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EAF PROCESS OPTIMIZATION: THEORY AND REAL RESULTS

OPTYMALIZACJA PROCESU EAF – TEORIA I RZECZYWISTE WYNIKI

The electric arc furnace (EAF) is the key point in most stainless-steel and in many carbon-steel melting plants. Siemens VAI developed a cyclic calculation which allows the online-description of the complex system, consisting of different charge materials (solid and liquid), steel, slag and offgas during the complete EAF-process including tapping. This includes heating, melting and solving of solid materials, chemical reactions and temperature losses. The same routines are used for a full cyclic Precalculation of the process before the EAF-heat is started, in order to optimize the heat processing. As result, a full dynamic approach for the mass and heat balance of the EAF-heat is created, in accordance to predefined values (*e.g.* for charge materials, electrical and chemical energy input), so that a complete set of setpoints is obtained. This is a major enhancement, compared to the simpler calculations used previously in most steel-plants. A charge calculation to determine the loading of the buckets is implemented using a simplex-algorithm.

The comprehensive group of Siemens VAI process models is referred to as SteelExpert. This process optimization system (Level 2) has been applied successfully to a wide range of treatment practices like using solid charge materials charged by buckets or through the 5th hole, continuous feeding of DRI in combination with liquid charge materials. Expectations for the system as well as actual experiences are presented, together with an outlook for future developments.

Keywords: Automation, Process models, Process optimization, Process control, Steel industry, Computer software

Elektryczny piec łukowy (EAF) jest głównym urządzeniem w większości stalowni przy produkcji stali nierdzewnej i węglowej. Siemens VAI opracował obliczenia cykliczne, które pozwalają na opis procesu on-line złożonych systemów, składających się z różnych materiałów wsadowych (stałych i ciekłych), stali, żużla, gazów wylotowych podczas całego procesu EAF łącznie ze spustem. Zawiera nagrzewanie, topienie i rozwiązania dla materiałów stałych, reakcji chemicznych i strat temperatury. Te same procedury są użyte do pełnych cyklicznych obliczeń procesu przed rozpoczęciem wytopu, aby go zoptymalizować. Jako wynik, tworzone jest pełne dynamiczne ujęcie bilansu masy i ciepła wytopu w EAF, zgodnie z predefiniowanymi wielkościami (dla materiałów wsadowych, pobranej energii elektrycznej i chemicznej), więc uzyskany jest kompletny zestaw żądanych wartości. Jest to główne udoskonalenie, w porównaniu do prostszych rozwiązań używanych wcześniej w większości stalowni. Obliczenia wsadu, w celu ustalenia ładunku koszów jest wykonane z użyciem algorytmu simplex.

Obszerna grupa modeli procesów firmy Siemens VAI odnosi się do SteelExpert. Ten system optymalizacji procesu z sukcesem został zastosowany do szerokiego zakresu praktyk jak ładowanie stałych materiałów wsadowych za pomocą koszy lub 5 otworu, ciągłe dozowanie DRI w połączeniu z ładunkiem materiałów ciekłych. Przedstawione są oczekiwania w stosunku do systemu, jak i obecne doświadczenia, razem z perspektywami rozwoju.

1. Introduction

The electric arc furnace (EAF) is the initial aggregate in most stainless-steel and in many carbon-steel melt shops. Usually the automation environment consists of the basic automation system (Level 1) as well as a level 2 system, i.e. real time collection of process related data and some static calculations for the required process-inputs like energy, oxygen, alloys, etc. Although the EAF is considered as a crude aggregate by many people, major efforts in improving its performance via automation systems have been made in recent years (*e.g.* [3]). The requirements regarding the process results at the EAF are getting higher, especially in the case of stainless steel plants without AOD converters.

Therefore, Siemens VAI, as one of the world's leading companies in steel plant automation, decided to overhaul its existing process optimization system, which has

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proven its merits over a number of years in many steel plants worldwide. The main objective of this newly developed system is to provide enhanced support to the operator throughout the whole EAF heat cycle.

2. Process Sequence

A typical time-based sequence of process steps and required activities (from a process point of view as well as from an automation point of view) taking place during production of a heat with basket-procedure at the EAF is the following:

(T-/+x.... Minutes before/after melting start)

1. T-120 Basket Ordering

The operator uses the charge calculation (SteelExpert Charge) to determine the necessary baskets for the next heat. This calculation is performed in order to reach the aim values, e.g. temperature, weight, analysis, slag-properties, for the next heat (see fig. 1). With these aims and using the schemes defined by the metallurgist in the Standard Melting Practice (SMP) for this grade, SteelExpert Charge first calculates the baskets to meet the aims for the charge-mix and then makes a full simulation of the heat from first power-on until tapping. The output of this iterative procedure is the required loading of the baskets, the demand of electrical energy, process-gases, alloys and slag-formers, and, if so desired, the materials to be added for alloying around the time of tapping. Afterwards, setpoints for the basket preparation can be sent to the scrap-yard.

2. T-x Basket Reordering

At any given time before the actual charging of the baskets into the furnace, the operator is able to repeat the run of SteelExpert Charge. Usually, this only takes place if the next heat will be produced with significantly different aims than those which were used for the first charge calculation, e.g. the grade has changed; the other case where the operator needs to repeat the charge calculation is if there was some problem and he has to use a preloaded basket instead of one of the baskets originally ordered for this heat. In this situation the operator assigns this preloaded basket to the order (also stating, whether this will be the first, second, ... basket), restarts SteelExpert Charge and sends new setpoints for the preparation of the remaining baskets to the scrap-yard.

3. T-20 Basket Deliverance

The scrap baskets for the next heat are delivered from the scrap-yard to the EAF-area.

4. T-5 Scrap Basket Charging

The first scrap-basket is charged into the furnace after tapping, regular checks and maintenance has been finished for the previous heat.

5. T-2 Precalculation (SteelExpert Prediction)

Using the data of the actual loaded baskets for this heat, the operator performs the Precalculation (see fig. 1), which is basically a repetition of the second part of the charge calculation, simulating cyclically the heat

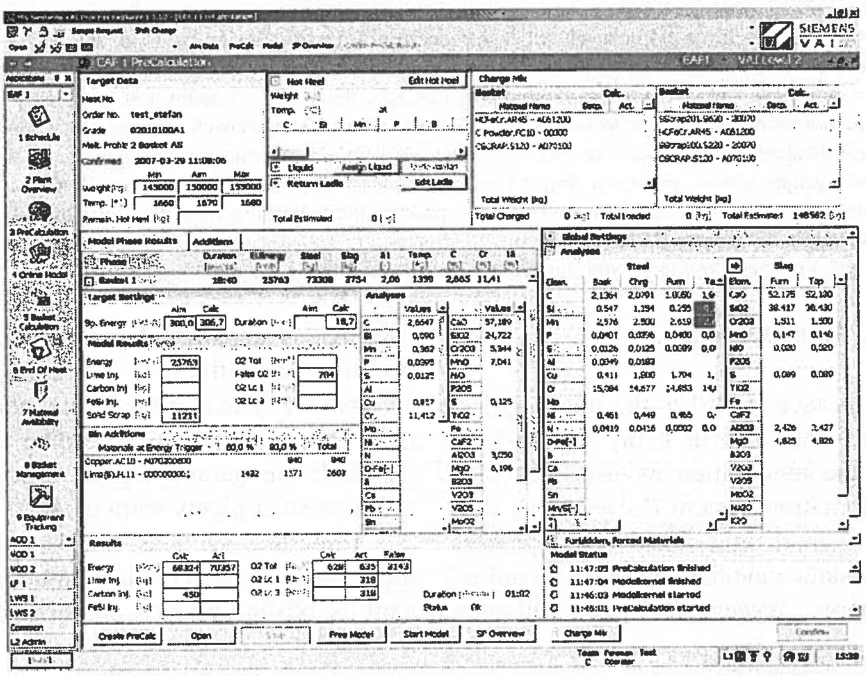

Fig. 1. Precalculation application. Shown are overall results and details for one step of the melting-profile

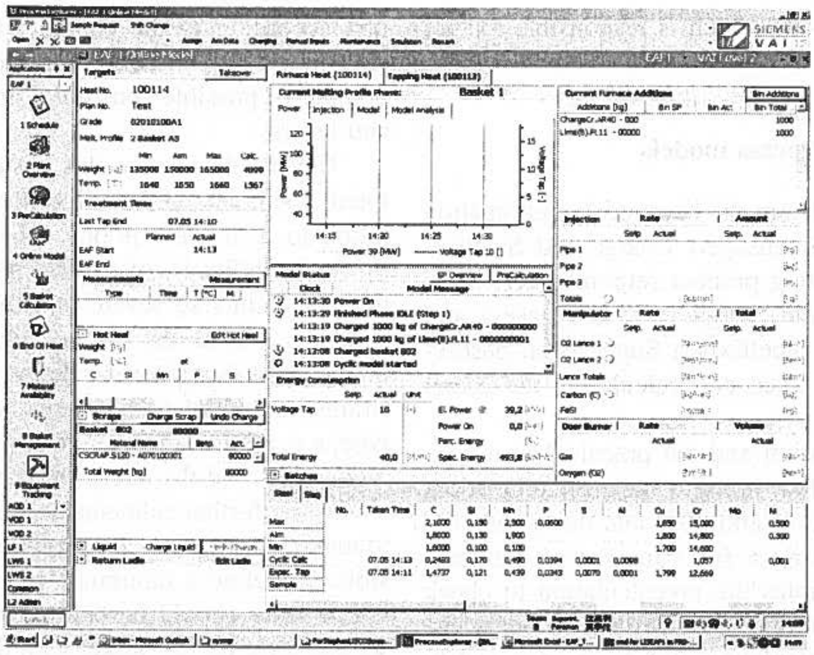

Fig. 2. Online window. Shows the actual process-signals from the level 1 and the results from the online-model

from power-on until tapping-end. The results are again the necessary inputs for the process, *i.e.* materials, gases, and energy. These process setpoints can be downloaded to the level 1.

6. T-0 Melting Start

With the first power-on the melting-process is started, and the previously calculated melting-profile is executed automatically. Also, the start of the online-model SteelExpert Supervision is triggered. It calculates cyclically weight, temperature and analysis of the melted steel and slag in the furnace (see fig. 2), considering the actual process conditions like power input, material additions.

7. T+15 Scrap Basket Charging

The next basket is charged, the online-model reacts to the charging-event and adds the basket-materials to the actual furnace content (melted and unmelted charge). Should the operator make a mistake, e.g. charge basket number 3 in the level 2 system, while actually basket number 4 was charged, he can proceed with undo the charging in the level 2 system and charge the correct basket.

8. T+30 Refining

When the charged materials are melted almost completely, the final actions are being taken: Oxygen is used to get rid of carbon (and silicon, for stainless EAF), the temperature of the melt is being raised towards the aim value, and the operator can now rely on the online-model to determine the actual state of the melt accurately; this is because during this phase the initial uncertainties about how much of which scrap is dissolved have all vanished.

9. T+50 Reduction/Tapping

When executing the melting-profile reaches its end, either with arriving at the precalculated energy, or with operator-interference based on the online-model, the melt is in principle ready for tapping. In case of stainless steel production, the reduction-reaction to regain the Cr from the slag is usually started by adding FeSi and starting tapping. In case of carbon steel production, a sample is taken and when the result is received from the laboratory, the Alloying Calculation (SteelExpert Alloy) is started to calculate the necessary alloys and slag formers during tap to reach the target chemical composition of the steel in the ladle. In order to save time, some steelplants already prepare a certain amount of the alloys, which were calculated by SteelExpert Prediction, so that around tapping they only have to draw the missing amount (a practice also common at the BOF). With the end of tapping the online-model terminates.

10. T+60 Next Heat

The furnace and the automation system are ready for the next heat.

In case of EAFs for carbon steel production with hot heel, the properties of steel and slag of the remaining hot heel are considered in the precalculation and online calculation of the next heat. The weight of the hot heel is estimated based on EAF tap data, and the analysis and temperature are derived from the online calculation of the previous heat (the one which is responsible for hot heel).

3. Process models

The process models are the heart of the automation system consisting of SteelExpert Charge and SteelExpert Prediction calculating process setpoints (*e.g.* input of electrical and chemical energy, materials, gases), and the Cyclic Calculation SteelExpert Supervision observing the actual actions taken and calculating the actual state of the system.

The charge calculation and the precalculation consist of two parts, the first being a balance-calculation, determining the amount of additions and the second the cyclic simulation, making a full run through the heat until tapping. This enables the precalculation to check whether the aims at tapping are fulfilled, to adapt the aims for the balance-calculation, if they are not, and to repeat this until convergence.

3.1. Charge Calculation – SteelExpert Charge

It determines the materials needed to reach the target charge-mix within some deviation limits, which is the sum of all materials to be added to the melt, via baskets and high level bins. In addition to these aim-values (weight and analysis), there are a number of constraints which must be fulfilled as well:

- *Fixed materials*. It is possible to define materials with fixed weights, e.g. to always use 3 tons of high carbon ferro-chromium. These constraints are linked to the steelgrade.
- *Forbidden materials*. It is possible for each steelgrade, to define materials which must not be used at all.
- *Charge mix*. Several material-types can be used to define how the charge-mix should be constructed in terms of minimum and maximum weight, e.g. alloyed scraps: 40-50 tons, unalloyed scraps: 30-45 tons, ...
- *Loading pattern*. For each material layer in a scrap basket the content can be defined in terms of percent of total basket-weight, where each layer contains one group, but one group can occur more than once per basket, e.g. layer 1: light Scrap 7-10%, layer 2: high carbon alloys: 0-15%, ...
- *Basket distribution*. The distribution of the total material input between the baskets and the high level bins must be defined in terms of %, e.g. basket 1: 55%, basket 2: 40%, bin: 5%.

The above types of constraints yield a large linear system of equations. Every material has to be classified according to the charge mix and loading pattern constraints, and therefore for each material there are a number of possible "positions" in the respective baskets and layers.

Nevertheless, once this system of equations is defined, a simplex-method algorithm yields readily the solution to it, if there is one. One danger of having this much flexibility is, of course, the possibility of imposing constraints so severe that the model cannot find a solution. This is the reason, why only the responsible metallurgist is allowed to define and change these constraints. Should there be more than one material of some type, e.g. more than one high carbon ferro chromium, the model will find the cheapest combination of materials.

Some further refinements are implemented in order to make it easier for the operation. For example it is possible, to define a minimum weight for a layer, so that, if one layer should be below this value and there is a second layer in this basket with the same group, the two layers are merged into one. This is done, because it is not feasible at the scrap-yard to load for example 210 kg of one material. Often the cranes cannot load less than 500 kg of one material.

In the case of EAF operations with high content of DRi in the charge-mix, the charge calculation is usually not applied, because mostly one basket is loaded according to a fixed scheme.

3.2. Precalculation – SteelExpert Prediction

The Precalculation is taking the scrap-baskets as fixed inputs, and calculates the remaining additions (materials, gases) to be introduced via bins, lances, burners, etc.

With these inputs, for all process steps the reactions are simulated until the end of the heat. Using an iterative procedure the Precalculation ensures that with the additions which are finally shown to the operator, the aim-values are fulfilled.

For all steps, detailed information is shown to the operator (Fig. 1), so that he will know in advance how the system will evolve.

Similar to the charge calculation, certain values can be fixed by the metallurgist or the operator, and the precalculation then determines the other input quantities.

3.3. Cyclic Calculation – SteelExpert Supervision

The Cyclic Calculation is the very core of the process-models, because it describes the important physical and chemical processes taking place in the furnace during the heat. The same functions are used for the precalculation and the cyclic calculation, thus ensuring consistency between the two models.

In one perspective the EAF is significantly different from any other aggregate in a steel-plant: its input mainly is made up of solid material. Even though the practice of adding liquid metallic charge, *e.g.* hot metal from the BF or liquid steel from the BOF, is becoming more frequent, the classical operation mode of 100% solid charge is still the more common one.

Due to this, any realistic physical and chemical description of the EAF process must be fundamentally different from other melt shop aggregates, which experience totally distinctive process starting conditions. Secondary metallurgy facilities start with already fully melted steel, AODs show a much smaller solid than liquid input, and even at the BOF, where the solid input is already significant, it is still not as large as at the EAF. Therefore, the processes involving the heating and melting of the materials were the main efforts in the recent development.

The energy input, which enters the system mainly by means of the electrodes, is used for heating and melting solid materials as well as for heating the liquid part.

Also, energy losses to the surroundings have to be taken into account. Radiation losses to the roof and the upper part of the wall, conduction losses to the bottom and the side walls of the lower vessel, and the losses via offgas (including false-air, sucked into the furnace via the slag-door and other crevices) play the biggest part. For the radiation and conduction losses, a proper way to describe the behavior of the areas which are visible, respectively are in contact with the liquid matter, must be found. In the beginning of the melting process, with little liquid matter and a lot of solid materials present, the furnace charge will shield the roof and walls from radiation. During the progress of melting more and more of the inner surface of the furnace will become visible. Similarly, the more liquid matter is present, the larger the contact area is during which conduction losses occur. Detailed investigations have shown that the ratio of liquid matter to total charged matter can be used as one of the main variables in describing the losses.

It is difficult to determine the actual shape of the liquid steel, so we assumed a cylindrical shape with circular basis, since the actual shape is not the deciding factor. Defining

$$\mu = \frac{M}{M_{Tot}} \tag{1}$$

as the ratio between the liquid weight M and the total charged metallic weight M_{Tot}, we can assume that the radius and the height of the cylinder grow proportional to μ to the power of 1/3.

Some additional losses are losses due to waiting time of the furnace in between heats and losses to the offgas. Due to the requirement of consistency between Precalculation and online-model, for the offgas-losses a fixed flowrate is defined for each process step.

More interesting and challenging are the processes around the heating and melting of solid materials. The actual bulk-melting of a material takes place above its melting-temperature and until that the major part of energy transferred to the material will be used in heating it up, but there is always some solving under bath convection in the EAF vessel present.

The physical properties of the materials, *e.g.* density and size, influence the heating, melting and solving considerably. However, in an actual production environment these data are mostly neither available nor reliable to the extent required in order to base the algorithms on them. Fortunately, the typical solution of this problem, *i.e.* to use some representative average values, instead of the actual ones, is sufficient in almost all steel plants.

In any case, the exact order in which the materials are melted and solved, is not too important, as long as one gets the proper amount and distribution of energy, which is consumed to achieve the melting. The application of bottom stirring elements in the EAF can lead to substantial improvement of the melting and solving processes, and hence to a remarkable increase of the energy utilization, which is very important especially for stainless EAFs with a high quantity of solid ferro-alloys in the metallic charge. Most active metallurgical processes, like blowing oxygen through the lance or the RCB (Refining Combined Blower), start at a time where the charge-mix is at least partially melted, which leads directly to the next item, the deoxidation.

Cyclically calculated thermodynamic driving forces are used to distribute the supplied oxygen to the elements in the steel bath. This method has been employed by Siemens VAI successfully already for several years in the AOD and BOF process calculations ([1], [2]), and it was only natural to adopt it for the EAF as well, applying reliable kinetic parameters. The driving forces determine for each element in the steel bath how far away it is from its equilibrium value using the Gibbs free energy ([4]), and less oxygen is allocated to the element which is closer to its equilibrium.

One other important factor is the oxygen supply through false-air which is sucked into the furnace from the ambience. This plays a minor role in the converter processes, where the vessels are basically airtight, but at the EAF the amount of oxygen delivered by false-air is significant, and therefore some oxidation takes part during melting even in the absence of oxygen-blowing.

For the oxidation one has to consider the reactions

$$x \cdot [Me] + \frac{y}{2} \cdot O_2 \rightarrow \left(Me_x O_y\right), \tag{2}$$

where $[Me]$ stands for elements solved in liquid iron (*i.e.* C, Mn, Cr, Ti, V, Si, Al) and Fe itself.

The equilibrium of the reaction is described by

$$\Delta G^{eq}_{Me_xO_y} = -R \cdot T \cdot \ln K_{Me_xO_y} = -R \cdot T \cdot \ln\left(\frac{a^{eq}_{Me_xO}}{(a^{eq}_{Me})^x \cdot (p^{eq}_{O_2})^{y/2}}\right) \quad (3)$$

where

$\Delta G^{eq}_{Me_xO_y}$	Standard Gibbs free enthalpy of reaction
$K_{Me_xO_y}$	Equilibrium constant
$a^{eq}_{Me_xO}$	Equilibrium activity of oxide
a^{eq}_{Me}	Equilibrium activity of element
$p^{eq}_{O_2}$	Equilibrium partial oxygen pressure
R	Universal gas constant
T	Absolute temperature (K)

The actual value is given by

$$\Delta G_{Me_xO_y} = -R \cdot T \cdot \ln K_{Me_xO_y} = -R \cdot T \cdot \ln\left(\frac{a_{Me_xO}}{(a_{Me})^x \cdot (p_{O_2})^{y/2}}\right) \quad (4)$$

with corresponding actual values for activities and partial pressure.

A driving force for each oxide can be defined using the difference between equilibrium and actual value:

$$F_{Me} = \left(\exp\left(-\frac{\Delta G^{eq}_{Me_xO_y} - \Delta G^{act}_{Me_xO_y}}{R \cdot T}\right)\right) = \frac{(K_{Me_xO_y})^{1/y} \cdot (a_{Me})^{x/y} \cdot p^{1/2}_{O_2}}{(a_{Me_xO_y})^{y/2}} \quad (5)$$

After introducing a total driving force

$$F_{Tot} = \sum_{Me} F_{Me} \quad (6)$$

one can calculate the fraction of the total supplied oxygen O_2^{Tot} which is used by each element

$$O_2^{Me} = O_2^{Tot} \cdot F_{Me} / F_{Tot} \quad (7)$$

In Fig. 3 typical results for the online calculation of the temperature and weight of the steel are shown for the case an EAF operation with approximately 25% of scrap (one basket) and 75% DRI (continuous feeding). This heat was chosen due to its clearly visibly reaction to a temperature-measurement at around 57 minutes of process time:

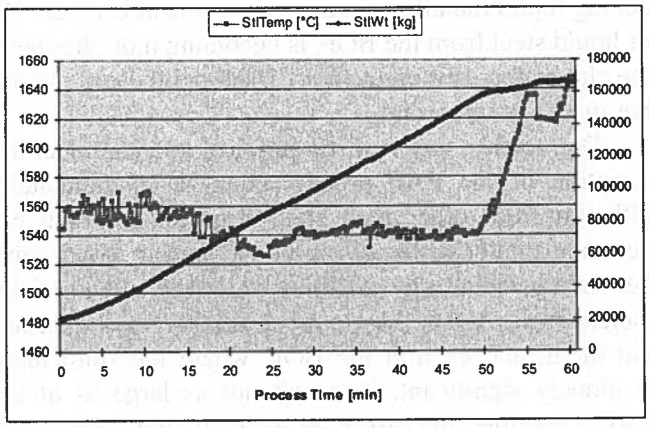

Fig. 3. Steel weight and temperature during EAF-process for DRI with one basket

4. Summary

The presented SteelExpert process models have been successfully commissioned in several steel-plants so far, covering operation modes from 100% solid, mixture of solid and liquid, and 100% DRI (continuous feeding where the model controls the feeding-rate). This strongly indicates that the chosen algorithms are adequately describing the actual situation during production, which is the only valid test of an automation system.

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