A process model for EAF steelmaking

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INTRODUCTION

Most current Electric Arc Furnace (EAF) steelmaking makes use of level-2 automation systems [Nil00, Hei97]. The instrumentation of the furnaces allows for a quantitative time dependent measurement of the energy and mass inputs. This data can be used for online or offline modelling of the meltdown process. The development of such models started in 1974 [Wal74] and – in simpler forms – they became state-of-the-art within the following decades [Ame81, Koh95, Koh99, Iro05]. The model developments were undertaken into several directions, e.g.

- Determination of overall process characteristic and process control, e.g. [Sch84, Bel99, Bek00, Bou03].
- CFD modelling of the Off-gas system [Tan03] or the heat transfer inside the furnace [Guo05].
- Modelling of meltdown and slag chemistry [Mat97, Bek99, Mor01] and slag foaming [Oos01, Mor02].

In most cases, the resulting models are specific to the EAF or even an individual plant. They use different approaches and models for offline and online applications. Details on model calculations using real industrial data are rare in the open literature, but the developments during the last decades and this paper have some important common properties:

1. The physical conservation laws of mass, energy and species are derived and solved.
2. The general numerical method is to set-up and solve a set of nonlinear ordinary differential equations (in most cases the trivial explicit integration scheme is used).
3. The models require initial values and (in general time dependent) data for the time dependent inputs like electrical- and chemical inputs and mass loads (scrap, DRI …).

From these general features, a universal approach for the modelling of metallurgical processes (**P**rocess **R**eactor **M**odel) was developed [Spi05]. This concept is applied to the EAF here. The process model presented is suitable for online as well as for offline applications and can be integrated into the steel plant IT system, e.g. in the framework of current level-2 automation systems [Mat03, Bho05]. To avoid confusion, the term *process model* is used for an algorithm implemented as a software subroutine using some initial values at start-up and a number of (measured or extrapolated) input values during operation for the calculation of output values like melt temperature `TM` or current mass of liquid metal `ML`. The **PRM** approach described in the first section is also used for other metallurgical processes like ladle furnace melt conditioning. The concept and software environment allows the balancing of mass, energy and species in a finite number of balance volumes. As described in the second section, the melt, the solid input (scrap, DRI …), the slag, the shell, the panels and the roof are modelled together with the gas mass and energy flows. The physical model of the EAF operation is set-up by defining source and exchange terms within and between the balance volumes. The energy and mass balances are solved time dependently. The model allows for a quantitative prediction of values like the melt temperature and is operated within a level-2 automation system as well as an independent offline model for optimizing the EAF operation. Finally the principal achievements, challenges and limitations of EAF process modelling are discussed.

THE PROCESS REACTOR MODEL

Modern steel plants make use of enterprise IT systems. Within these systems, level 1 (control, e.g. PLC) and level 2 (unit, e.g. EAF-plant) automation requires process models. During the production cycle, a number of important quantities are unknown or can not be measured for fundamental reasons, e.g.

- The current (average) temperature of the solid material (scrap, DRI …) is not observable.
- The current melt and slag temperature are difficult of measure in the EAF [Lam05].
- The current mass of the melt in the furnace can not be measured.

The use of online process models can therefore enhance the knowledge on the current process state and thus support optimized process operation by providing additional input data for process control. Additionally, these models can use extrapolated input data to predict the future trends of the process variables. The same models can be used offline with real or artificial process operation data to optimize the plant operation or to analyse the impact of process innovations. During the installation and optimization of such a process model the requirements of the model justify and support the implementation of advanced measurement systems, e.g. in order to get precise data on the energy and mass inputs into the furnace. As shown in Figure 1, the process model (for online and offline use) is an important part of the EAF process and operation optimization cycle. The instrumentation of the furnace (weighting of scrap, DRI …) continuously delivers measurement data during the operation which is feed into the model. To enhance the models abilities to predict important parameters like melt mass and temperature, new or more precise measurements can be implemented. The more precise data gives than better opportunities to test and furthermore enhance the model. Such more detailed or accurate models will allow better control during the operation (online model) or the development of optimized process operation modes. As a conclusion, the model and its development cycle is principally linked to the development of the EAF operation itself. Some of these relations will be analysed later within this paper by a so called sensitivity analysis using the 7 balance volume process model `EAF07`.

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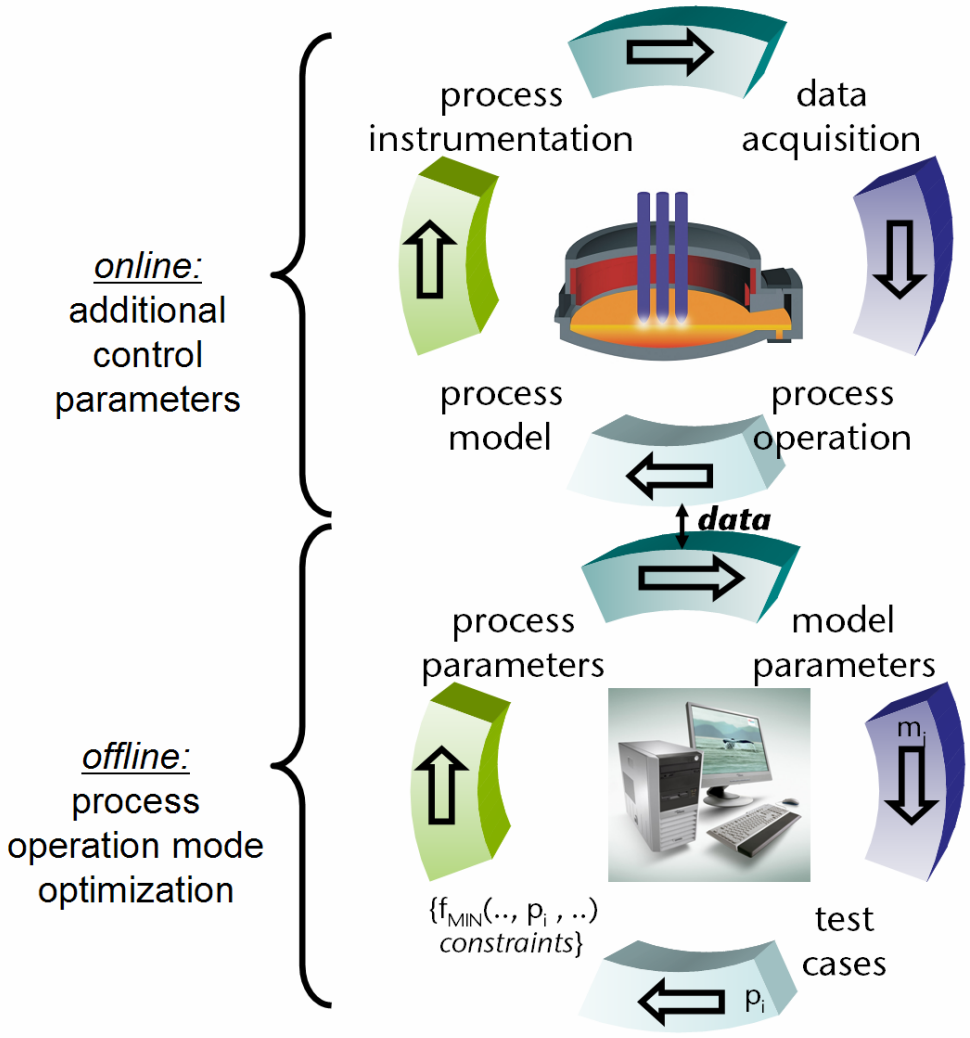

Figure 1: Process modelling in the context of the plant optimization cycle.

As sketched in Figure 2, the process model itself is deduced from a universal toolbox for the development of **P**rocess **R**eactor **M**odels, especially for metallurgical processes. The approach is to use as much fundamental physics as possible and only a minimum of process dependent coefficients. The model solves equations from physical conservation laws for mass, momentum, energy and species. For a conserved quantity ψ_i in the balance volume i, the differential equation for the time evolution of ψ_i is

$$\frac{d}{dt}\psi_i = \sum_{\forall j \neq i} F_{\psi,i,j} + S_{\psi,i}\,, \tag{1}$$

whereas $S_{\psi,i}$ is the sum over all source terms of the balanced quantity ψ_i in the balance volume i and $F_{\psi_i,i,j}$ is the interaction term for ψ_i between the balance volumes i and j. For the simple case of heat transport without mass or species transport between two balance volumes, the interaction term for the enthalpy content H is

$$F_{H,i,j} = A_{i,j}\,\alpha_{i,j}\,(T_{i,j}^{boundary} - T_i)\,. \tag{2}$$

The interaction area $A_{i,j}$ and the heat transfer coefficient $\alpha_{i,j}$ must be provided, while the actual boundary temperature $T_{i,j}^{boundary}$ can be calculated from the symmetry/conservation relations. The heat conduction inside the balance volumes is included in $\alpha_{i,j}$ as a special case of the boundary layer concept used by defining $\alpha_{i,j}$ in equation (2). For interactions like melting or chemical reactions, where combined heat and species transport takes place, the interrelations of the $F_{\psi,i,j}$ have to be taken into account, i.e. by solving the resulting (nonlinear) equation system to determine all $F_{\psi,i,j}$ self consistently. The source terms $S_{\psi,i}$ are used to include external parameters like electric arc heating, alloying, reaction for internal thermodynamic equilibrium, charging etc. and are thus strongly depending on the application, e.g. the EAF, as described in the following section.

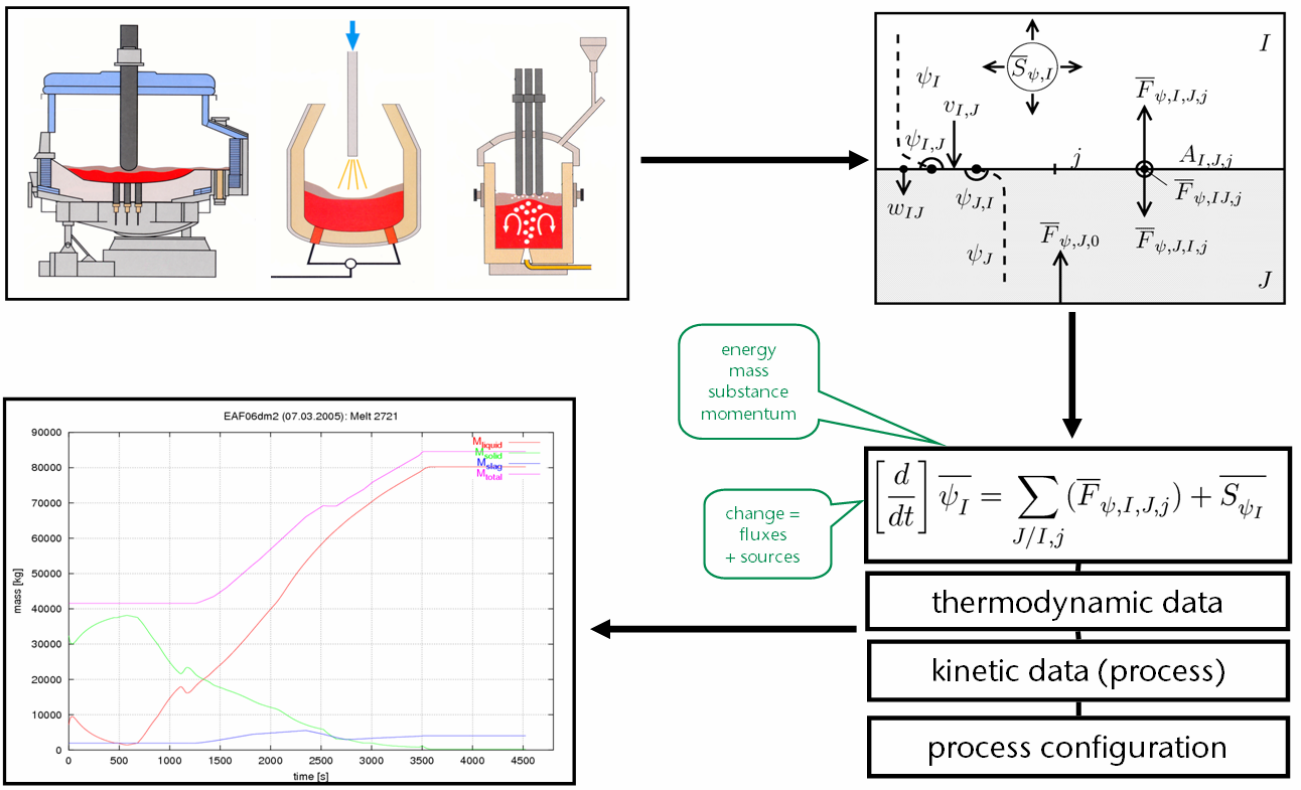

Figure 2: **P**rocess **R**eactor **M**odel concept.

MODELLING OF THE EAF OPERATION

For the application of the PRM concept described above to a running EAF model, several steps are required:

1. Analysis of the EAF operation: The primary function is the melting of solid material by electrically generated energy.
2. Definition of input and output quantities:
   - ~20 time dependent values like current electric arc power `PEL` or DRI feeding rate `MDR`.
   - ~20 process parameters like furnace dimensions and heat transfer coefficients.
   - ~20 output results like melt mass `ML` and temperature `TL`.
   - several parameters for the model installation and control, including the energy distribution parameter `LEL`.
3. Definition of the balance volumes and quantities to be balanced, see Table I, e.g.
   a. Upper shell ①, lower shell ⑦, roof ⑥: Energy balance for the calculation of an average temperature.
   b. Liquid metal ②, solid metal ③ (scrap, HBI, DRI): Mass-, energy- and carbon- balance.
   c. Slag ④ and gas ⑤: Mass and energy balance.
4. Definition of the interaction functions between the balance volumes: Energy transport as defined in (2) or energy and mass transport (melting/solidification).
5. Definition of the special features and source terms for the individual balance volumes (see below).
6. Definition and acquisition of data sets for initial values and time dependent input data.
7. Implementation and test using the data sets from step 6.
8. Commissioning at an industrial EAF.
9. Iterative optimization as described in Figure 1.

No./balanced quantity		0	1	2
1	upper shell	H [J]		
2	liquid metal	H [J]	M [kg]	M_C[kg]
3	solid metal	H [J]	M [kg]	M_C[kg]
4	slag	H [J]	M [kg]	
5	gas	H [J]	M [kg]	
6	roof	H [J]		
7	lower shell	H [J]		

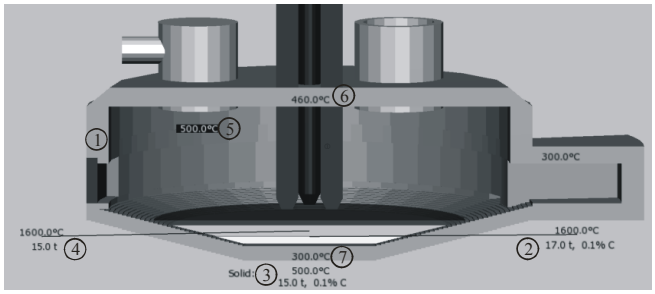

Table I: Definition of the `EAF07` module.

The model memory can be adapted to a specific plant situation as required and the model includes a database for the specific enthalpy depending on composition and temperature. The calculations are performed using time step of e.g. 1s. For the EAF, a number of features were included as follows:

Electrical Energy
For each time step, the electrical (arc) energy input is specified by the value of `PEL` [W]. The constant global model (fit-) energy distribution parameter `LEL` and the current mass values determine the energy distribution between liquid, solid, slag, wall and gas balance volumes.

Chemical Energy
Time dependent input values for oxygen blowing, gas burners etc. are used and their energy input is distributed to the corresponding balance volumes.

Material Input
For some applications, the initial scrap basket is modelled as an initial value for the balance volume solid ③, while in general time dependent additions like `MDR` [kg/s] for DRI addition is used by the source term concept explained above.

Energy Losses
The losses of the shell to the environment are modelled by cooling power input values which can be directly calculated from cooling water flow and temperature difference measurements. Losses to ambient air, e.g. for the lower shell, are modelled by a heat transfer coefficient to the balance volume "⓪", the environment. Tapping or deslagging is modelled using the source terms.

Gas and Waste Gas
Currently, the balance volume "gas,⑤" is modelled by assuming a constant mass of gas inside the furnace and the input parameter waste gas flow `MAG` [kg/s] and the output parameter leakage air flow `MAI` [kg/s].

RESULTS

The model in this example is running in online mode at an industrial 80t EBT AC EAF furnace [Spi05]. The tested operation mode is as follows:

1. Initial scrap basket of ~36t containing ~30% heavy scrap, ~15% return scrap, ~50% DRI and ~5% lime.
2. After reaching the full power level (see Figure 3), continuous DRI feeding with up to 30kg/s provided the rest of the required solid material for reaching the tapping level of ~80t.
3. Additional refining and temperature adjustment and tapping after 60 to 75min.

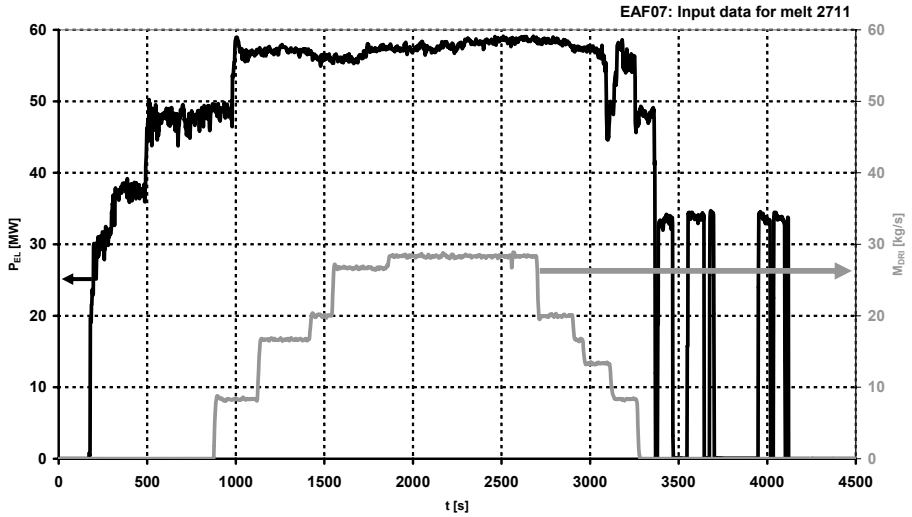

Figure 3: Input data used for the calculations.

The results of the model calculations are shown in Figure 4 and Figure 5. The initial basket leads to some freezing of the initial melt (sump), followed by solid scrap heating within the first 20 minutes. After reaching full power level and start of DRI feed, the mass of liquid metal continuously increases, while the mass of solid material in the furnace decreases. The model predicts an end of the meltdown phase after 45 minutes. During the meltdown phase, the liquid steel temperature stays at liquidus level (1750 K = 1477°C). To avoid confusion, the melt and solid temperatures in Figure 5 are shown only when there is a relevant amount of mass within that balance volumes. The drop in slag temperature after 15 minutes is related to the onset of DRI feeding at t=875 s which also increases slag mass. The decrease of the average solid material temperature after 40 min, surprising on the first sight, results from the increasing cooling effect of the added DRI on the decreasing amount of solid material during the last 15 minutes of the meltdown phase. The slag is initially equilibrating with the solid material and about 200 K cooler than the melt in the overheating phase.

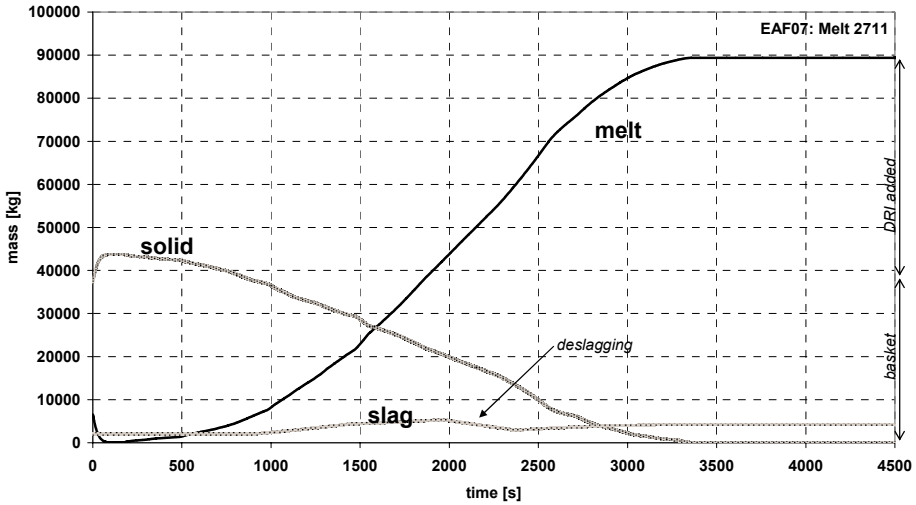

Figure 4: Calculated masses during meltdown.

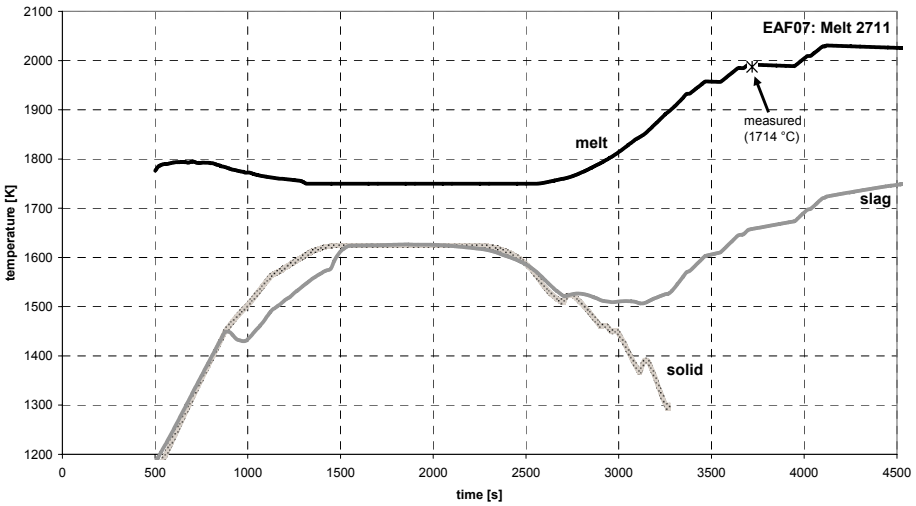

Figure 5: Calculated temperatures during meltdown.

In Figure 5 the temperature measured 10 min before tapping is marked. These temperatures were used to determine the model parameter `LEL`. This parameter is used to distribute the electrical power of the arc between the melt, solid and slag (`LEL`=1) and the gas (`LEL`=0) balance volumes. Using the input data from a number of melts, the calculated melt temperature `ML` at the time of measurement was compared with the experimental value and a mean square deviation function is calculated. A single representative value of `LEL` was obtained by minimisation of that function.

The model does therefore not rely on temperature measurements to predict values like the end of the meltdown phase. The well known rescaling of the model data with the information from actual measurements is possible but not recommended. A better approach is to determine the model parameters like `LEL` (see above) by comparison of measurements with the model predictions for a larger number of heats. Principal parameters not depending on the plant configuration, e.g. heat transfer coefficients between the liquid and solid material (`H23` and `H32`) can also be determined by separate experiments or modelling.

Sensitivity analysis

Before validating the quality of a model or the determination of model parameters, a sensitivity calculation can provide important information on the models requirements regarding the measurement of input data. By investigating the effects of a variation of input data for single time steps or better for a number of typical complete test cases ("melts", "batches"), important quantitative information on the overall system behaviour is obtained. Selected values of such an analysis are shown in Table II.

EAF07 Sensitivity Map:		t [s] =	t [s] =	Absolute Values:		Percentage Values:		Relative Values:		Target ΔTM[K]:	
Melt:	*2721*	0	4000	1954	3641	100%	100%	-	-	10	Allowed
Category:	Input:	Value:	Error:	$TM_{t=4000s}$ [K]	$t\|_{MS=0}$ [s]	$\Delta TM_{t=4000s}$	$\Delta t\|_{MS=0}$	$\Delta TM_{t=4000s}$ [K]	$\Delta t\|_{MS=0}$ [s]	$TM_{t=4000s}$	Error:
initial value	TIB [K]	573.15	10%	1954	3641	0.0%	0.0%	0.5	0	N/A	N/A
initial value	TIS [K]	773.15	10%	2004	3661	2.6%	0.5%	49.9	20	2.0%	15
initial value	MII [kg]	34000	10%	1811	3735	-7.3%	2.6%	-142.5	94	0.7%	239
parameter	DDR [m]	0.015	10%	2002	3643	2.5%	0.1%	48.0	2	2.1%	0.0003
parameter	H23 [W/m^{2}K]	2000	10%	1954	3635	0.0%	-0.2%	0.3	-6	N/A	N/A
parameter	H32 [W/m^{2}K]	500	10%	1943	3632	-0.6%	-0.2%	-11.3	-9	8.8%	44
parameter	LEL [1]	0.25	10%	1892	3649	-3.2%	0.2%	-62.3	8	1.6%	0.00
time dep. input	PEL [W]	6.0E+07	10%	2229	3603	14.1%	-1.0%	275.5	-38	0.4%	217774
time dep. input	MDR [kg/s]	35	10%	1810	3718	-7.3%	2.1%	-143.5	77	0.7%	0.24

Table II: Calculated sensitivity map.

The analysis was undertaken using real industrial data for the initial values and the time dependent values of electrical power `PEL` and DRI feeding rate `MDR`. The rows represent these input values and the columns show the values and relative variations of the modelling results for a variation of 10% in the input. The reference data for melt number 2721 computed from 0 to 4000 s is 1954 K for the melt temperature `TM` at t=4000 s and 3641 s for reaching the value `MS`=0, i.e. melting all solid material. In line 4 of the table (the first line with results), one can see that a variation of the initial (t=0s) lower shell temperature `TIB` by 10% does not influence the selected results (`TM`(t=4000 s) and t(`MS`=0)). The initial temperature of the solid material `TIS` (representing the temperature of the scrap basket as it was modelled by initial values in that installation) has some impact on the melt temperature before tapping. A 10% or 77 K increase in scrap basket temperature gives 50 K more for the predicted "tapping" `TM`(t=4000 s) temperature. The next line shows the effect of weighting precision of the initial scrap basket. At this point, the last 2 columns ("Target Δ`TM` [K]") should be explained: If the model should predict the temperature of the melt after 4000 s with 10 K precision, the initial scrap weighting must have a 0.7% accuracy. This is a physical limitation, because if the amount of energy is fixed, additional initial mass means a later onset of the overheating phase. Finally, the computational results of the sensitivity analysis give the following conclusions:

- The model is able to predict tapping temperature, i.e. there is no dependency on hidden or unknown parameters.
- The model is able to predict the meltdown status within the furnace.
- A ΔT=10 K tapping temperature (or 0.5%) precision implies the following requirements to the input data:
    - 0.5% weighting precision of solid (scrap, DRI , …) additions.
    - 0.4% measurement precision for real electric power.
    - About 2% accuracy for other initial values like solid temperature, DRI properties, …
    - Less than 2% variation in the power distribution parameter `LEL` for different data sets during the parameter determination phase.
    - Less than 9% variation in the heat transfer coefficient `H32` (solid->liquid) for different data sets during the parameter determination phase for different sets of experimental data.

Problems with the last topic can be fixed by more complex and detailed models or a smaller variation in the furnace operation parameters. It should be emphasized that a good agreement between measurement and model prediction after this parameter determination phase does not necessarily validate the model. A final validation of such a model should fulfil a number of additional requirements:

- Validation of the prediction accuracy for different plant implementations and differing furnaces.
- Validation of the prediction accuracy for differing test cases, e.g. with and without DRI feeding.
- Measurement of model parameters independently from the EAF, e.g. independent determination of heat transfer coefficients.

If disagreements are found for that last point, the fundamental assumptions used for the model should be revised and the need may arise for more detailed or complex descriptions. This top down approach can thus stimulate fundamental research by providing detailed and quantitative knowledge of the practical impact of the expected results.

SUMMARY, CONCLUSIONS AND OUTLOOK

The device and application independent **P**rocess **R**eactor **M**odel was briefly introduced as a concept and toolbox for the development of process models for metallurgical plants. It was used for the development of the EAF07 module, a software component which is capable for the online and offline modelling of the meltdown process in the EAF.
The results for the time characteristics of the masses and temperatures in the furnace are in good agreement with expectations and measurements. Only one EAF-specific fit parameter, describing the distribution of the electrical energy inside the furnace, was used. The available data supports the *well defined* property of the model, i.e. it is not depending on parameters changing their values from tap to tap. The model can be used to predict tapping temperature or meltdown status within a precision determined primary by the precision of the measured input values and only secondary by the model or its parameters. The application of the model for a so called *sensitivity analysis* gives additional hints for the further development of the mathematical process description and the plant instrumentation. For *high-end* applications, a number of enhancements are under development:

- Enhancements of the energy balance (more detailed chemical energy contributions).
- Enhancement of the gas and waste gas modelling.
- Implementation of additional metallurgical operations (e.g. decarburization by oxygen blowing).
- Slag foaming effects.

These require additional features implemented in the underlying **PRM** itself as well as additional complexity to the EAF specific parts and additional process values to be measured. The small number of balance volumes assures the online capability of the model. Compared to a competing CFD approach, the computer hardware requirements are reduced to single CPU PC hardware or even long term stable systems like the Siemens SIMATIC S7-400 application module FM 458. Additional benefits are expected from the model generalization itself and the integration into a seamless industrial automation environment.

ACKNOWLEDGEMENTS

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