic control for the input of post-combustion oxygen based on the off-gas analysis at the GMH furnace

- The total oxygen consumption remains more or less constant
- The more efficient input of post-combustion oxygen leads to an energetic benefit of about 20 kWh/t
In-situ off-gas measurement via LINDARC® system at the Marienhütte furnace

- Laser based delay-free in-situ off-gas analysis installed in the elbow of the furnace
- Analysis of CO, O₂ and CO₂ possible
- Additionally measured temperature is not representative for the off-gas temperature
- For measurement of CO₂ in addition to CO a separate laser is required
Dynamic control of post-combustion oxygen supply based on LINDARC® off-gas analysis

- 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
Analysis of EAF process operation regarding post combustion oxygen input at LSW

- EAF is equipped with 3 Jet burners and 3 post combustion tuyeres for oxygen input to post-combust CO to CO$_2$ inside the furnace vessel (CO Post-Combustion)
- Post combustion oxygen is added according to fixed operating patterns
- With the help of an off-gas analysis system (laser-based, extractive) for trial campaigns the energetic efficiency of this oxygen input was analysed and optimised
- Investigation of the effect of modified post combustion oxygen input on the energetic performance of the EAF
- Evaluation of heats directly before and after a modification of the operating pattern for control of the post combustion oxygen input

Heat with old pattern for PC oxygen

Heat with new pattern for PC oxygen
Comparison of measured offgas analysis for old and new operating pattern regarding post combustion O₂

Old pattern PC oxygen

New pattern PC oxygen
Evaluation of the energetic performance of the different operating patterns of post combustion O₂

- Evaluation of heats directly before and after the modification of the PC oxygen input
- Increase of the PC oxygen input with parallel decrease of injector oxygen
- Decrease in electrical energy consumption of 33 kWh/t
- Evaluation with the statistical model reveals that about 17 kWh/t of this decrease are caused by the modification of the operating pattern for PC oxygen
- Savings in electrical energy of about 4% by optimised PC operating pattern were confirmed in long term industrial operation

<table>
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<tr>
<th>Variable</th>
<th>energy demand kWh/t</th>
<th>energy consumption kWh/t</th>
<th>tapping weight t</th>
<th>over input of scrap kg/t</th>
<th>slag formers kg/t</th>
<th>tapping temp. °C</th>
<th>Power on min</th>
<th>Power off min</th>
<th>natural gas Nm³/t</th>
<th>Nm³ t</th>
<th>PC oxygen Nm³/t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Old pattern PC oxygen</td>
<td>426</td>
<td>469</td>
<td>98</td>
<td>1183</td>
<td>34</td>
<td>1655</td>
<td>45.5</td>
<td>19.7</td>
<td>4.7</td>
<td>21.1</td>
<td>3.5</td>
</tr>
<tr>
<td>New pattern PC oxygen</td>
<td>411</td>
<td>436</td>
<td>102</td>
<td>1149</td>
<td>28</td>
<td>1641</td>
<td>41.3</td>
<td>21.6</td>
<td>4.8</td>
<td>17.4</td>
<td>5.0</td>
</tr>
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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 Carbon balance with inputs:
  - charged scrap types and carbonaceous materials with information on C content
  - blown lance carbon input
  - lance / injector oxygen input

- C content is calculated cyclically from carbon input and decarburisation by oxygen input

- Decarburisation efficiency of oxygen input depends on current carbon content of the melt

- O content is calculated according to equilibrium conditions

- 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

stand. dev.: 216 ppm

stand. dev.: 157 ppm
Conclusions and prospects

- Statistical model for calculation of the electrical energy demand is a simple tool for objective analysis and judgement of the energetic performance of the EAF
- 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 optimize and to control the EAF process with regard to end point control, energy and oxygen input
- 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
- Off-gas analysis is an important tool to close the energy balance of the EAF, and to provide information for online control of the chemical energy input, e.g. post-combustion oxygen
- The model can be used to optimize and to control the melting process:
  - The control of oxygen input for post-combustion based on a continuous off-gas analysis leads to a reduction of the electrical energy consumption of up to 20 kWh/t
Thank you very much for your attention!

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