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THE OPTIMISATION OF ELECTRIC ENERGY CONSUMPTION IN THE ELECTRIC ARC FURNACE

OPTYMALIZACJA ZUŻYCIA ENERGII W ELEKTRYCZNYM PIECU ŁUKOWYM

The paper presents actions aiming at indicating the optimal demand for electric energy in the process of steel production in the electric arc furnace (EAF). Calculation models for electric energy demand were chosen on the basis of the analysis of the available literature. Computer software was developed on the basis of methods employing the genetic algorithm. The software enables the utility analysis of particular models for the work of a particular arc furnace. It was established that the use of artificial intelligence methods used for the analysis of the electric arc furnace's parameters was one of the ways of improving the indexes of its work. It could also be a way of setting new trends concerning the necessary changes enabling a decrease in production costs.

Keywords: Optimization, EAF, Electric Energy, AGEAF software

W artykule przedstawiono wyniki mających na celu optymalizację zużycia energii elektrycznej w procesie produkcji stali w piecu łukowym (EAF). W oparciu o dostępne dane literaturowe dokonano wyboru najkorzystniejszego modelu do obliczenia zapotrzebowania na energię elektryczną. Opracowano oprogramowanie komputerowe oparte o metody algorytmów genetycznych. Oprogramowanie umożliwia przeprowadzenie analizy dla kilku modeli obliczeń energii zastosowanych do warunków pracy konkretnego pieca łukowego. W oparciu o uzyskane wyniki badań dla dwóch stalowni elektrycznych stwierdzono, że zastosowanie metod sztucznej inteligencji do analizy parametrów pracy pieca łukowego jest jedną z możliwości poprawy ich wskaźników eksploatacyjnych. Zaproponowana metodyka umożliwia także wprowadzenie nowych rozwiązań, które umożliwią zmniejszenie kosztów produkcyjnych.

1. Introduction

The aim of steel production in the arc furnace is obtaining the liquid metal bath from the scrap metal as quickly as possible and using as low costs as possible. The structure and the construction of the furnace is subordinate to the aim. So it is the technological method of running the process. The technology of the process encompasses proper preparation and loading of the charge materials (scrap metal, slag forming materials, carburizing materials) as well as their melting by means of electric energy transformed into heat in the electric arc. The optimal control of the work of an arc furnace with the alternating current is a complex process due to the quantity and variety of the work parameters. Many physical phenomena as well as chemical reactions take place during the melting process. Their precise mathematical description does not seem possible. At the same time the competition at the steel market requires the furnace to work economically which is tantamount to a decrease in production costs. It is impossible to optimize the furnace work in a way that would decrease the costs and produce high quality steel in a universal way at the same time. Different producers apply different methods of controlling the production costs. These methods usually cannot be applied in the cases of other furnaces.

Therefore, an attempt has been made to optimize the demand for electric energy used in the production process in the arc furnace. The used energy is one of the most important components of the production costs. If one plans such parametres of the furnace that would optimize the use of energy, the costs will go down.

2. The concept of the model

Many physical and chemical phenomena, which take place during the steel melting process in the electric arc furnace, can be presented by means of the physical and chemical models decribing these phenomena. One

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of such phenomena is calculating the demand for electric energy. Preparing a model of electric energy demand will enable the optimisation of the electric energy consumption. So far many models used in industrial practice have been described in literature [1-5]. The most often used methods included the method of selecting the equation's form and determining the facors. The use of modelling based on the physical chemistry of the process is a difficult task on account of a large amount of simultaneous physical and chemical phenomena requiring a complex mathematical description. Therefore, an attempt was made to use a method based on the calculus of probability. The genetic algorithm method was used in order to identify the available statistical equations describing the use of electric energy in the arc furnace (Figure 1). Computer software based on genetic algorithm was developed. It was then tested on the parametres of the arc furnaces in two steel plants.

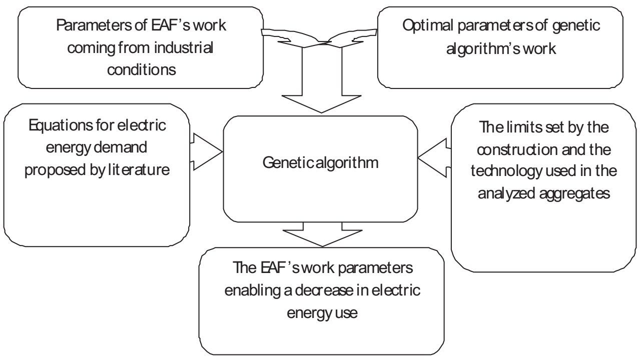

Fig. 1. A diagram of the proposed model

The equations published by S. Köhle [2-5] and W. Adams [1,3] were used as the equations describing the process in the electric arc furnace. Three different equations developed by S. Köhle and two developed by W. Adams were taken into account:

– equations developed by S. Köhle [2-5]

$$W_R = 300 + 900 \cdot \left[\frac{G_E}{G_A} - 1\right] + 1600 \cdot \frac{G_Z}{G_A} + 0.7 \cdot [T_A - 1600] + 0,85 \cdot (t_S + t_N) - 8 \cdot M_G - 4,3 \cdot M_L \quad (1)$$

$$W_R = 300 + 900 \cdot \left[\frac{G_E}{G_A} - 1\right] + 1600 \cdot \frac{G_Z}{G_A} + 0.7 \cdot [T_A - 1600] + 0,85 \cdot (t_S + t_N) - 4,3 \cdot M_L - 8 \cdot M_G - 2,8 \cdot M_{O_2} + 80 \cdot \frac{G_{DRI/HBI}}{G_A} - 300\frac{G_{HM}}{G_A} - 15 \cdot CON \quad (2)$$

$$W_R = 391 + 450 \cdot \left[\frac{G_E}{G_A} - 1\right] + 800 \cdot \frac{G_Z}{G_A} + 0,35 \cdot [T_A - 1600] + 0,43 \cdot (t_S + t_N) - 2,1 \cdot M_L \quad (3)$$

– equations developed by W. Adams [1, 3]:

$$W_R = W_E + 110\frac{G_A}{G_E} - 100 \cdot \frac{G_{DRI/HBI}}{G_E} + 450 \cdot \frac{G_{HM}}{G_E} + 10,5 \cdot M_G + 5,2 \cdot (M_{O_2} - 2,0 \cdot M_G) \quad (4)$$

$$W_R = W_E + 110\frac{G_A}{G_E} - 100 \cdot \frac{G_{DRI/HBI}}{G_E} + 450 \cdot \frac{G_{HM}}{G_E} + 10,5 \cdot M_G + 11 \cdot M_{Oil} + 8 \cdot M_{LPG} + 5,2 \cdot (M_{O_2} - 2,0 \cdot M_G - 2,0 \cdot M_{Oil} - 1,5 \cdot M_{LPG}) \quad (5)$$

These are statistical equations which present the most important factors influencing the electric energy consumption. The factors include:

G_E – total weight of the metallic charge, Mg,
G_A – the expected weight of the metal bath, Mg,
G_Z – slag weight, Mg,
T_A – tapping temperature, °C,
t_S – time of energy consumption, min,
t_N – tap to tap time, min,
M_G – natural gas used in the process, m^3/Mg,
M_L – the amount of technical oxygen, m^3/Mg,
M_{O2}– the oxygen weight used for oxidizing the carbon, m^3/Mg,
$G_{DRI/HBI}$ – the weight of the initially reduced iron and the weight of iron in the form of briquettes, Mg,
G_{HM} – the weight of the remaining liquid metal, Mg
CON –information suggesting whether the analyzed cast is a continuation or a starting cast,
M_{oil} – the inserted amount of oil, Mg/Mg $_{metalbath}$,
M_{LPG} – the inserted amount of gas, m^3/Mg.

All of the above mentioned factors are noted for each melt on the melting form and kept in the database or they can be derived from simple relations.

The issue to be solved consists in the evaluation and analysis of the equations describing the use of electric energy in the arc furnace. The environment consists in the admissible range of particular process factors which influence the electric energy consumption. It is the function of the aim which is subject to optimization. The issue is solved by means of genetic algorithm method. Computer software, later called "AGEAF", was developed for the purpose of the project. The developed software consists of two parts, each of which is developed on the basis of the implemented genetic algorithm:

– the first part is a test one. It enables the control over the genetic algorithm and the assessment of its optimal parameters,
– the second part is the actual optimization of the electric energy demand.

3. The obtained results

AGEAF software was used to calculate such factors of the melting process that would ensure minimal demand for the electric energy. The obtained results were compared with minimal, maximal and medium values from the actual melts. The calculations were made separately for the furnace working in the Steelworks I and Steelworks II.

Table 1 presents the minimal and maximal values for particular factors of the furnace's work. The values were obtained on the basis of data coming from research melting processes in Steelworks I. The parameter values presented in table 1 were obtained by selecting the minimal and maximal value from all the available ones. Only the melting processes with complete and error free data were taken into account during the calculations. The slag weight and the flow down temperature were assumed to be stable. In the case of temperature this fact is mainly related to the requirements set by the receiving element, that is the ladle. The slag weight for the furnace from Steelworks I was stable and amounted to 10 Mg.

The developed software AGEAF was used to calculate the optimal demand for electric energy in the steelmaking process in the electric arc furnace. The above mentioned factors with values ranging from the minimal to maximal values from table 1 were used as the entry data. The values of the factors were established according to the AGEAF algorithm in order to obtain minimal demand for electric energy. The energy was calculated by mean of equations (1)÷(4). The obtained results and average values for the real melting processes were shown in table 2.

TABLE 1

The entry parameters for the optimization process in AGEAF software for the furnace working in Steelworks I

Factor's name	Values	
	Minimal	Maximal
Weight of the metallic charge, Mg	148	165
Weight of melted metal, Mg	128	153
Weight of remaining metal, Mg	0	10
Slag weight, Mg	10	10
Oxygen used for the process, m^3/Mg	30	36
Gas used for the process, m^3/Mg	2	5
Temperature of the metal bath before the tapping, °C	1609	1609
Tap to tap time, min	45	67
Time of energy consumption by the furnace, min	35	45

The minimal demand for electric energy calculated on the basis of equations (1)÷(4) is in each case smaller than that for the real melting processes. Consequently, it is possible to select such values of particular factors that would lower the demand for electric energy. The analysis of particular values of different factors led to the conclusion that equation (2) best reflects the real working conditions of the investigated arc furnace. In order to optimize the demand for energy, it is advised to use the above mentioned equation. As can be seen from the data in table 2, the calculated values of particular factors are different from the average values from real melting processes. The smallest difference that can be noticed is that in the time from one melt to another and the biggest difference is that in the melted metal weight.

TABLE 2

The average values from real melts and the obtained factor values which enabled minimal energy consumption and which were calculated the AGEAF software use

Factor's name	Average values of real melts	Predicted values			
		Equation 1	Equation 2	Equation 3	Equation 4
Calculated value of the electric energy demand, kWh/Mg	396	294	273	293	285
Weight of metallic charge, Mg metalicznego, Mg	157	151	145	153	159
Weight of melted metal, Mg	140	145	148	149	152
Weight of remaining metal, Mg	10	6.2	4.6	7.6	3.0
Slag weight, Mg	10	10	10	10	10
Oxygen used for the process, m^3/Mg	33	33,5	35	32	34
Gas used for the process, m^3/Mg	3.4	2.8	2.15	3.5	4.9
Temperature of the metal bath before tapping, °C	1609	1609	1609	1609	1609
Tap to tap time, min	52	58	53	55	61
Time of energy consumption by the furnace, min	40	35	40	44	42

Such results show that the time from one melt to another has the biggest influence on the energy demand. The factor showing the biggest difference from the average real value has the least significance when it comes to energy demand. Similar relations were obtained as far as other analyzed equations are concerned.

Analogical analysis was conducted for the arc furnace in Steelworks II. The database obtained from the investigated melts required in this case a more thorough selection. On account of the lack of data concerning the amounts of inserted intensifying substances the equation (4) was not analyzed. Table 3 presents minimal and maximal values for the selected factors of the furnace work. The values were obtained on the basis of the data from the research melts.

TABLE 3

The entry parameters for the optimization process in AGEAF software for the furnace working in Steelworks II

Factor's name	Values	
	Minimal	Maximal
Weight of the metallic charge, Mg	54	85
Weight of melted metal, Mg	65	78.4
Weight of remaining metal, Mg	6	6
Slag weight, Mg	1.7	2.0
Oxygen used for the process, m^3/Mg	–	–
Gas used for the process, m^3/Mg	–	–
Temperature of the metal bath before the tapping, °C	1630	1630
Tap to tap time, min	–	–
Time of energy consumption by the furnace, min	40	73

The values of the process parameters, which were shown in table 4, were also obtained by selecting the minimal and maximal value from the database. The metal weight after each flow down and the temperature of the flow down were assumed to be stable.

AGEAF software was used to calculate the optimal demand for electric energy used in the melting process in the arc furnace. The above mentioned factors, whose values ranged from the minimal to maximal value from table 3, were used as the entry data. The obtained results together with average values for real melts were shown in table 4. The minimal demand for electric energy calculated on the basis of the equations (1) ÷ (3) is in each case higher than the obtained value for the real melts.

It proves that it is impossible to select such factors for the entry values which would enable a decrease in the energy demand to an amount below the average one form the real melts. The quality and quantity of the available data can be the cause of such values. The limited number of analyzed factors meant not considering all sources of heat present in the process.

Particular factors thanks to which the energy consumption is minimal were analyzed in relation to average real values. It turned out that the smallest demand for energy was calculated on the basis of equation (3). Therefore, equation (3) in comparison to others best illustrates the real working conditions of the arc furnace. In order to optimize the energy demand of this furnace it is recommended to use the above mentioned equation. As can be seen from date in table 4, the calculated values of particular factors are different from the average values from real melts. The smallest difference can be noticed when it comes to the slag weight and the biggest one when it comes to the metal weight after the melt. Such results prove that the slag weight has the biggest influence on the analyzed factors. The factor differing most from the average value has the smallest influence

TABLE 4

The average values from real melts and the obtained factor values which enabled minimal energy consumption and which were calculated the AGEAF software use

Factor's name	Average values of real melts	Predicted values		
		Equation 1	Equation 2	Equation 3
Calculated value of electric energy demand, kWh/Mg	431	631	680	498
Weight of the metallic charge, Mg	77	79	84	76
Weight of melted metal, Mg	68	66	65	70
Weight of remaining metal, Mg	6	2.0	5.8	0.4
Slag weight, Mg	2	1.8	1.7	2.0
Oxygen used for the process, m^3/Mg	–	–	–	–
Gas used for the process, m^3/Mg	–	–	–	–
Temperature of the metal bath before tapping, °C	1630	1630	1630	1630
Tap to tap time, min	–	–	–	–
Time of energy consumption by the furnace, min	51.7	55	64	58

on the energy demand. Similar relations were indicated in the case of the remaining equations.

TABLE 5
Theoretical parameters for the optimization process in AGEAF software for the furnace in Steelworks I

Factor's name	Values	
	Minimal	Maximal
Weight of the metallic charge, Mg	140	165
Weight of melted metal, Mg	120	162
Weight of remaining metal, Mg	0	0
Slag weight, Mg	10	10
Oxygen used for the process, m^3/Mg	0	50
Gas used for the process, m^3/Mg	0	10
Temperature of the metal bath before the tapping, °C	1600	1600
Tap to tap time, min	45	55
Time of energy consumption by the furnace, min	35	45
DRI weight	0	5
HBI weight	0	5

The analysis of the results shows that the quality of the database used for optimizing the energy demand is not the best (as far as Steelworks II is concerned). It can be said that the minimal and maximal values used in optimizing the energy demand were coincidental to a large extent. That is why theoretical minimal and maximal values of particular factors were assumed. They were prepared on the basis of the furnace's construction parameters and technological data. Such values were prepared for both furnaces. The values were shown in tables. Table 5 presents theoretical factors for the furnace in Steelworks I.

AGEAF software was again used to calculate the electric energy demand on the basis of minimal and maximal values from table 5. The results were presented in table 6. The results presented in table 6 show that the calculated value of optimal, i.e. minimal, demand for energy assessed on the basis of equations (1)÷(4) differs depending on the equation. The smallest value was obtained in the case of equations (1) and (4). Higher values were obtained in the case of equations (2) and (3). It means that for such working conditions it is good to use equations (1) and (4). Equations (2) and (3) are less useful in this case.

The values of the factors which cause the optimal energy consumption show that it is recommended to work on the melting technology. It is recommended to develop such technologies that would use those factors that make the energy demand optimal. Similar analyses were conducted for the furnace in Steelworks II. The theoretical minimal and maximal values were assumed as in the case of the first furnace. AGEAF software was again used to calculate the electric energy demand. This time the values were taken from table 7. Table 8 presents the calculation results.

The results shown in table 8 prove that the smallest calculated value was obtained in the case of equation (4). Higher values were obtained for all other equations. It means that it is good to use equation (4) in order to control the energy consumption. The use of equations (2) ÷ (3) does not lead to obtaining factors safeguarding the optimal electric energy demand.

TABLE 6
The average values from real melts and the obtained factor values which enabled minimal energy consumption and which were calculated the AGEAF software use

Factor's name	Predicted values			
	Equation 1	Equation 2	Equation 3	Equation 4
Calculated value of electric energy demand, kWh/Mg	297	349	350	298
Weight of metallic charge,	144	151	159	150
Weight of melted metal, Mg	141	146	147	142
Weight of remaining metal, Mg	8	4.9	9.0	7.7
Slag weight, Mg	10	10	10	10
Oxygen used for the process, m^3/Mg	42.36	32	32.9	40
Gas used for the process, m^3/Mg	3.8	2.7	8.2	7.3
Temperature of the metal bath before tapping, °C	1600	1600	1600	1600
Tap to tap time, min	52.9	50	52	46.5
Time of energy consumption by the furnace, min	38	37.6	38	38
DRI weight	–	4.47	–	2.65
HBI weight	–	1	–	2

TABLE 7

Theoretical parameters for the optimization process in AGEAF software for the furnace in Steelworks II

Factor's name	Values	
	Minimal	Maximal
Weight of the metallic charge, Mg	67	75
Weight of melted metal, Mg	66	74
Weight of remaining metal, Mg	0	5
Slag weight, Mg	3	3
Oxygen used for the process, m^3/Mg	0	40
Gas used for the process, m^3/Mg	0	7
Temperature of the metal bath before the tapping, °C	1600	1600
Tap to tap time, min	58	70
Time of energy consumption by the furnace, min	40	50
DRI weight	0	5
HBI weight	0	5

TABLE 8

The factor values which enabled minimal energy consumption and which were calculated the AGEAF software use

Factor's name	Predicted values			
	Equation 1	Equation 2	Equation 3	Equation 4
Calculated value of electric energy demand, kWh/Mg	352	333	320	316
Weight of metallic charge, Mg	69	71	72	69
Weight of melted metal, Mg	66	68.6	69	66
Weight of remaining metal, Mg	4	2.48	1	3
Slag weight, Mg	3	3	3	3
Oxygen used for the process, m^3/Mg	33.8	28	37	33.8
Gas used for the process, m^3/Mg	3	5	2.6	5.4
Temperature of the metal bath before tapping, °C	1600	1600	1600	1600
Tap to tap time, min	67.5	59.7	63.0	68.0
Time of energy consumption by the furnace, min	43	46	47	46
DRI weight	–	4.4	–	2.8
HBI weight	–	1.0	–	0.17

4. Conclusions

The conducted analyses allowed to set theoretical optimal values required for the process. These values were shown in tables 2, 4, 6 and 8. These are theoretical factors and their utility can only be checked by conducting melting tests based on values similar to the set parameters. The obtained factors are abstract values as they were obtained on the basis of geometrical and technological factors of the analyzed furnace's work. They can be, however, successfully used as factors illustrating the necessary changes. The changes should be made with the aim of obtaining new melting technology enabling a decrease in the electric energy consumption.

The conducted analyses proved that equations coming from the literature are correct in the case of aggregates similar to the furnaces for which they had been developed.

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