Optimisation of EAF operating practice using iCSMelt

An optimisation tool developed by CSM for the EAF has been implemented at Duferco La Louvière where in different configurations a reduction of close to 1% in total specific energy consumption and of 3.25% in specific electrical power consumption has been obtained depending on charge mix and optimisation strategies used.

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THE iCSMelt® – ‘Intelligent Care Steel Melting’ is a tool developed by Centro Sviluppo Materiali (CSM) of Italy with the aim of optimising EAF operating practices (OOP) in terms of yield, tap to tap time, energy consumption and on repeatability of performance in order to reduce production cost. Therefore attention has been focused on individual processes by monitoring and control through combinations of:

- Hardware sensors, commercially available, for process monitoring (such as off-gas analyser, liquid bath temperature measurement, slag level, etc);
- Software sensors for generating information not directly available from measurements (eg a metallurgical model to estimate slag and steel composition and temperature);
- Operating patterns for steel production in the EAF is necessary as target for each control system in use (yellow blocks in Fig 1).

The iCSMelt tool has been developed by CSM coupling static mass and energy balance with an optimisation tool. This article describes the customisation of iCSMelt for the DC electric arc furnace at Duferco La Louvière (DLL) in Belgium and presents results of its application in the frame of the project ‘Control and optimisation of scrap charging strategies and melting operations to increase steel recycling ratio’ (CONOPT-SCRAP) which has been carried out with the help of a financial grant from the Research Fund for Coal and Steel of the European Community.

The iCSMelt tool has the aim of obtaining optimised operating practices (OOP), starting from standard operating practices (SOP) in use on the specified EAF, following selected objective functions (OF). The iCSMelt tool includes different modules (Fig 2):

- iCSMelt Process Model (iCSMelt-PM), the process simulator;
- iCSMelt Calibrator (iCSMelt-Cal) the tool, based on Genetic Algorithm (GA), for automatic tuning of calibration parameters of the iCSMelt-PM;
- iCSMelt Optimiser (iCSMelt-Opt), the optimisation tool based on the GAs.

In the specific case of Duferco La Louvière, the iCSMelt modules have been integrated with an on-line data acquisition system (DAS) and a process data analyser (iCSMelt-PDA), the plant data viewer and inputs generator for the process model. Presently the relevant data for each heat are recorded in a dedicated database that can be read by iCSMelt-PDA.

**iCSMelt Process Model**

The iCSMelt-PM can be classified as a pseudodynamic mass and energy balance. Each heat is represented by several charge baskets (two for DLL), each subdivided into several phases (four and six respectively for DLL), (Fig 3).

The end of each phase is defined by a fixed level of a particular process parameters, or their combinations, following specific plant customisation. Each phase is divided in time steps (At) for which static mass and energy balance is calculated (Fig 4). Terms included are:

- Material inputs and their energies (white in Fig 4);
- Process outputs (green): steel, slag and off gas;
- Terms from the SOP managed/exchanged between iCSMelt-PM and iCSMelt-Opt (red): electrical voltage, current, total natural gas flow rate, total oxygen flow rate, total carbon flow rate.

Different options are available in iCSMelt-PM:
- **By Plant Data:** iCSMelt works using SOP acquired by iCSMelt-DAS and converted by iCSMelt-PDA in input for iCSMelt-PM.
- **By Model Strategy:** heat simulation is performed following a SOP defined by process engineer; two strategies for definition of end of phases are possible:
  - *Technological strategy*: phases end is granted by technological steps as in Fig 3;
  - *Operator strategy*: phases end is set by specific electrical energy consumption levels.

End of simulation defines the condition of termination of the simulation according to:

- **End Point Temperature**: termination corresponds to desired steel target temperature;
- **Until Last Data**: heat simulation terminates at the end of defined SOP.
The ‘End of Simulation/last data’ is used in a calibration procedure when model parameters are set to reach the target tapping temperature, while the ‘End of Simulation/End Point Temperature’ is used during the optimisation procedure when it is necessary to evaluate the duration of the heat to reach the tapping temperature.

**iCSMelt-Calibrator**

Calibration parameters are available in iCSMelt-PM to reach the best fitness with process data at the end of the heat. Manual calibration is also possible. However data available in DAS also allows the automatic re-calibration of the parameters, treating a higher number of calibration data in a limited time, in case of changes of process management or the charge mix used.

**iCSMelt Optimiser**

iCSMelt-Opt is based on the GAs (Genetic Algorithms) method. The objective functions (variables yi) are:

- mathematical parameters for the GAs management (GAs Management Parameters);
- range of variability of the SOP parameters for each phases (SOP Constraints);
- mathematical parameters for the GAs management (GAs Management Parameters);
- value reachable for specific targets of interest (heat aims).

At each iteration of the optimisation process iCSMelt-Opt receives as input:

- indications of phases to be optimised (Phase Optimised Selection);
- range of variability of the SOP parameters for each phases (SOP Constraints);
- mathematical parameters for the GAs management (GAs Management Parameters);
- value reachable for specific targets of interest (heat aims).

These are depicted in Fig. 5. iCSMelt-Opt evaluates results of proposed OP through the iCSMelt-PM. If the target is not reached the sub-module, named ‘GAs practice generator’, calculates a new OP to obtain better results with respect to the previous calculated simulation. The formula for
the target function which results in minimisation is given in Equation 1.

\[ T = \sum_{j}^{m} \frac{\left( \gamma_j - x_j \right)^2}{\gamma_j^2} \cdot W_j \cdot \sum_{i}^{m} \left( \gamma_i - x_i \right)^2 \cdot W_i \cdot \gamma_{\text{ref}}^2 = 0 \]

Equation 1

\[ T = \sum_{j}^{m} \left( \gamma_j - x_j \right)^2 \cdot W_j \cdot \sum_{i}^{m} \left( \gamma_i - x_i \right)^2 \cdot W_i \cdot \gamma_{\text{ref}}^2 = 0 \]

Equation 2

where:
- \( T \) is the target function value;
- \( \gamma_j \) are main output of heat simulation for objective functions and steel melt composition;
- \( x_j \) are quantities \((x)\) of model output fixed for objective functions as aims of heat;
- \( w_j \) are weights of single model output fixed as objective function.

The constraint regions are implemented as an extension of the target function evaluation: if the GAs practices generator builds a new OP that contains one or more variables that are outside of constraints, the output of the EAF model is forced to a very high value (equation 2).

where:
- \( V \) is the set of valid operating practice values;
- \( u_k \) is each of \( m \) specific component of OP.

The optimisation process ends when convergence occurs or when the time limit of the procedure is reached. Since the aim of the optimiser is to find a good solution in a reasonable time, the control of genetics algorithms is included in the GAs practices generator. Two parameters, configurable by the user, allow the management of the GAs practices generator: 1) size of population 2) number of generations.

Implementation at Duferco La Louvière

The main characteristics of the EAF at Duferco La Louvière (DLL) are given in Table 1.

Five main steps have been taken during the installation of iCSMelt at DLL. These correspond to the implementation of the main modules (Fig 6).

Step 1 Acquisition: The iCSMelt tool has been integrated at DLL for data interchange with level 1 automation. As per today, EAF process signals corresponding to relevant heat data are recorded in a database, DAS, that can be read by the iCSMelt-PDA and transferred to iCSMelt.

Step 2 Calibration: The calibration parameters of iCSMelt-PM to obtain the best fitness with the results of real heats are defined for the EAF. Since the off-gas measurements are not available at DLL, typical values for EAF process are assumed. In addition, the charge mixes typically used at DLL are named ‘Menu 30’, ‘47’, and ‘70’. The definition of calibration parameters has been performed for homogeneous groups of heats.

Fig 7 shows, as an example, the variability of the calibration parameter K_O_Inj, related to the efficiency of oxygen injection on the steel/slag bath, for charge mix 70.

Moreover different calibration procedures have been performed to obtain a sensitivity analysis of the effect of the different calibration parameters to simulations results.

Step 3 Simulation: The simulation of the heat by iCSMelt-PM. This step requires general inputs such as plant configuration data, different scrap grades in use (to be filled in the available data base) and a description of the heat phases in addition to a SOP. Criteria for phase transition has been customised based on specific process practices at DLL. In Fig 8, an example of energy balance for menu 70 is shown where:
- Electrical energy is 55% of total energy input while chemical energy is 45%.  
- Energy to the steel/slag bath is 68% of total energy while 32% are energy losses.

Step 4 Definition of Improved Operating Practice (IOP): in this step iCSMelt-PM is used alone as support to evaluate the effects of OP modifications. In particular at DLL two main optimisation scopes have been pursued:
- IOP 2: reduction of specific carbon consumption, at least by 10%;
- IOP 3: reduction of specific electrical energy consumption.

Fig 9 shows the results of simulations performed at different levels of oxygen flow rate used to define IOP1 characterised by a reduction of 10% of the carbon flow rate and 2.5% of oxygen flow rate at each step with respect to the previous standard practice (SOP).

The IOP2 gives a reduction of 9.97% in specific carbon consumption and 1.73% of specific oxygen consumption, without significant variation of specific electrical energy consumption and with a small decreasing of specific total energy consumption (~0.25%).

IOP3 (Fig 10) has been defined with the scope of achieving a reduction of specific electrical energy consumption to respond at a lower production scenario. Therefore, the increase of power-on time is considered acceptable in a range of plus 5% with respect to DLL standards.

The iCSMelt simulation shows a reduction of specific electrical energy consumption of ~3.1%, and as expected, an increase in the power on time of +1.2% as indicated in Table 3.

Step 5 Definition of Optimised Operating Practices (OOP): In the automatic definition of the OOP, to optimise the objective function (OF) selected by the process engineer, the modules iCSMelt-PM and iCSMelt-Opt are involved. At DLL, OOP has been generated for charge menu 47 (OOP47) and subsequently the procedure has been adapted to the other two charging mix (OOP30 and OOP70).

The target of OOP47 has been to minimise the total specific energy consumption. Simulation of OOP47 has achieved a reduction of 2.4% of total specific energy input (Fig 9, Table 3). Furthermore iCSMelt-Opt has been used to define OOP for charging mix 70 for other objective functions: minimisation of specific coal consumption and minimisation of specific total cost.

Industrial test of iCsmelt at Duferco La Louvière

The new OPs obtained with iCSMelt for different charge mixes and different objective functions (minimising specific consumption of total energy, minimising specific total cost of the heat, minimising specific total coal consumption) have been tested at DLL. Two example are reported here.

Test with IOP3

Starting from the total oxygen, natural gas and carbon calculated by iCSMelt for IOP3, the sets for each of the injectors have been obtained following the DLL indication. Comparison of data for heats with SOP and heats performed with IOP3 (Table 4) shows a 3.24% reduction of specific electrical energy
and a 2.83% increase in power-on time, values very close to those estimated by iCSMelt in Table 2 (3.1% and 3.2% respectively). The decrease in natural gas and carbon consumption is also in line with the iCSMelt evaluation.

**Test with OOP47**

A test of the implementation of OOP47 has been made by DLL at heat 56293 with some adaptation for distributing iCSMelt total flow rates in various EAF zones. In particular, modifications were:

- adjust the ratio between oxygen and gas flow rate in the step 3 of first basket;
- in phases 5 and 6 of basket 2 the carbon flow rate was left at the same value as in step 4

In detail, simulation of the original OOP47 showed a reduction of 2.9% in total energy consumption corresponding to 2.4% in terms of total specific energy consumption. Using the adjusted OOP47 the reduction of total specific energy consumption results in a 1.2% reduction (Table 3). Heat 56293 performed with an adjusted OOP47 results with a reduction in total specific energy consumption of 0.7% while the power-on time remained in the range of traditional DLL practice (33.5 minutes) and very close to the predicted 34.07 minutes.

Acknowledgement

The authors are grateful to Mrs E Malfa and Mr V Volponi, for their useful collaboration in preparing this paper.

**References**

2. [8] P. Clerici et others, 2nd European Steelmaking Conference, Athens, Greece 2004

**Table 1** Main characteristics of EAF at Duferco La Louvière

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Tapping temperature</td>
<td>1659°C</td>
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<tr>
<td>CO consumption</td>
<td>0.7%</td>
</tr>
<tr>
<td>Methane consumption</td>
<td>0.7%</td>
</tr>
<tr>
<td>Power On</td>
<td>31-32</td>
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<td>Total specific energy</td>
<td>5.6%</td>
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<tr>
<td>Total Carbon</td>
<td>30</td>
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<tr>
<td>Productivity max</td>
<td>ton/hour</td>
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**Table 2** Schematic view of comparison between simulation of IOP3 and SOP by iCSMelt

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comparing Temperature</td>
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<tr>
<td>Tapping Temperature</td>
<td>IOP3</td>
</tr>
<tr>
<td>CO consumption</td>
<td>SOP</td>
</tr>
<tr>
<td>Methane consumption</td>
<td>IOP3</td>
</tr>
<tr>
<td>Power On</td>
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<td>Total Carbon</td>
<td>SOP</td>
</tr>
<tr>
<td>Productivity max</td>
<td>IOP3</td>
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**Table 3** Comparison between SOP, OOP47, OOP47 adjusted simulated and heat results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power on</td>
<td>kWh/ton</td>
</tr>
<tr>
<td>Methane Consumption</td>
<td>Nm3/kg</td>
</tr>
<tr>
<td>Oxygen Consumption</td>
<td>Nm3/kg</td>
</tr>
<tr>
<td>Carbon Flow Rate</td>
<td>kg/min</td>
</tr>
<tr>
<td>Specific energy</td>
<td>kWh/ton</td>
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</tbody>
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**Fig 10** Comparison between SOP and IOP3 for the electrical and chemical parameters

**Fig 11** Comparison between SOP used and OOP47 defined

**Table 4** Comparison between heat data with actual standard operation (SOP) and that predicted by IOP3

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power on</td>
<td>kWh/ton</td>
</tr>
<tr>
<td>Methane Consumption</td>
<td>Nm3/kg</td>
</tr>
<tr>
<td>Oxygen Consumption</td>
<td>Nm3/kg</td>
</tr>
<tr>
<td>Carbon Flow Rate</td>
<td>kg/min</td>
</tr>
<tr>
<td>Specific energy</td>
<td>kWh/ton</td>
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