Improving the engineering-and-economical performance of ore-thermal electric furnaces in the smelting of silicomanganese

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Abstract. Ways of increase of ore-heating electric furnaces, used for production of silicomanganese, engineering-and-economical performance are analyzed. Questions of data of the electric, thermal and technological modes of the furnace functioning collecting and processing for use in operation of an advanced control system of the furnace providing increase in technical and economic efficiency of technological process and an adaptability to quality of burden stock are considered.

1. Introduction
This paper discusses the issues of improving engineering-and-economical performance of ore-thermal electric furnaces, used for producing ferroalloys, in particular, of silicomanganese. The article is based on the results of theoretical studies and practical works performed with the aim of improving engineering-and-economical performance in one of the furnaces for producing silicomanganese (with a power of 9 MVA) at “Kuznetskie Ferrosplavy” Company (Novokuznetsk city, Russia).

Need of researches is in the field connected with the fact that the modes of operation of furnaces which have developed in practice often aren't optimum from the point of view of engineering-and-economical performance, especially at the changing quality of burdening materials (ore).

Has the following reserves of improving engineering-and-economical performance of ore-thermal furnaces:

- reduction of electrical losses in current lead and increase in electrical efficiency;
- reduction of heat losses through the liner and the exhaust gases and increase in thermal efficiency;
• reduction in compliance of the electric modes of operation of furnaces to the changing technological conditions and increase in technological efficiency.

The used approaches are applicable not only to furnaces for producing silicomanganese, but also to ore-thermal furnaces for other materials.

2. Experimental investigations on the furnace

To identify opportunities to improve engineering-and-economical performance, experimental investigation on existing furnace, objectives which are:

- Measurement of electrical parameters (for each phase separately) on the sides of high voltage and low voltage, the determination of resistance and reactance of current lead and molten bath in different periods of the technological process of melting, the calculation of the electrical characteristics of the furnace based on the obtained data.
- Measurement of the temperature field of the furnace casing by the thermal imager for gauge of heat losses based on measurement.
- Measurement of temperature and air flow rate in each channel of the cooling hearth to assess the cooling efficiency and gauge of heat losses.
- Measurement of temperature of busbars at different points from the terminals of the transformer to the flexible part in the operating mode for the evaluation of conditions of current lead.
- Measure temperature of exhaust gases and melt, discharged from the furnace, for gauge of heat losses.
- Spectrum analysis of voltage and current for power quality.
- Formation of the file of electro-technological parameters of furnace operation (for the month), its mathematical processing and analysis to determine a rational regime of melting.

Before carrying out experimental investigation on the furnace the theoretical calculation of resistances and reactances of all phases of furnace circuit and building of the electrical characteristics of the furnace for operating voltage steps of the transformer by the method of [1] were carried out. This calculation is required for pre-selection of parameters of electric mode of furnace (current, voltage) on power factor (cosφ) and electrical efficiency.

Electrical efficiency is defined as

$$\eta_e = \frac{R_b}{R_b + R_{c.l.}},$$

where $R_b$ – the resistance of the molten bath, $R_{c.l.}$ – the resistance of the current lead. For a given furnace design value of the electrical efficiency of 0.92.

By results of measurements on the furnace dependence of inductive reactance of an furnace circuit of $X_{circ}$ (milliohm) on current of $I$ (kA) is received. For the considered furnace this dependence is approximated by a power function

$$X_{circ} = 2.263I^{0.17}$$

Taking into account this dependence electrical characteristics of the furnace are calculated further.

The operating electric mode of the considered furnace is characterized by the following parameters: the secondary voltage of the transformer of 139.5 V, current of 33.0 kA, apparent power of the furnace is 8 MBA on average, average power factor (cosφ) of 0.885. This mode practically corresponds to the parameters chosen on cosφ and electrical efficiency, but is reached only at the expense of a 12 percent overload of the used transformer (current of 33.0 kA at nominal current of 29.4 kA).

Fluctuations of voltage on primary side of the transformer (6 kV) by results of measurements on the operating furnace are small and are in limits of 2% that conforms to qualifying standards.

In the analysis of a range of current existence of significant harmonious components with numbers 2, 3, 5, 7, 23, 25, 35, 37, 47 and 49 is revealed, at the same time values of the 23rd and 25th harmonious components (1.7% and 1.3% respectively) exceed qualities of the electric power, admissible according to the Russian state standards. These harmonious components can exert bad
impact on the condenser installations installed in distributing devices of 6 kV and on cable lines of 6 kV, reducing reliability of its work.

Thermal measurements on a casing of the electric furnace were carried out for the purpose of an assessment of heat losses through side liner, and also distributions of these losses on the area of a casing. Measurements are carried out with use of the Testo 880 thermal imager. Temperatures by sectors into which the surface of a casing is divided by vertical stiffening ribs and horizontal stiffening rings have been taken.

Besides, temperature and speeds of an air stream in channels of compulsory air cooling of a hearth are taken. According to these measurements and thermovision measurements on a casing heat losses through liner of the furnace are calculated (for the considered furnace heat losses are 384 kW: 166 kW through a side surface and 218 kW through a hearth).

Results of thermal measurements can be used for an energy audit, and also for modification of a liner design for the purpose of increase in thermal efficiency at modernization of the furnace.

3. Electrical characteristics on steps of voltage of the furnace transformer

Under electrical characteristics (Figures 1, 2) understand dependences of the active power consumed by the furnace and the useful power (the power which is allocated in a bath) on current for each step of voltage of the furnace transformer. Each line on graphs in Figures 1, 2 corresponds to the step of voltage.

![Figure 1. Electrical characteristics of the ore-heating furnace (active power).](image1)

![Figure 2. Electrical characteristics of the ore-heating furnace (useful power).](image2)

Electrical characteristics are under calculation taking into account the measured value of resistance of a current lead and dependence of inductive reactance of an furnace circuit on current (2).

The analysis of electrical characteristics shows that maxima of active $P_a$ and useful $P_u$ powers don't coincide (the maximum of useful power comes at smaller value of current) and as the course of processes in a molten bath of the furnace is defined by useful power, its maximum should be supported at regulation of the electric mode.

In the considered furnace at the 11th, 13th, 15th and 17th steps of voltage follows from electric characteristics of the considered furnace that the maximum of useful power at these steps is reached at values of current of 52, 49, 46.5 and 43.5 kA (useful power respectively 8330, 7550, 6930 and 6310 kW), however the possibility of achievement of such capacities is limited to admissible current of the transformer of 28 kA (dashed lines in Figures 1, 2) therefore real values of a maximum of useful power at these steps of voltage make 6200, 5840, 5540 and 5220 kW.

It is possible to draw a conclusion that the available furnace transformer doesn't correspond to parameters of this furnace and its current lead, doesn't provide a supply of necessary power with the necessary ratio of voltage and current and demands replacement by more powerful transformer with calculated parameters.
4. Melting electro-technological mode model

High engineering-and-economical performance of operation of the furnace can be provided with only correctly picked up electro-technological operating mode. The choice of a rational electro-technological operating mode of the ore-thermal electric furnace, unlike the electric mode without connection with technology, represents a multiple-factor task in which output indicators (furnace productivity, a specific power consumption, extraction of the leading element, etc.) depend on a large number of the influencing factors which treat the characteristic of the furnace charge (the chemical composition, the size of fraction, humidity on each of charge components), the electric mode, including deepening of electrodes in a molten bath. At the same time even the skilled founder isn't able to support constantly manually the optimum electro-technological mode, especially at frequent changes of conditions during melting.

Maintenance of the optimum electro-technological mode is possible only with use of the mathematical model connecting input parameters of technological process in ore-thermal furnace with output parameters.

It is almost impossible to construct such model by analytical methods as the task of the mathematical description of process is multiple-factor, and character of many factors is probabilistic. Therefore connection between input and output parameters can be established most authentically by collection of information directly on the operating furnace and the subsequent its mathematical processing (the regression analysis) with use of special software.

The advanced control system of ore-thermal electric furnace uses such model. Formation of the file of input data for creation of regression model consists of several stages:

- Formation the initial file of parameters of the electric mode of the furnace with a 5-minute interval of data recording during from beginning to end each melting, association of the file with data on the analysis and a consumption of raw materials, daily and operational cards of the electric furnace. Sources of information are furnace control systems data, data of registration of electric parameters in real time by the programmable analyzer of energy consumption of the AR-5 series, and also documentation which is constantly maintained on the furnace by operational personnel.
- An exception of the data which are misses from the file (rejection).
- A filtration (to exclude fluctuations) and averaging of data of the electric mode on necessary time intervals with the purpose to track and determine consistent patterns of their change during melting.
- A filtration and averaging of electro-technological parameters on time intervals lasting one melting for the purpose of determination of the rational furnace operating mode.

Processing of experimental data is based on engineering algorithms.

As a result of processing and the analysis of the file of the data melting processes decide on the most rational electric indicators and engineering-and-economical performance. The selected melting processes are grouped in the range of change of the size $\cot \phi$ from 4 to 5.5 ($\phi$ is a phase angle between voltage and current). Angle $\phi$ cotangent value is directly connected with deepening of electrodes, with the characteristic of composition of the furnace charge, with engineering-and-economical performance of the furnace operation, etc.

Examples initial and smoothed (by a filtration and averaging) dependences of electric parameters (active power and current) on time during melting are presented in Figures 3, 4.

As a first approximation each melting can be broken into three time intervals which correspond to an initial stage of melting after melt discharge (a smooth growth in power to the maximum value with growth in resistance and decrease in reactance of a bath), to the most long period of the stable electric mode and the final period before melt discharge. Electrical characteristics on intervals (in dynamics during melting) allow to receive the optimum design mode of this melting and to compare it with the actual mode.
The choice of the optimum mode in case of fluctuations of quality of furnace charge and technology of melting demands continuous processing of information arriving from the furnace in real time with updating of data file.

![Figure 3. Change of active power during melting.](image)

Figure 3. Change of active power during melting.

![Figure 4. Change of current (average value on phases) during melting.](image)

Figure 4. Change of current (average value on phases) during melting.

The data file received on the operating furnace is presented in the form of a matrix which lines contain values of entrance parameters factors (usually 8–12 most technologically significant) and output indicators (usually 3–4). This matrix with a time interval in one melting is processed by means of specially developed software of the regression analysis. Receiving the equation of regression connecting values of each of output indicators \( y_j \) with factors \( x_1, x_2, ..., x_n \) is result of processing. The equation of regression has an appearance of a square polynomial

\[
y = b_0 + b_1x_1 + b_2x_2 + \cdots + b_nx_n + b_{11}x_1^2 + b_{22}x_2^2 + \cdots + b_{nn}x_n^2
\]

Content of manganese ore, reducer (coal), dolomite and slag in furnace charge, the active power, operating voltage, electrode current can be examples of factors \( x_i \), examples of output indicators \( y_j \) are productivity of the furnace (t/h), and a specific expense of the electric power (kWh/t). At the choice of the rational electro-technological mode it is expedient to use the integrated indicator of efficiency of process \( IIE \) considering (with various weight coefficients \( k_j \) received by an expert assessment) various output engineering-and-economical performance

\[
IIE = k_1y_1 + k_2y_2 + \cdots + k_my_m.
\]

Use of the software of the regression analysis demands installation on the furnace of the registering measuring devices (for registration of electric and power parameters) and records of entrance technological parameters and output operational performance in the form (manual input) coordinated in advance for further automatic processing of data file.

Processing of the prepared file of the experimental data obtained on the studied furnace with use of the software of the regression analysis is carried out in the following order:

1. Coefficients of the polynomial of regression (3) for an integrated engineering-and-economical performance (indicator of efficiency) are determined.
2. Little significant input parameters are excluded.
3. The extremum of the response surface described (3), that is combination of values of factors at which the best value of a engineering-and-economical performance is reached is found. The corresponding value of current (at the known characteristics of furnace charge) is used by the furnace current regulator as a set point, value of active power – for the choice of a step of voltage (according to electrical characteristics). Also on the basis of an extremum of a response surface it is possible to carry out correction of composition of furnace charge for achievement of the best engineering-and-economical performance.
The software of data processing is integrated into an advanced control system of the furnace, the file of input data is formed in the automatic mode. The calculated values of current, power, furnace charge parameters corresponding to the optimum electro-technological mode can be given the program in the form of advice to the operator. At the subsequent stages of introduction and development of advanced control system transition to operation in the supervisory mode with automatic change of set points of current and voltage according to the calculated optimum mode is possible.

5. Conclusion
Theoretical and experimental investigation have found opportunities to improve engineering-and-economical performance of ore-thermal furnaces, used for producing ferroalloys, including, connected with reduction in compliance of the electric modes of operation of furnaces (current, step of voltage) to the changing technological conditions and increase in technological efficiency. Maintenance of the optimum electro-technological mode is possible only with use of the mathematical model connecting input parameters of technological process in ore-thermal furnace (current, a step of voltage, the characteristic of furnace charge, etc.) with output parameters. Such model makes by collection of information directly on the operating furnace and the subsequent its mathematical processing (the regression analysis) with use of special software, and information arriving from the furnace continuously is processed in real time with updating of data file.

The special software integrated into an advanced furnace control system and realizing the offered technique of collecting and data processing in the automatic mode allows to pick up the electric mode of melting at which the best value of an integrated indicator of efficiency of process IIE (which considers the furnace productivity, a specific expense of the electric power, extraction of the leading element, indicators of the electric power quality, etc.) is reached. Calculation of correction of furnace charge composition for achievement of the best engineering-and-economical performance is also possible.

References
[1] Dantsis Ya B 2007 Secondary current leads and electrical parameters of arc electric furnaces (Moscow: Metallurgy) 320 p
[2] Kondrashov V P, Kolyvanov S Yu, Lykov A G, Pogrebisskiy M Ya, Saprykin A I and Savalyk N A 2010 Rational operating conditions for ore-heating electrofurnaces Steel in Translation Volume 40, Issue 2, pp 145-152
[3] Kondrashov V, Pogreibisskiy M and Salmanova E 2015 Development of ways of increase of ore-heating electric furnaces for production of ferroalloys efficiency Proc. Int. Conf. AMTEE’15 – Advanced Methods of the Theory of Electrical Engineering (Pilsen: University of West Bohemia) p I-5
[4] Mraz J 2011 The interpretation of electrical measurements of submerged arc-resistance furnace Proc. Int. Conf. AMTEE’11 – Tenth International Conference on Advanced Methods in the Theory of Electrical Engineering (Pilsen: University of West Bohemia) pp VI-5-VI-6
[5] Machulec B 2011 Equilibrium model of the ferrosilicon melting process in the submerged arc-resistance furnace Proc. Int. Conf. AMTEE’11 – Tenth International Conference on Advanced Methods in the Theory of Electrical Engineering (Pilsen: University of West Bohemia) pp VIII-3-VIII-4