The improving of the energetic regime of the small Electric Arc Furnaces, working with foaming slag

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Abstract: The paper presents a method for the improving of the energetic regime of the Electric Arc Furnaces (EAF) with small capacity (up to 10 tonnes), in the case when during the melting of the steel into the furnace, foaming slag is used. In this situation an increasing of the thermal efficiency is obtained, through the minimisation of the thermal losses through radiation to the walls and to the vault of the furnace, as a result of the arc covering by the foaming slag.
Instead of the furnaces with big capacity, which are using the best technologies for the drawing up and the energetic control of the steel melting, for the small furnaces (generally used in Small and Medium Size Entreprises), such technologies are rarely used. Therefore, in the paper a mathematical model and the due algorithm are presented. These tools are used for the melting programmes optimisation, in the case of small EAF, working with foaming slag.

Key-Words: energy efficiency, Electric Arc Furnace, foaming slag, mathematical model, melting programmes

1. General framework

In present, in Romania, apart from the electric arc furnaces (EAF) with big capacity (75, 85 or 100 tonnes), wich are working into iron and steel plants from Targiviste, Campia Turzii or Hunedoara, there are many other EAFs, with small capacities (between 5 and 10 tonnes). These are located within such iron and steel units, which are using for the melting of steel, mainly Basic Oxygen Furnaces (BOF), for instance Arcelor Mittal Steel SA Galati., or within some Small and Medium size Entreprises (SMEs) for metal processing (for instance DUCTIL Buzau, UZTEL Ploiesti, etc.). Unlike the EAFs with big capacity, which are using now the newest technologies for energetical control of steel melting (control with process computers, intelligent electronic systems for electrodes positioning, oxy-fuel burners, foaming slag technology, etc.), for small EAFs such technologies are rarely used.

For such types of EAFs [1] a big potential to improve the energetic indicators (specific energy consumption, thermal efficiency, electric efficiency) exists, simultaneously with the reduction of gaseous emissions.

One of the most important technology, which is to be approached in these paper, and which can improve the energetic indicators and the electrical regime in the supplying circuit of the small EAFs, is the using of the foaming slag in the melting stage of the charge. The foaming of the technological slag produced by the melting of charge, is to be achieved through simultaneously blowing with two spears, one for oxygen and one for powder . The inclination of the spear for oxygen is bigger, therefore the oxygen is to be blowed in the metallic bath, or at the interface bath – slag. The inclination of spear for coal powder is smaller, hence the coal is to be blowed inside the technological slag. The blowing flow of the coal powder is, generally, 0.5 kg / t_{steel}·min. For the coal powder it is recommended a granulation between 1 and 3 mm, and the carbon content should be very high (in order to increase the conductivity of the foaming slag).

The foaming slag is produced due to the presence of CO in the technological slag. CO is appearing here as a result of the bath decarburization (expulsion of carbon, due to the reaction between carbon and oxygen blowed into the bath, or with FeO_2 from slag. Besides, foaming slag could appears as a result of the FeO_2 reduction with C blowed as coal powder.

The favourable effects of the foaming slag are both energetically, namely the increasing of thermal efficiency (the reduction of thermal losses to the walls and to the furnace vat), and electrically, due to the appearance of some current ways, if the foaming slag has conductive properties. In this case the charge is heated through Joule effect.

2. Energetic regime in the case of the technology with foaming slag

In order to understand the technological process in the case of the immersion of the arc inside the foaming slag, the interraction between arc and slag should be explained.

From the observations due until now [2], is emerging that, due to the interractions between electromagnetic and hydrodinamic forces which act between electric arc and slag bath, in the area of the electrodes pick is appearing a demieliptical meniscus, the slag having a rotary motion arround the electrodes, as powerfully as the slag thickness is bigger.

Depending on the relative position of the electrodes towards the meniscus, the electric arc could be:

- non-shunted $h_{fs} = l_a$, the electrode rarely touch the meniscus, the thermal energy is reflected by meniscus, caused the wear of the refractory walls at 60 cm up the slag;
- demi-shunted $h_{fs} = 1.5\ l_a$, the electrode touches locally the meniscus, and the fluctuation of the arc regime is generated by the change of the contact surface, that means due to the electric resistance change. The refractory wear is possible only to 75 cm up to the slag;
- shounted, $h_{fs} = 2.5\ l_a$, the electrode is immersed into the slag, having as effect a stable working regime of the electric arc.

The meaning of the above notation is:

- h_{fs} – the heigh of the foaming slag layer;
- l_a – the length of the arc.

Sintetically, the amount of transmission efficiency of the electric power towards metallic bath, depending on the variable high of foaming slag layer, is shown in the Fig. 1.

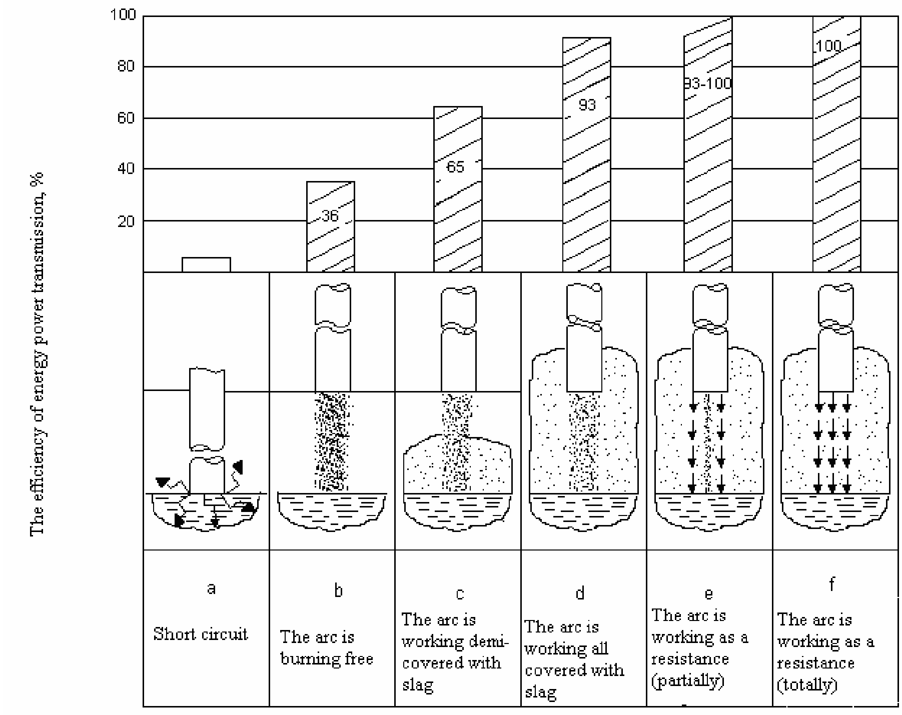

Fig. 1. The transmission efficiencies of the electric energy towards metallic bath

Taking into the account that for an arc with $l_a = 250$ mm, is corresponding a minimum intensity of the field of 1 V / mm arc, and the supplementary voltage appears at the crossing electrode – arc and arc – bath. The value of these supplementary voltage is 40 V, then the total fall in arc voltage is 290 V. Also, the electric energy is distributed proportionally with voltage falls. Therefore, the power developped in arc is 86% from the total power, the rest of 14% being transformed in caloric energy at the electrode pick.

With these observations, we can conclude:

- at the short circuit (between electrode and charge – figure 1a), all the electric energy is transformed in thermal energy;
- when the arc is working free (figure 1b), 36% from electric energy is transmitted towards the bath (1/3 from 86% energy radiated by arc, spread out in three directions – bath, walls and vault + ½ from 14% thermal energy at the electrode pick, spread out in two directions – bath and furnace space);
- when the arc is working with half of his height covered by slag (figure 1c) or all covered (figure 1d), the electric efficiency is increasing from 65% (2/3 from 86% + ½ from 14%). The energy is transmitted by slag towards the bath by conductivity;
- if the thickness of the slag layer is choosed depending on his conductivity, the slag will work as a resistance, the metallic bath heating is partially (figure 1e) or totally (figure 1f) resistive (Joule effect). In this case the energy efficiency is 93 – 100%.

The simulations performed using ANSYS software [4], for an 3D model, confirm the above theory and the experimental results. The thermal energy developped through Joule effect into the liquid steel bath, will increase in the case of the using of a foaming slag with conductive properties, compared to the case when the slag doesn't have such properties. This effect is produced due to the appearance of some current ways, in parallel with the electric arc through the slag (Fig. 2).

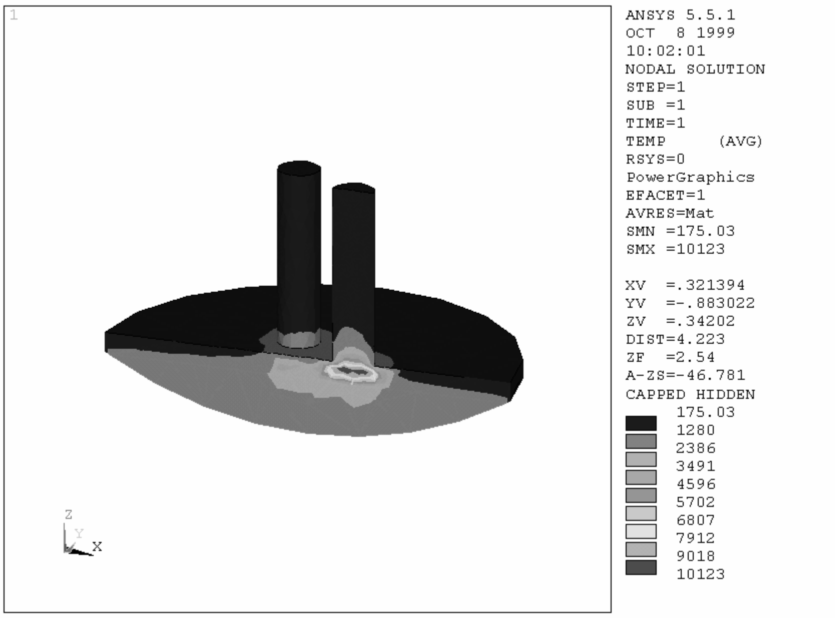

Fig. 2. The thermal field through the arcs, electrodes and the liquid steel bath, in the case of the use of a conductive foaming slag

Therefore, it is confirming the fact that in the case of an immersed arc into a conductive foaming slag, the heating of the bath is partially or totally resistive (figure 1e and 1f). In this case, the distorsion factors of the voltage and of the intensity of the electrode current of the arc is to be reduced, having positive impact to the network and to the other consumers supplied from the sane network.

3. Mathematical model for the optimisation of the steel melting programmes, in the case of the foaming slag technology for EAFs with small capacity

Based on energetical balances made for small EAFs [2,3], it can be established the simplified hypothesis for the calculus of electrical and thermal losses for the mathematical model for the optimisation of the steel melting programmes into small EAFs.

Therefore, in the case of such furnaces without oxy-fuel burners and preheated charge (current situation of the EAFs located in Romanian SMEs), the input energy in the energetical balance contour of furnace $\Sigma W_{i,j}$, is:

$$\sum W_{i,i} = W_{ee} + W_{el} + W_{ex} \tag{1}$$

where:

W_{ee} – the electric energy consumed from the network ;

W_{el} - the energy produced by the electrodes burning;

W_{ex} – the energy of exotherme reactions.

The other components of the input energy are neglectibles, having a small weight up to 1 % [2], or the differences between input and output are arround zero (for instance the cooling water).
With the same simplified hypothesis, the output energy $\Sigma W_{o,j}$ is composed from:

$$\sum W_{o,j} = W_{st} + W_{sl} + W_l \quad (2)$$

where:
W_{st} – the energy needed for the melting of the steel;
W_{sl} – the energy neede to obtain the technological slag;
W_l – the sum of all electrical and thermal energy losses, the other output energies being neglectibles.

By the equalizing of the input and output energies from the balance contour, we get:

$$W_{ee} + W_{el} + W_{ex} = W_{st} + W_{sl} + W_l \quad (3)$$

If it is taked into account that:

$$W_l = W_{ell} + W_{tl} \quad (4)$$

where
W_{ell} - electrical losses;
W_{tl} – thermal losses
and this result is to be replaced in (3) we get:

$$W_{ee} - W_{ell} + W_{el} + W_{ex} = W_{st} + W_{sl} + W_{tl} \quad (5)$$

But the difference of the total electric energy W_{ee} and of the electric losses W_{el}, is exactly the energy of the electric arc, W_a [2]:

$$W_a = W_{ee} - W_{ell} \quad (6)$$

Hence, the relation (5) becomes:

$$W_a + W_{el} + W_{ex} = W_{st} + W_{sl} + W_{tl} \quad (7)$$

The energy corresponding to the thermal losses W_{tl}, in the case of the foaming slag technology is getting, depending on the foaming slag height, by the amounts from figure 1 and by the 3D simulations results.
The energy produced by the electrodes burning W_{el} is proportional with the quantity of the burned carbon from electrodes, and with the reaction heat corresponding to the carbon Q_c, so W_{el} is proportional with the quantity of electrodes consumed Δm_e.
By his turn, the electrodes consumption Δm_e has two components, the proper consume Δm_{ep} and the lateral oxidation Δm_{eo}. Theoretical and experimental researches [5], shown that:

$$\Delta m_{ep} = k_1 I^2_2 \quad (8)$$
$$\Delta m_{eo} = k_2 t$$

where:
k_1, k_2 - constantes
I_2 – the current through electrode;
t – the charge duration
Hence

$$\Delta m_e = k_1 I^2 + k_2 t \quad (9)$$

and

$$W_{el} = k'_1 I^2_2 + k'_2 t \quad (10)$$

where:

$$k'_1 = k_1 Q_c \quad (11)$$
$$k'_2 = k_2 Q_c$$

If the relations (10) are inserted in (7), and the energy of the electric arc will be expressed depending on the arc resistance R_a and arc current I_{2i} (the current in the secondary circuit of the supply transformer), will get:

$$3R_{ai} \cdot I^2_{2i} \cdot t_i + k'_1 \cdot I^2_{2i} + k'_2 \cdot t_i - W_{tli} = W_{st} + W_{sl} - W_{ex} \quad (12)$$

where:
i – the step of the transformer, choosed for melting of the steel;
t_i – the melting time for the step i
It can be observed that the sum ($W_o + W_z - W_{ex}$) doesn't depends by the choosed voltage step. The calculus for the energies W_{sl} , W_{ex} si W_{st} is presented bellow.
Therefore, the sensitive heat of the slag, W_{sl}, could be achieved with the relation:

$$W_{sl} = G_{sl} \times [C_{sl} \times (T_{sl} - T) + L_{sl}] \quad (13)$$

where:
G_{sl} – the quantity of the liquid slag, kg;
C_{sl} - the specific heat average of the slag, between the input temperature of the charge T and the temperature of the liquid slag T_{sl}, kcal / kg K;
L_{sl} – the melting latent heat of the slag, kcal / kg

The contribution in energy of the exotherm reactions, W_{ex}, is to be calculated, for the burning elements, with the relation:

$$W_{ex} = \Sigma M_{Ai} \times Q_{Ai} \quad (14)$$

where:
M_{Ai} – the quantity of the chemical element i, kg;
Q_{Ai} – the heat of the reaction due to the burning of the element i, kcal / kg
For the calculus of the energy nedeed for the melting of the steel, W_{st}, it is considering the situation in which the scrap is loaded in m skips, in the skip j being the quantity M_j. The total amount of scrap loaded into the furnace (with m skips) will be:

$$M_t = \sum_{j=1}^{m} M_j \quad t$$

The energy needed to melt the steel will be:

$$W_{st} = \frac{1000}{860} i_{st} \cdot \sum_{j=1}^{m} M_{st,j} \quad kWh \quad (15)$$

where:
i_{st} – the enthalpy of the liquid steel, kcal/kg;
$M_{st,j}$ – the quantity of the scrap loaded in the skip j, tonnes.

The calculus of the $M_{st,j}$ amounts is undertaking in the case of the incomplete melting of the scrap in the first (m - 1) skips, in order to increase the stability of the arc. Hence, we can suppose that from the total weight of the scrap loaded in the first skip, a fraction p_1 (%) is going to be melted. Then, a fraction p_2 (%) from the quantity of the scrap loaded in the second skip will be melted, plus the unmelted quantity from the first one. This process will continue with the melting of the charge from the third skip, plus the unmelted quantity from the first two skips.

Depending on the number of the skips, the process will continue until the last skip, when all the scrap remained unmelt, will be melt.

The quantity of the scrap melt in the skip j, $M_{st,j}$ can be expressed as follows (16) and the energy nedeed for the steel melting in the interval of time from the loading of the skip j, until the loading of the skip (j + 1) is presented in relation (17).

$$M_{st,j} = \frac{1}{100} p_j \sum_{i=1}^{j} [M_j (1 - \frac{1}{100} \sum_{k=1}^{j} p_k - \frac{1}{100^{j-i+1}} \cdot \prod_{k=1}^{j-1} (-1)^k p_k)] \quad (16)$$

$$W_{st,j\to j+1} = \frac{1000}{860} \{ \frac{i_{st}}{100} [p_{j+1} \sum_{i=1}^{j+1} (M_i (1 - \frac{1}{100} \sum_{k=1}^{j} p_k - \frac{1}{100^{j-1}} \cdot \prod_{k=1}^{j} (-1)^k p_k)) - p_j \sum_{i=1}^{j} (M_i (1 - \frac{1}{100} \sum_{k=1}^{j-1} p_k - \frac{1}{100^{i-j+1}} \prod_{k=1}^{j-1} (-1)^k p_k]\} \quad (17)$$

Besides the calculation of the energy $W_{st,j\to j+1}$, the energies $W_{z,j\to j+1}$ si $W_{ex,j\to j+1}$ shoud be calculated for the intervales [j, j+1], where j = 1,2, ... m-1. This has to be done because for each one of such intervals must be established, using the mathematical model, the selected l_j working points. The working parameters of the furnace in these points, arranged successively, will form the efficient (optimized) melting program, for each technological case.

Based on this programme, both technological and energetic correct control of the melting will be issued, for various technological scenarios, with foaming slag use including.

In the Fig. 3 is shown the melting programme for the 6 t EAF, working with foaming slag.

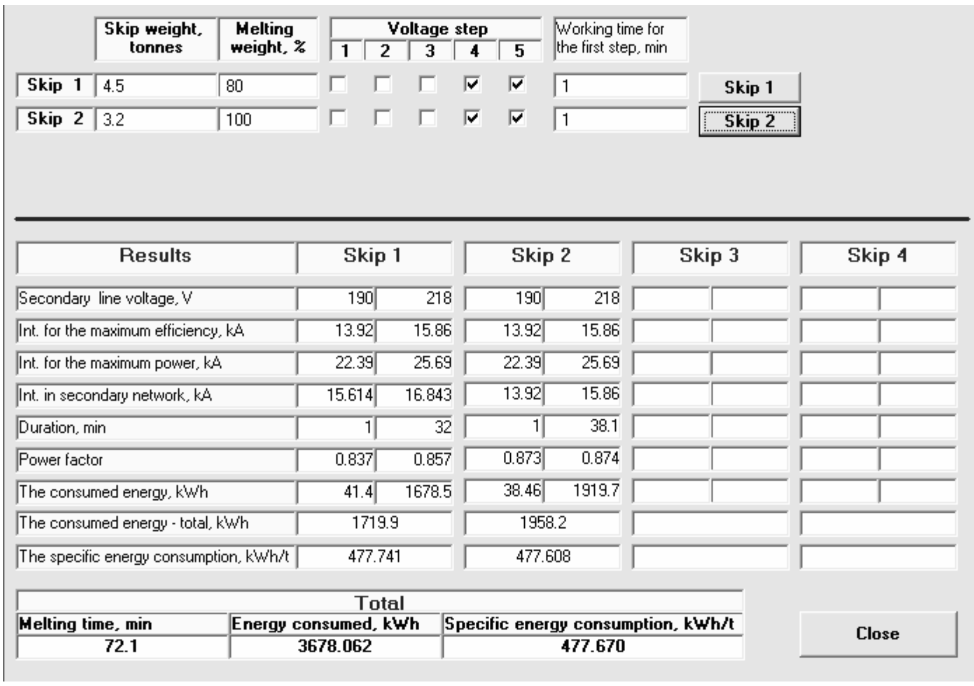

Fig. 3. The melting programme for the 6 tonnes EAF, in the case of the use of the foaming slag technology

Comparing the melting programmes, with and without foamig slag technology, for the same 6t EAF, we can get some conclusions. So, in the case of the use of the foaming slag during the melting of the charge, the specific energy consumption is to be reduced at 478 kWh / t charge, comparing with 589 kWh / t charge, when the furnace is working without foaming slag. Besides, in the case of the foaming slag technology, the melting time is to be reduced to 72 min. from 110 min.

Conclusions

The improving of the energetic indicators of the electric arc furnace with small capacity can be achieved through various technological methods, or through the optimisation of the melting regime. In the second case, the desired improve should be realized acting especially over the steel melting process control, using mathematical models and algorithns like those presented in this paper.

By using the foaming slag during the melting of the metallic charge, the transmission efficiency of the electric power towards the steel bath is to be increased from 36%, when the electric arc is burning free, to arround 93-100 %, when the arc is totally covered by foaming slag (the amount of 100 % will be achieved when the slag is conductive).

The simulations performed using ANSYS software, for an 3D model, confirm the theory and the experimental results. The thermal energy produced through Joule effect into the liquid steel bath, will increase when the foaming slag is conductive. This effect is produced due to the appearance of some current ways in paralel with the electric arc through the slag.

Otherwise, comparing the melting programmes, with and without foamig slag technology, for the same EAF with 6 tonnes capacity, we get important conclusions over the specific energy consumption and the charge duration.

Therefore, in the case of the technology with foaming slag, the specific energy consumption is to be reduced with 110 kWh / t charge (arround 850 kWh for the entire charge, tap to tap, for an aggregate quantity of 7.7 tonnes scrap, taked into account during the simulations) compared with the melting without foaming slag. The charge duration has been reduced with arround 38 minutes.

The reduction of the specific energy consumption has indirecte positive effects over the air emissions as well. This will be done through the reduction of CO_2, NO_x, SO_2 emissions and particulate matter at the stack of the energy producer, especially in the case when a big weight from the total energy power at the national level is producing in thermo-electrical power station so as is the case of Romania.

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