The determination of rational technological parameters of ferrosilicon manganese melting based on the process electrical characteristics

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ABSTRACT

The influence of process parameters of ore-thermal furnace operation on electrical characteristics in order to control the melting process by changing the burden composition and adjusting the slag depending on the near-electrode zone resistance during ferrosilicon manganese melting has been analyzed. It has been shown that intention to improve one indicator may lead to deterioration of another one. In order to achieve maximal performance with minimal power consumption it is necessary to provide for optimal resistance of near-electrode space zones and ensure rational power distribution in the near-electrode space between the arc, burden and melt.

INTRODUCTION

The intensification of electrometallurgical ferroalloy production processes, the growth of unit capacity of ore-smelting furnaces and their productivity and the severization of requirements for alloys quality require creating the high-performance systems of operational management related to the harmonization of process parameters and electrical characteristics.

From this perspective, it is important nowadays to develop an efficient and reliable technology for ferrosilicon manganese production by establishing quantitative and qualitative relationships between the electrical characteristics and process parameters, which will allow managing effectively the melting process.

The thermodynamics of carbothermic manganese and silicon reduction during the ferrosilicon manganese melting is characterized by the predominance of the endothermic reactions proceeding with consumption of large amount of heat, which is compensated by transformation of electric power into thermal one released in the near-electrode zone in the furnace bath [1, 2]. Thus, the near-electrode space, through which the electric current flows, is the primary reaction zone, where the pivotal elements of ferrosilicon manganese production process are reduced. The intensity of electric energy release in the near-electrode space depends on the voltage determined by the transformer operating stage and on the electrical resistance of near-electrode space, which is driven by the physical and chemical properties of burden components, melting products and arc process intensity. The monitoring and control of factors affecting the intensity (active power) and the nature of power release in the near-electrode space of the furnace (distribution by the specific zones – burden, arc, melt) by determining the electrical characteristics of the process [3] will make it possible to harmonize them with process parameters in order to optimize technical and economic parameters.

The ore-smelting electric furnace is a multifactorial object, where physical and chemical, thermal and electrical processes [4, 5] occur simultaneously. The technical and economic parameters (TEP) of the furnace operation are generally determined by the harmonized development of these processes. The key TEP are as follows: furnace capacity (C_F, t/hour), specific power consumption (Q_{sp}, kW·h/t) and efficient use of raw materials. During the ferrosilicon manganese melting, the degree of raw materials use is primarily determined by the coefficient of manganese recovery in the alloy (η_{Mn}, %).

2. EXPERIMENT

The efficient conditions of technological process implementation can be created only on the basis of long-term study of all major factors that affect the operation of ferroalloy furnace and selection of values of such factors, which provide for achievement of the best performance indicators.

When implementing the automatic process control system, Nikopol Ferroalloy Plant carried out a large amount of the preparatory and organizational work [6], which made it possible both to consider a great number of factors affecting the progress and efficiency of ferrosilicon manganese continuous production process and define the basic task of the above described process control. The energy is provided in the furnace with self-sintering electrodes; the active furnace power is determined as the total power of each electrode. Since the electrode size remains constant value during the operational control of technological process, the main control parameter is a specific resistance of near-electrode space, which depends on the specific resistance of burden materials, slag, metal and arc resistance.

The active resistance value of the furnace near-electrode space (R_E), along with the magnitude of the voltage applied to the electrodes, is a major factor in determining the influence on the electrical characteristics and technological parameters of the process.

However, the experience of R_E deployment as the main control parameter demonstrated disadvantageous features of the furnace electric mode control oriented towards the integral parameter, which does not always lead to the optimal position of the reaction zone and efficient energy distribution in the near-electrode space.

The adopted furnace bath structure [4, 7] and the current distribution patterns reflect the slag process of ferrosilicon manganese melting, the near-electrode space of which incorporates three energy bands: arc – the power is released on the non-linear arc resistance (R_A); burden – the power is released on the burden resistance shunting the arc (R_B); melt – the power is released on the melt resistance – (slag and metal) (R_M), connected in series with parallel resistance of arc and burden.

It has been suggested to represent the near-electrode space as two energy bands typical for slag process of ferrosilicon manganese production: arc-shunt area, the resistance of which includes the arc parallel resistance and the resistance of burden materials shunting the arc (R_{AB}), and melt zone (R_M), the resistance of which is determined by the resistance of slag-metal area. The active power of arc-burden zone is released in the burden area and of melt zone is released in the molten slag (including coke layer) and in the metal. The band size is determined by the furnace operation conditions, which are dependent on the electric characteristics of the technological process.

The algorithm that allows creating the database of controlled parameters with given recording frequency has been implemented on the basis of developments [6] at Nikopol Ferroalloy Plant as part of automatic electric mode control system (AEMCS) of the furnace, using the model for determining the electrical characteristics of the work space areas [6]. The regression analysis of databases that characterize the process parameters and the electric mode of furnace operation, the condition of near-electrode space and energy distribution therein provides for establishment of relationships between the electrical characteristics and the process parameters that determine quality and quantity of the charged raw materials and the resulting alloy.

In order to examine the basic functional relationships between the process parameters, electrical characteristics and technical and economic parameters, the data package on six-electrode rectangular furnace RPG-63, on which the ferrosilicon manganese was melted within 176 shifts using the burden materials listed in Table. 2.1, has been analyzed.

Table 2.1. Chemical composition of burden materials

Item No.	Material designation	Composition of components, %						
		Mn	SiO_2	CaO	MgO	Al_2O_3	Fe	P
1	Manganese concentrate (Ukraine)	27.7-45.5	12.2-24.7	5.1-12.3	1.2-2.1	1.3-1.9	1.2-2.4	0.17-0.28
2	Manganese ores (imported)	29.1-49.7	4.1-14.1	0.7-6.1	0.2-4.6	1.3-7.0	0.8-12.4	0.04-0.12
3	Manganese slag (charge)	34.5-35.5	30.2-31.0	7.1-8.8	2.4-2.6	7.6-8.9	0.34-0.35	0.003-0.005
4	Recycled manganese materials	31.0-35.0	18.4-20.6	6.7-7.8	3.3-3.7	1.0-1.7	2.1-4.2	0.14-0.15
5	Quartzite	-	96.1-96.7	0.4-0.6	0.2-0.3	1.3-1.6	0.3-0.5	-

The co-reduction of manganese and silicon from Mn-containing raw materials and quartzite during the ferrosilicon manganese melting is attributed to the behavior of complex physical and chemical processes; however, the burden materials go through the different temperature zones, undergoing a number of transformations: dehydration, dissociation of oxides and carbonates, partial or complete reduction of oxides, slag formation, separation of melting products by slag and metallic phases, final formation of their composition.

At such multiple-factor influence on the process results, two or three final process parameters and as an integral indicator – changes in the economic efficiency are usually chosen as the performance criteria. As the criteria characterizing the ferrosilicon manganese melting process efficiency, we have chosen as follows: furnace capacity – a criterion that evaluates the main process objectives; degree of the most valuable pivotal element (manganese) recovery; specific power consumption.

3. RESULTS

The most effective method of establishing the quantitative assessments and known behaviors existing in the process is based on the investigation of statistical relationships of actual data characterizing the process over a long-term period.

An appropriate processing of the results of observations over the composition of burden materials, technological process progress, quantity and quality of the manufactured products provides for forecasting the possibility of violation of the required production parameters, when the alloy quality is within the prescribed limits, and timely introduction of the relevant adjustments to ensure the operating schedule stability.

The intensity of the technological ferroalloys production process in the ore-thermal electric furnace is directly related to the magnitude of the active power released in the near-electrode area of each electrode. The active power is determined by the square of current and the active resistance of near-electrode space. The following technological parameters depend on the process reaction rate: burden quantity consumed by the furnace, consumed power and weight of the produced metal and slag respectively.

As a result of regression analysis, the equations of influence of the input variables values on the furnace operation TEP are obtained: capacity C_F, manganese recovery $\eta_{Mn} = [Mn]/\langle Mn\rangle$; specific power consumption $Q_{sp} = Q_F/[Me]$ for various melting duration (t_{met}), depending on the input power:

$$C_F = 0.0039 \cdot I_E^{1.852} \cdot R_E^{0.959} \cdot t_{met}^{-0.049} \quad (3.1)$$

$$\eta_{Mn} = \frac{[Mn]}{\langle Mn \rangle} = 0.007 \cdot I_E^{0.436} \cdot R_E^{-0.005} \cdot t_{met}^{0.453} \quad (3.2)$$

$$Q_{sp} = \frac{Q_F}{[Mn]} = 2.217 \cdot I_E^{0.019} \cdot R_E^{-0.132} \cdot t_{met}^{0.093} \quad (3.3)$$

Fig. 3.1-3.3 illustrate 3D graphics of relationship between TEP and main electrical characteristics I_E and R_E at constant average value t_{met}.

The nature of the influence of electrical characteristics changes on TEP is as follows: Q_{sp} depends mainly on the resistance of near-electrode space and slightly grows, when the electrode current increases (Fig.3.1). The growth of specific power consumption, in case of I_E increase, is attributed to the growth of electric power losses for heating of the transformer low-voltage circuit and windings. The manganese recovery grows, when the strength of current flowing through the burden, arc and melt increases. The influence of R_E changes within the investigated range on η_{Mn} (Fig. 3.2) is not much more prominent. The furnace capacity increases, when the current and resistance are growing, and reaches its maximal value at the highest values of I_E and R_E (Fig.3.3).

Thus, the obtained relationships make it possible to predict the behavior of TEP changes, in case of increase or decrease of the factor variables involved in the ferrosilicon manganese melting process. For instance, when R_E increases, Q_{sp} decreases respectively, which affects TEP favorably and results in higher furnace capacity, the finished metal is stored up in less time and considering that furnace melting space is limited, the tapping is to be conducted earlier, reducing t_{met}, which leads to η_{Mn} reduction.

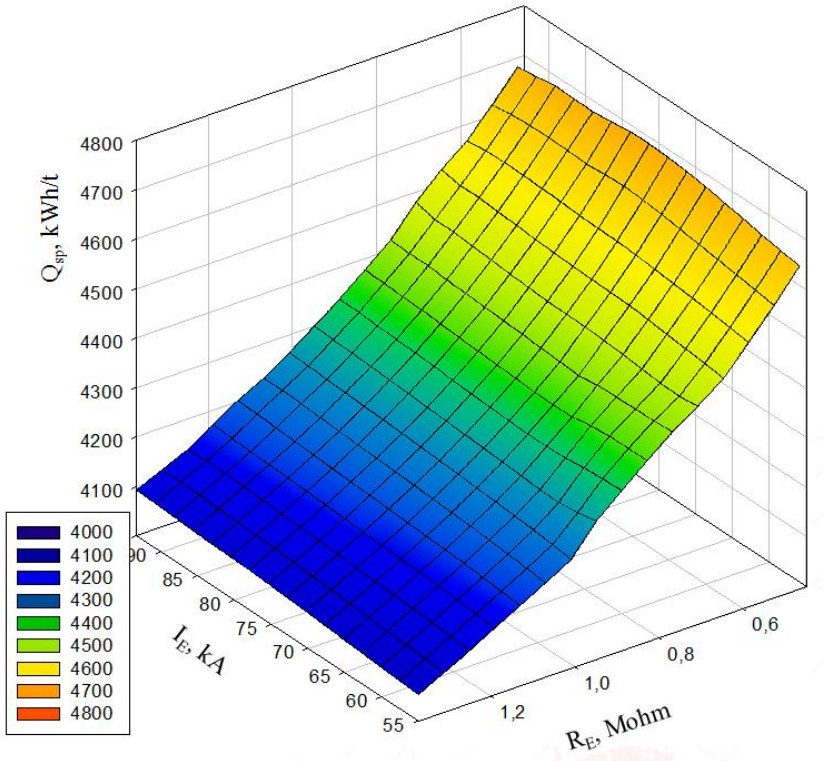


Figure 3.1: The influence of electrode current (I_E) and near-electrode space resistance (R_E) on specific power consumption (Q_{sp})

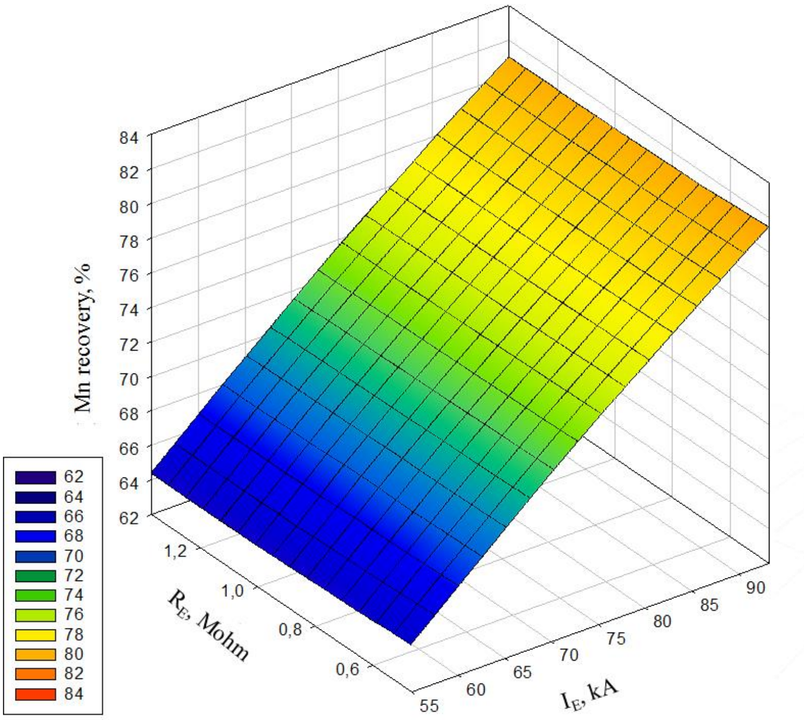


Figure 3.2: The influence of electrode current (I_E) and near-electrode space resistance (R_E) on manganese recovery (η_{Mn}).

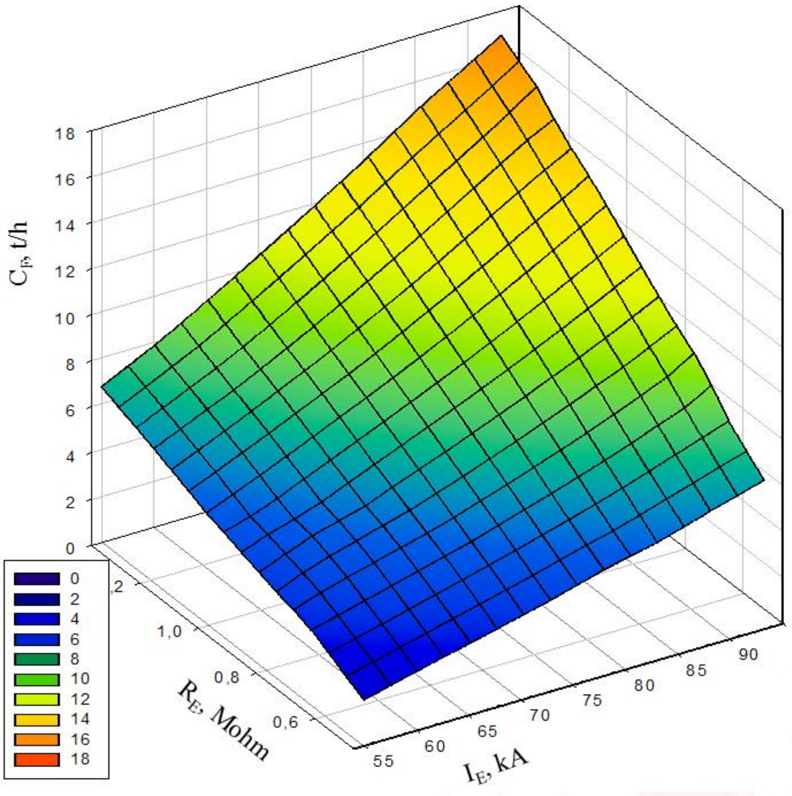


Figure 3.3: The influence of electrode current (I_E) and near-electrode space resistance (R_E) on furnace capacity (C_F).

4. DISCUSSIONS

The analysis of the realized models demonstrated that intention to improve one indicator may lead to deterioration of another one. Furthermore, the composite index R_E prevents the separate assessment of contribution of near-electrode space resistance components (R_M, R_B, R_A) [7], which reflect the energy distribution depending on the burden

$<C_{solid}>/<Mn+SiO_2>$ and melt $(CaO+MgO)/(SiO_2)$ characteristics. For this purpose, we processed the available data package using the paired regression analysis.

The established operating schedule, which provides the aimed TEP, is characterized by strictly defined electrical characteristics, the change of which represents violation of process regulations. One of the critical process characteristics is a near-electrode space resistance, which can be represented by the following expression:

$$R_E = R_M + \frac{(R_A \cdot R_B)}{(R_A + R_B)} \tag{4.1}$$

The near-electrode space resistance incorporates two energy near-electrode bands typical for slag process: arc-burden zone R_{AB} and melt zone R_M. The resistance R_B is characterized by electrical conductivity of the initial burden, which, along with the influence of chemical and particle composition of the burden, is mainly determined by specific consumption of reducing agent – coke breeze, expressed by the ratio $<C_{solid}>/<Mn+SiO_2>$ in the burden. In its turn, the optimal quantity of carbon given by the coke breeze with burden defines the reduction degree of pivotal elements (manganese and silicon), thus, establishing the relationship between the ratio of $<C_{solid}>/<Mn+SiO_2>$ and R_{AB} will make it possible to determine the rational value R_{AB} and adjust the burden composition by its value.

The melt resistance R_M is determined by the chemical composition of metal and slag. When producing the standard ferrosilicon manganese, the alloy resistance remains practically constant, so changes in R_M depend, to a greater extent, on chemical composition and physical properties of shag phase estimated by the slag basicity $(CaO+MgO)/(SiO_2)$ and the given burden basicity $<CaO+MgO>/<SiO_2>$.

The resulting relationship makes it possible to predict the behavior of technical and economic parameters in case of factor variable ($R_{AB,}$ R_M) increase or decrease. The minimization of specific power consumption at maximal productivity presupposes the determination of the values of the process technological characteristics, at which R_{AB} and R_M are within the optimal range. Using $<C_{solid}>/<Mn+SiO_2>$, $<CaO+MgO>/<SiO_2>$ and $(CaO+MgO)/(SiO_2)$ as experimental variables, we processed the data package to determine their influence on factor variables of near-electrode space resistance and their components. The list and characteristics of the data being used are presented in Table 4.1. The results are illustrated in Fig. 4.1.

Table 4.1: List and characteristics of initial data

No.	Parameter name	Designation	UOM	Average value
1	Electrode resistance	R_E	Mohm	0.93
2	Melt resistance	R_M	Mohm	0.69
3	Arc-shunt resistance	R_{AB}	Mohm	0.24
4	Specific reducing agent consumption	$<C_{solid}>/<Mn+SiO_2>$		0.19
5	Burden basicity	$<CaO+MgO>/<SiO_2>$		0.31
6	Slag basicity	$(CaO+MgO)/(SiO_2)$		0.546

The coke breeze is used as reducing agent during carbothermic processes. In case of its weighted portion change, which is characterized by proxy variable $<C_{solid}>/<Mn+SiO_2>$ (Fig. 4.1a), a noticeable change of R_E is observed. Notably, when $<C_{solid}>/<Mn+SiO_2>$ increases, R_E decrease is caused by the resistance drop of both near-electrode zones R_{AS} and R_M under the question. Such type of relationship is attributed to the coke breeze quantity applied per ton of burden, since its electrical resistance is the smallest one among the burden materials.

The change in the burden basicity affects slightly R_{AB} (Fig. 4.1b) and variable part of R_E is determined by the value of melt resistance R_M decreasing with basicity growth. The same behavior is attributable to R_E dependency on the slag basicity. The growth of burden and slag basicity (Fig. 4.1b, c) results in the melt zone resistance drop. The melt zone before tapping includes slagged burden, which transforms into slag with alloy inclusions near the electrode end.

We determined the optimal limits of electrode resistance for the furnace operation with minimal specific power consumption Q_{sp} and maximal productivity (R_E = 0.9-1.1 Mohm; R_M = 0.7-0.8 Mohm; R_{AS} = 0.2-0.3 Mohm respectively).

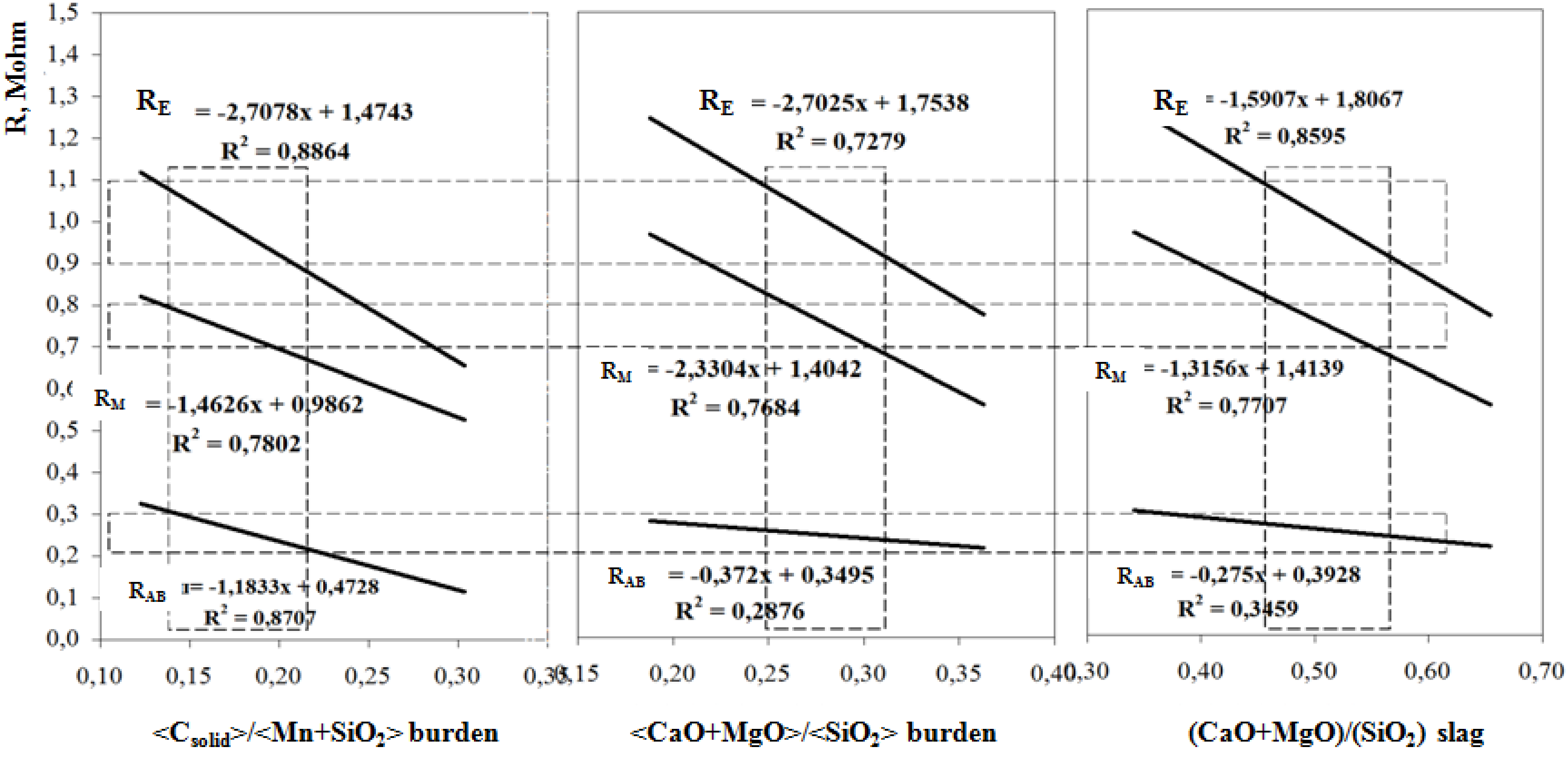
Having imaged the crossing points of straight lines $R_E = f(<C_{solid}>/<Mn+SiO_2>)$, $R_M = f(<C_{solid}>/<Mn+SiO_2>)$, $R_{AB} = f(<C_{solid}>/<Mn+SiO_2>)$ on the axis *X*, we determine process factors resulting in changes of the recommended electric characteristics. The recommended optimal electrode resistance during ferrosilicon manganese melting in the range over 0.9-1.1 Mohm includes resistances R_M and R_{AB}. Consequently, when the values R_{AS} are above or below the recommended parameters it is necessary to provide for efficient ratio between the reducing agent and Mn and Si oxides in the burden over the range of 0.14-0.22 (Fig. 4.1a).

The violation of process parameters related to the burden and slag basicity is entirely characterized by the changes in the slag and burden physical properties. Having imaged the crossing points of straight lines $R_E = f(<CaO+MgO>/<SiO_2>)$, $R_M = f(<CaO+MgO>/<SiO_2>)$ on the axis *X*, we determine value of the burden basicity corresponding to the optimal value of R_M at constant $R_{AB.}$ If the value <CaO+MgO>/<SiO_2> falls outside the values limits of 0.24-0.32 (Fig. 4.1b), which represents violation of process parameters attributable to the quartzite lack or excess in the burden.

Through variation of R_M (Fig. 4.1c) $R_E = f((CaO+MgO)/(SiO_2))$, $R_M = f((CaO+MgO)/(SiO_2))$ the violation of process parameters is almost completely determined by the slag composition, which may be caused by the shortage or excess of the amount of (CaO+MgO) and varying degree of silica reduction. The optimal values of (CaO+MgO)/(SiO_2) are within the range of 0.45-0.57 (Fig. 4.1c).

The obtained data make it possible to adjust the recommended limits of the main process ratios to minimize specific power consumption and raw materials.

Therefore, in order to achieve the furnace operation conditions with specified productivity and quality of the finished products, it is required to deploy the automatic control systems, which are able to stabilize the main electrical characteristics and technological parameters of the ferrosilicon manganese melting process.



a) b) c)

Figure 4.1: Relationship between integral resistance of near-electrode space (R_E) and its differential components: relationship between resistance of arc-burden zone (R_{AB}) and resistance of melt zone (R_M) and:

a) – solid carbon ration <Csolid> to Mn and SiO_2 in the ore burden <Csolid>/<Mn+SiO_2>;

b) – burden basicity <CaO+MgO>/<SiO_2>;

c) – slag basicity (CaO+MgO)/(SiO_2).

SUMMARY

It has been shown that electrical characteristics (electrode current and active resistance) have a directly-proportional impact on the furnace capacity. It grows with their increase. As the electrode current increases, manganese extraction grows; specific power consumption does not depend on the electrode current. The increase in the active near-electrode space resistance results in the reduction of specific power consumption and affects slightly the manganese recovery. It has been established that the more the time spent for metal production is, the more the manganese recovery and specific power consumption is. The furnace capacity does depend on the time.

The obtained models of paired nonlinear regression represented by the second order polynomial allowed determining the optimal values of integral active resistance of near-electrode space and its differential components of the arc-burden zone and the melt zone resistances in terms of improving TEP of ferrosilicon manganese production process.

The linear regression equations, the relationship between the resistances of near-electrode space of melt, burden-arc zones and their integral value R_E and main process ratios (specific carbon consumption, burden and slag basicity) have been obtained. It has been demonstrated that increase in the specific carbon consumption leads to the resistance drop of both near-electrode space zones, and the growth of basicity results only in the melt resistance reduction, and the resistance of burden-arc zone remains unchanged.

The optimal values of process ratios, on which the resistance values of characteristic zones of near-electrode space are dependent, has been determined. It has been found that deviation of near-electrode space zone resistances from the optimal values indicates the technological process violation. The nature of the deviation makes it possible to determine the parameter to be adjusted in order to recover the normal process.

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