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IMPROVING ELECTRIC ARC FURNACE (EAF) OPERATION THROUGH MATHEMATICAL MODELLING

Adrian IOANA[1], Anda PREDA[2], Liviu BEŞEA[3], Petru MOLDOVAN[4], Nicolae CONSTANTIN[5]

The starting point for this article is the presentation of principles specific to mathematical modelling aimed at optimizing the operation of electric arc furnaces (EAF). Thus, we define the following principles in this article: the analogy principle, concepts principle, hierarchization principle, uncertainty principle, internal model principle. In this article we will also present the conception of the modelling system for electric arc furnace operation improvement. This is based on the mathematical model that determines the objective function and on 6 other modelling subsystems: Mathematical Model that prescribes the Objective Function (MMOF); Charge Calculation Mathematical Model (CCMM); Melt Management Mathematical Model (MMMM); Charge Preheating Mathematical Model (CPMM); Reactive Powder Injection Mathematical Model (RPIMM); Preheating Recuperative Burners Design Calculation Mathematical Model (PRBDCM). We will also present the main results obtained by simulating the application of the mathematical model that prescribes the objective function.

Keywords: energetic efficiency; electric arc furnace; mathematical model

1. Introduction

Mathematical modelling of processes developing in the electric arc furnace (EAF) that aims to optimize the functional and technical performance of this complex equipment is based on the following principles [3-5]:

A. The principle of analogy – requires the competent observation and analysis of the modelled reality, using both analogy to other areas of research and logical homology.

[1] Lecturer, Faculty of Material Science and Engineering, University POLITEHNICA of Bucharest, Romania
[2] PhD student, Faculty of Material Science and Engineering, University POLITEHNICA of Bucharest, Romania
[3] PhD student, Faculty of Material Science and Engineering, University POLITEHNICA of Bucharest, Romania, e-mail: besealiviu@yahoo.com
[4] Prof., Faculty of Material Science and Engineering, University POLITEHNICA of Bucharest, Romania
[5] Prof., Faculty of Material Science and Engineering, University POLITEHNICA of Bucharest, Romania, e-mail: nctin2014@yahoo.com

According to this principle, the development of mathematical models requires taking the following steps:

- ***defining the objective that will be modelled*** – it represents the primordial step in modelling analysis; this stage has to meet both the goal and the objectives of the system, as well as ensuring their compatibility;
- ***defining the efficiency criteria*** – this step is conditioned by the correct definition of system objectives, and it allows the optimization of modelling solutions;
- ***options development*** – based on accessing realistic, efficient and original solutions;
- ***alternatives assessment*** – depending on the efficiency criteria set;
- ***choosing the final solution*** – based on the comparative analysis of the different solutions obtained through modelling.

B. Concepts principle – is based on the concepts of system theory, including the feed-back concept.

C. Hierarchization principle – it requires creating a hierarchical model system in order to structure the decision and coordinate interactive systems.

D. Uncertainty principle – is generated mostly because of the high level of complexity of the processes related to the EAF. In addition, the existing interactions between component subsystems – interaction that cannot always be predetermined – existent nonlinearities in the system and the subjectivity of choosing and prescribing the objective function contribute to the increase of uncertainty factors.

It's useful to mention that, based on this modelling principle, as system complexity increases, needing a hierarchical structure, the precision of created models decreases but their level or relevance increases.

E. Internal model principle – states that a dynamic system is stably structured only if:

- it uses the negative reaction of controlled parameters;
- its reaction loop incorporates a reduplicate model of the dynamic structure of exogenous signals; this internal model provides the signals intended to asymptotically compensate for disturbances in the considered EAF system.

2. State-of-the-art

The electric arc furnace (EAF) is a complex and important unit. The importance of the electric arc furnace lies in his benefits. Of these, the most important ones are:

- Flexibility in operation.

- High Productivity.
- Several possibilities of automation complex.

At a world level, the optimal EAF (including mathematical modelling application) is spread [6, 7, 9].

In our country, the application of mathematical modelling EAF leadership is far less.

A happy exception in this area is the electrical steel mill Tenaris TO Calarasi. Here, an EAF with a capacity of 90 t is completely automated and the procedures of management shall be online in real time.

Among the direct Electric Arc Furnaces (EAF) for the scrap iron process, the most famous type is Héroult electric arc furnace supplied with three-phase electric current through three electrodes which goes inside of the furnace through its vault.

The changing of the electric energy into heat takes place mostly inside of the electric arc, where the temperature goes above 2500 ^{0}C. The heat transfer from the electric arc to the charge in the furnace it is done through conduction and radiation [8, 10].

One of the main advantages of the EAF is also the possibility of using scrap iron as a main charge to obtain the steel. This allowed the EAF development and affirmation as a steel melting assembly.

3. Conception of the modelling system

Based on these principles we have developed the block diagram for the modelling system of the processes related to the electric arc furnace, shown in Figure 2.

The core aspect of the developed modelling system for EAF processes lies in the objective function (criteria) of the system. Considering that the study of EAF related processes is subservient to obtaining high-quality steel, the Objective Function (OF) of the modelling system is the quality / cost ratio [1,2]:

$$OF = \left(\frac{Quality}{Cost} \right)_{\max} \tag{1}$$

The maximization of the objective function is ensured by the Mathematical Model that prescribes the Objective Function (MMOF).

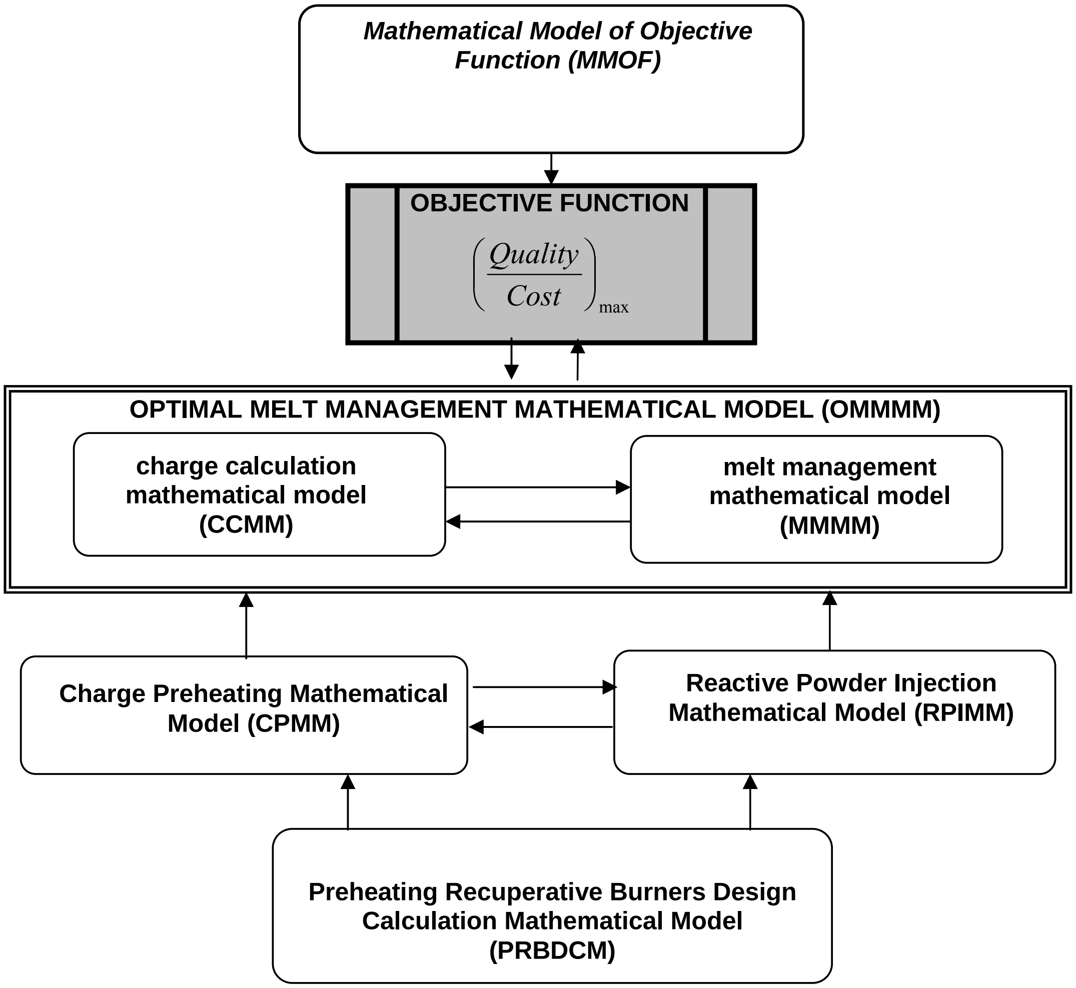

Fig. 2. EAF management system block diagram

The modelling system developed for EAF processes is composed of six subsystems represented by the following mathematical models:

- Mathematical Model that prescribes the Objective Function (MMOF);
- Charge Calculation Mathematical Model (CCMM);
- Melt Management Mathematical Model (MMMM);
- Charge Preheating Mathematical Model (CPMM);
- Reactive Powder Injection Mathematical Model (RPIMM);
- Preheating Recuperative Burners Design Calculation Mathematical Model (PRBDCMM).

Next we will present the stages and calculation algorithms for each model, as well as modelling results, including validation experiments for the developed models.

4. Mathematical model that prescribes the objective function (MMOF)

Prescribing (setting) the objective function (OF) of the modelling system for EAF processes is based on the qualitative– economic analysis of these processes. To this end, the development of a new product (a quality steel grade in this case) must ensure both profitability and quality requirements.

The conception of the mathematical model that prescribes the objective function is based on quantifying the objective function (OF) as a qualitative – economic matrix $\boldsymbol{M_{CE}}$, as per the diagram in figure 3.

Objective function prescription levels are obtained by applying a composition algorithm for three vectors.

- $\overline{T}$ vector – technical parameters vector (t_i);
- $\overline{E}$ vector – economical parameters vector (e_j);
- $\overline{P}$ vector – shares vector (p_l).

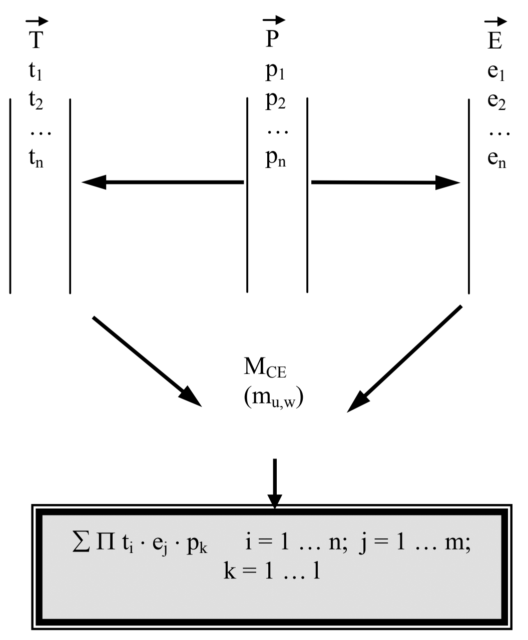

Fig. 3. Modelling system objective function quantification

The components of the two vectors $\overline{T}$ and $\overline{E}$ are considered to have important shares in the quantification (prescription) of the objective function.

t_1 – steel chemical composition (steel grade requirement);
t_2 – steel purity (gases);
t_3 – steel purity (inclusions);
e_1 – raw materials specific consumption;
e_2 – energy specific consumption;
e_3 – EAF steelmaking process productivity.

Value assignment for the components of the two vectors was based on a relative scale using an optimal level as reference (NO), as follows:

NO = value 10
NO $\pm$ 10 % = value 9
NO $\pm$ 20 % = value 8
NO $\pm$ 30 % = value 7
...
NO $\pm$ 100 % = value 0.

The optimal level (NO) for each component of the two vectors is as follows:

- for t_1 – arithmetic average of the prescribed limits for the composition of the produced steel grade;
- for t_2 – minimum prescribed gas content;
- for t_3 – minimum prescribed inclusion content;
- for e_1 – minimum standardized specific raw materials consumption;
- for e_2 – minimum prescribed specific energy consumption;
- for e_3 – maximum standardized productivity for the steelmaking process.

5. Results of the objective function (OF) prescription mathematical model

These results represent the validation experiments.

Shares: P = (0.20, 0.65, 0.15)

Limits imposed on the criteria: T[1]+ T[2]+ T[3] = const. (10)

Technological criteria: *0.000 ≤ T[1] ≤ 10.000; 1.000 ≤ T[2] ≤ 10.000; 3.000 ≤ T[3] ≤ 10.000*

Economic criteria: $0.000 \leq E[1] \leq 10.000$; $0.000 \leq E[2] \leq 10.000$; $0.000 \leq E[3] \leq 10.000$

E[1]+ E[2]+ E[3] = const. (10)

RESULTS – best 8 prescription levels:

1. OF = 45.090
   a = (0.000, 7.000, 3.000)
   b = (0.000, 9.900, 0.100)

2. OF = 44.680
   a = (0.000, 7.000, 3.000)
   b = (0.000, 9.800, 0.200)

3. OF = 44.635
   a = (0.000, 7.000, 3.000)
   b = (0.100 , 9.800 , 0.100)

4. OF = 44.448
   a = (0.000, 6.900, 3.100)
   b = (0.000, 9.900, 0.100)

5. OF = 44.446
   a = (0.100, 6.900, 3.000)
   b = (0.000, 9.900, 0.100)

6. OF = 44.270
   a = (0.000, 7.000, 3.000)
   b = (0.000, 9.700, 0.300)

7. OF = 44.225
   a = (0.000, 7.000, 3.000)
   b = (0.100, 9.700, 0.200)

8. OF = 44.180
   a = (0.000, 7.000, 3.000)
   b = (0.200, 9.700, 0.100)

Figs. 4 and 5 show the dependency of objective function prescribed levels on the T (T1, T2, T3) vector component shares variation and the E (E1, E2, E3) vector component shares variation respectively.

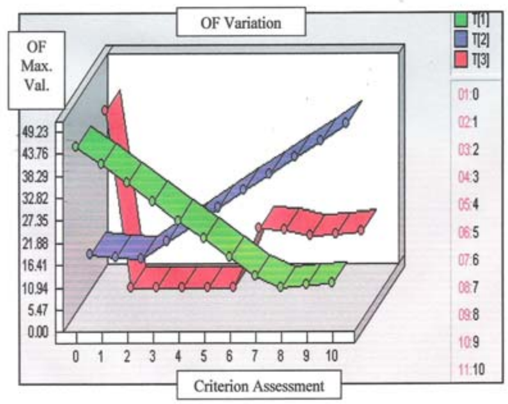

Fig. 4. Objective function (OF) prescribed levels dependency on the T (T1, T2, T3) vector component shares variation

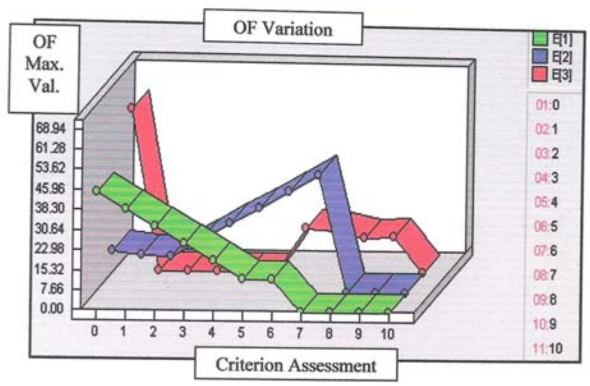

Fig. 5. Objective function (OF) prescribed levels dependency on the E (E_1, E_2, E_3) vector component shares variation

The industrial validation of the research results has been done by industrial experimentations on electric arc furnaces of the following capacities: 10t, 60t, 90t. The validation experimentations have confirmed the truthfulness of the research.

Energy efficiency improvements of the EAF have been experimented and implemented in the industrial procedures: recuperative burners for drying and pre-heating casting pots; oxy-fuel burners.

6. Conclusions

To compensate the increase in electrical energy consumption during melting, boosting of the melting process is required through: charge preheating, introduction of the oxy fuel process.

A simulation of the application of the mathematical model for objective function prescription yielded the following results:

- $OF_{[T],\,max}$ = 49.23 for [T2].
- $OF_{[T],\,min}$ = 10.23 for: [T1] and [T3].
- $OF_{[E],\,max}$ = 68.94 for[E3].
- $OF_{[E],\,min}$ = 0.00 for: [E1], [E2], [E3].
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Furthermore, managing the steelmaking process with the help of a computer can further increase energy efficiency during EAF operation. This requires the simultaneous use of both a thermal model and a metallurgical model (that can be developed using the algorithm show previously) to control and manage the process through a computer. Energy savings of about 25 kWh/t and a decrease of specific electrode consumption of about 0.25 kg/t can be achieved by using this method.

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