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RELATION BETWEEN ACTIVE POWER OF THE SUBMERGED ARC FURNACE AND THE ELECTRIC ENERGY CONSUMPTION INDICATOR IN THE PROCESS OF FERROSILICON SMELTING

Higher active power of a submerged arc furnace is commonly believed to increase its capacity in the process of ferrosilicon smelting. This is a true statement but only to a limited extent. For a given electrode diameter d, there is a certain limit value of the submerged arc furnace active power. When this value is exceeded, the furnace capacity in the process of ferrosilicon smelting does not increase but the energy loss is higher and the technical and economic indicators become worse. Maximum output regarding the reaction zone volumes is one of parameters that characterize similarities of furnaces with various geometrical parameters. It is proportional to d^3 and does not depend on the furnace size. The results of statistical analysis of the ferrosilicon smelting process in the 20 MVA furnace have been presented. In addition to basic electrical parameters, such as active power and electrical load of the electrodes, factors contributing to higher resistance of the furnace bath and resulting lower reactive power P_x demonstrate the most significant effect on the electrothermal process of ferrosilicon smelting. These parameters reflect metallurgical conditions of ferrosilicon smelting, such as the reducer fraction, position of the electrodes and temperature conditions of the reaction zones.

Keywords: ferrosilicon, FeSi65, FeSi75, submerged arc furnace, active power of furnace, electric energy consumption

1. Introduction

Ferrosilicon smelting is a continuous process carried out in the submerged arc furnaces with the Søderberg self-baking electrodes [1-3]. Respectively granulated raw materials are charged into the furnace from the top, in the form of the mixture batch consisting of:

- quartzite,
- carbon reducers – hard coal, coke and wood chips,
- carriers of iron – mill scale or iron chips,

and CO and SiO gases flow through the bed towards the surface of the batch, overcoming the flow resistance [4-7]. Ones of the most important structural elements of the ferrosilicon furnaces are, immersed in the charge electrodes, which bring electricity required for the process. Most often these are self-baking Søderberg electrodes [2]. Necessary heat for the highly endothermic reduction reactions of silica is generated through resistive heating directly in the furnace charge as a result of current flow and through arc radiation in the arc gas chambers located near the electrode tips. Periodically, approximately at equal time intervals, molten metal is tapped into the ladle through one of the tap holes located in the side wall near the furnace hearth. Significant effects on the efficiency of the process are shown by metallurgical conditions of the reaction zones, particularly the appropriate balance of coal and heat distribution in the reaction zones.

Decisions relating to furnace control are mainly based on the electrical measurements but also on the process observations involving trends of electrodes movement, appearance of charge in the furnace bath, intensity of gas blowers, the course of metal tapping, etc.

In spite of modern computer systems for recording and visualization of measurement data, metallurgical parameters of the process are not directly measured. Still, these assessments are based to a large extent on intuition and experience of the operating staff of the furnaces, and have a qualitative and subjective character. This type of control and the lack of unambiguous criteria are the reasons of periodic disturbances of the process, and the associated losses.

Therefore, the working space inside the ferrosilicon furnace and reaction zones cannot be considered as the structure not changing over time. Depending on a number of technological factors, SiC walls thickness of the gas chambers might increase or decrease, or may even completely disappear. The internal structure of the furnace and temperature distribution in the reaction zones have a close relationship with the proportions of the heat generated in the furnace by resistance heating and by arc

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heating. The electric arc is one of the most unstable components of the electrical circuit in the ferrosilicon furnace and the heat distribution has a stochastic nature. With the stable running of the furnace, there are conditions for the continuous evolution of new products of the silica reduction. This is associated with periodic penetration of liquid silica and the charge lumps inside the arc chambers, and this process shows a cyclic nature. The transient dynamic properties of the ferrosilicon process can be observed on historical graphs over a sufficiently long period of time. The reason of the transient dynamic properties and the presence of waveform with very low frequency in measuring signals from the ferrosilicon process can be explained by slow

change of properties of raw materials defaulting on landfills as well as transient properties of the internal structure inside the furnace working space. The electric arc and temperature conditions of the ferrosilicon process have a direct relationship with the position of electrode tips in the furnace. Optimal position of the electrodes leads to minimization of economic indicators of the process. In the ferrosilicon submerged arc furnace, carbon electrodes burn out as a result of arc erosion and chemical reactions of silica reduction. In order to prevent shortening and maintain the correct electrical and temperature conditions of the process, periodical slipping of electrodes is necessary. This process usually takes place cyclically with the hydraulic system of electrode slipping. The feed electrodes is carried out at approximately equal intervals $\Delta t \approx 1$ h (hour) about 10 to 25 mm but the amount of movement depends mainly on the experience and intuition of the furnace staff. The effects of lack of the proper algorithm are that the position of the electrodes tips in the furnace is subject to change during the process. In extreme cases, the electrical arc may disappear due to too deep or too shallow position of electrode tips. The presence of the electric arc as a high temperature heat source is necessary to conduct highly endothermic reactions that take place in the arc gas chambers located near the electrode tips [8]:

$$\left.\begin{array}{l} 2SiO_2 + SiC = 3SiO(g) + CO(g) \\ SiC + SiO = 2Si + CO \\ SiO_2 + 2SiC = 3Si + 2CO(g) \end{array}\right\} \qquad (1)$$

The electrode position has also an impact on the temperature of the upper zones of the furnace where the condensation reaction of the gaseous SiO oxide takes place [8]:

$$SiO(g) + 2C = SiC + CO(g) \qquad (2)$$

Reaction (2) is exothermic and therefore, the condensing process of SiO promotes respectively deeper positioning of electrodes and a lower temperature of charge in the upper zone of the furnace. Reaction (2) can also occur in low-lying areas of the furnace with carbon charge, but also with the carbon of electrodes. Deficiency of coal in the reaction zones leads to increased wear of the electrodes. The statistical research on the ferrosilicon smelting process was carried out for about 192 days using the open 20 MVA submerged arc furnace with self-baking Søderberg electrodes of $d = 1.2$ m diameter.

2. Relation between the furnace active power load and electric energy consumption

Higher active power of a submerged arc furnace is commonly believed to increase its capacity. This is a true statement but only to a limited extent. It can be assumed that for a given electrode diameter d, there is a certain limit value of the submerged arc furnace active power. When this value is exceeded, the furnace capacity does not increase but the energy loss is higher and the technical and economic indicators become worse. Based on the theory of similarity, it has been determined that the active power of ferrosilicon-producing furnaces should be proportional to the electrode diameter in the exponential function 1/3 [3]. A similar relation has been determined with the use of statistical analysis for a population of ferrosilicon-producing furnaces with various geometrical parameters [2]:

$$d = 0.48344 \cdot P_R^{0.3257}, \text{ m} \qquad (3)$$

where: d – electrode diameter, m; P_R – active power, MW.

Based on this, it can be deduced that the maximum daily output for the furnace is proportional to the electrode diameter d in the exponential function 3, which is associated with the volumes of reaction zones surrounding the electrodes [3]. Thus, we can consider this parameter as one of similarity criteria for furnaces of various geometrical parameters. Its value has been determined based on industry data for the FeSi75 ferrosilicon smelting process in furnaces with 12 MVA transformers and electrodes with $d = 0.9$ m. At the beginning, these furnaces were operated using too high active power P_R in relation to the electrode diameter: higher than that resulting from the formula (3). The effects were unsatisfactory technical and economic indicators of the FeSi75 ferrosilicon smelting process but the maximum daily FeSi75 output was determined, $w = 20.94$ Mg. Based on this, the volume performance index for the reaction zones was calculated:

$$\frac{w}{3 \cdot 24 \cdot d^3} \cong 0.399 \frac{\text{Mg}}{\text{m}^3 \cdot \text{h}} \qquad (4)$$

where: w – daily output for the furnace, Mg; d – electrode diameter, m.

For a given electrode diameter d, based on (4), simple formulas can be determined for the maximum daily output w and the active power P_R concerning the submerged arc furnace with 3 electrodes in the process of FeSi75 smelting:

$$w = 3 \cdot 24 \cdot 0.399 \cdot d^3, \text{ Mg/24 h} \qquad (5)$$

$$P_R = 3 \cdot 0.399 \cdot E \cdot d^3, \text{ MW} \qquad (6)$$

The physico-chemical model [8] and industrial data [9] show that for a proper FeSi75 smelting process, the energy consumption indicator E should not exceed 8 MWh/Mg. By transforming (6), a formula similar to the statistical formula (3) can be obtained:

$$d = 0.47091 \cdot P_R^3, \text{ m} \qquad (7)$$

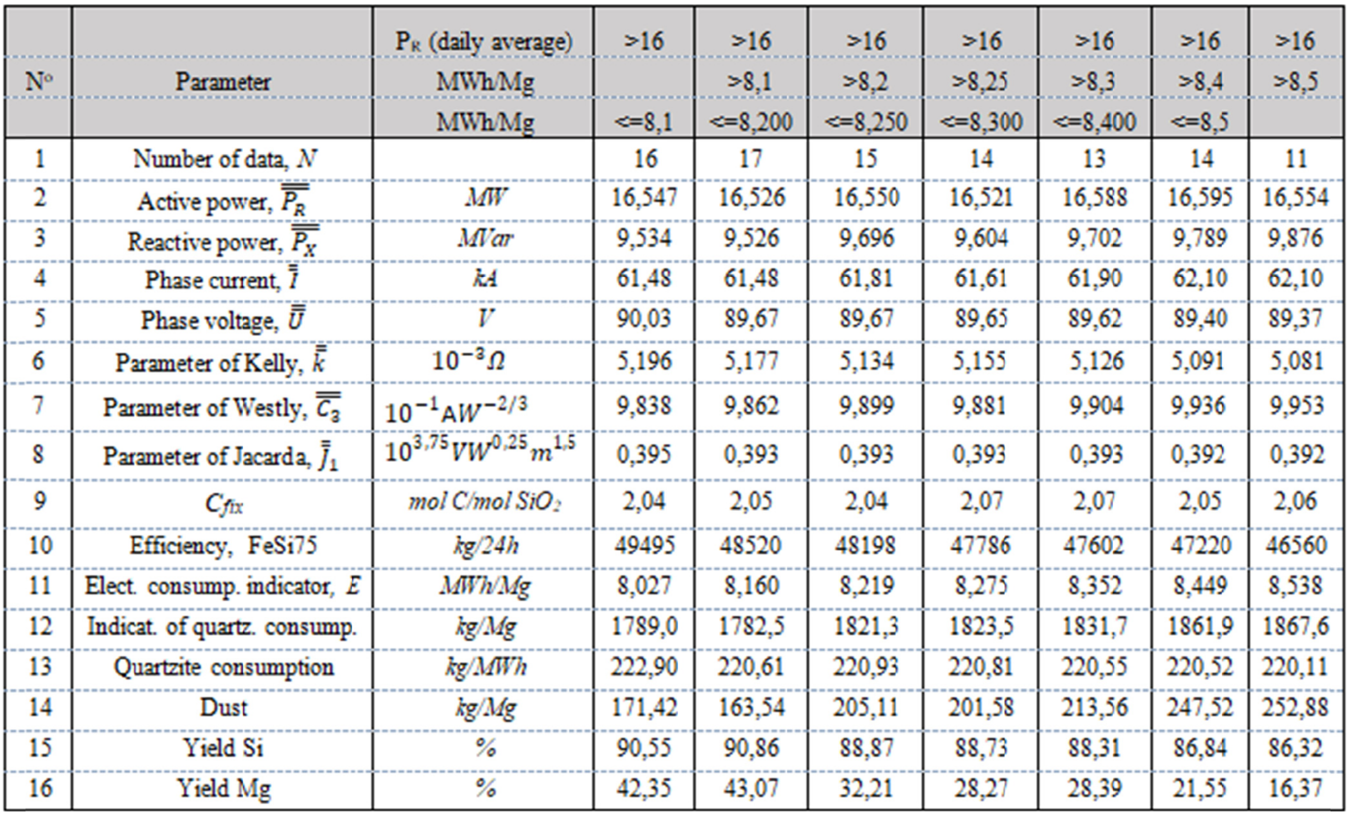
Formula (6) shows that for the furnace with electrodes of the diameter $d = 0.9$ m, the maximum output $w = 20.94$ t can be achieved with the minimum active power $P_R \approx 7.0$ MW. A higher power of the furnace does not influence its capacity but only results in an increased electricity consumption indicator. By analogy, for a furnace with the 20 *MVA* transformer and three electrodes of the diameter $d = 1.2$ m, the maximum daily output is $w = 49.64$ Mg. This can be achieved with the minimum active power $P_R \cong 16.6$ MW, which has been confirmed by statistical findings for ferrosilicon smelting in the 20 MVA furnace.

3. Statistical analysis of the ferrosilicon smelting process in the 20 MVA furnace with three electrodes of the diameter *d* = 1.2 m

In the analysis of FeSi75 ferrosilicon smelting process, data recorded in 2017-2018 by the measuring system of 20 MVA submerged arc furnace with open-hood and three Søderberg electrodes of diameter $d = 1.2$ m, symmetrically arranged at an equilateral triangle vertices, were applied. The statistical data were initially processed. To identify electrical parameters that significantly affect the process of ferrosilicon smelting, days with no idle periods, meeting specific requirements depending on the mass balance of Si and Fe, were considered. For the statistical analysis, database functions and statistical processing tools of Excel and *R* environment were used [10]. Typically, over a long period, electrical operating parameters of the ferrosilicon furnaces are stable and the charge mixture adjustment, connected with reducer presence, occurs at a low level. The statistical analysis of FeSi75 ferrosilicon smelting process involved the data covering $N = 192$ days. To eliminate stochastic disturbances, daily statistical data were grouped as per energy consumption indicator, and mean values of technological parameters were calculated for each group. Measurement data grouping, group sizes and mean values of the ferrosilicon smelting technological parameters are presented in Tables 1 and 2. The data refer to furnace operations periods with active power of ~16.5 MW and ~15.0 MW, respectively. The furnace system recorded electrical parameters every 1 minute and, therefore, the arithmetic means are based on $24 \times 60 = 1440$ measurements. The data regarding raw materials and energy consumption as well as the furnace capacity were recorded on the daily basis. This enabled identification of electrical parameters which, in addition to active power and current load of the electrodes, affect the efficiency of the ferrosilicon smelting process. Figures 1 to 3 demonstrate significant effects of the furnace reactive power P_X and the Andrea-Kelly parameter k [1-3] on the ferrosilicon smelting output. These parameters are strictly related to charge row material resistivity, the position of electrodes and temperature conditions of the reaction zones. Factors contributing to higher furnace bath resistance (a higher k value) and resulting lower reactive power P_X show a favourable effect on the process. Active power and phase currents are basic electrical parameters of

TABLE 1

Grouping and mean values of furnace parameters during the period of furnace operation with active power $P_R \approx 16.5$ MW, FeSi75, the 20 MVA furnace with 3 electrodes of d =1.2 m



N°	Parameter	P_R (daily average)	>16	>16	>16	>16	>16	>16	>16
		MWh/Mg		>8,1	>8,2	>8,25	>8,3	>8,4	>8,5
		MWh/Mg	<=8,1	<=8,200	<=8,250	<=8,300	<=8,400	<=8,5	
1	Number of data, N		16	17	15	14	13	14	11
2	Active power, $\overline{\overline{P_R}}$	MW	16,547	16,526	16,550	16,521	16,588	16,595	16,554
3	Reactive power, $\overline{\overline{P_X}}$	$MVar$	9,534	9,526	9,696	9,604	9,702	9,789	9,876
4	Phase current, $\bar{\bar{I}}$	kA	61,48	61,48	61,81	61,61	61,90	62,10	62,10
5	Phase voltage, $\bar{\bar{U}}$	V	90,03	89,67	89,67	89,65	89,62	89,40	89,37
6	Parameter of Kelly, $\bar{\bar{k}}$	$10^{-3}\Omega$	5,196	5,177	5,134	5,155	5,126	5,091	5,081
7	Parameter of Westly, $\overline{\overline{C_3}}$	$10^{-1}AW^{-2/3}$	9,838	9,862	9,899	9,881	9,904	9,936	9,953
8	Parameter of Jacarda, $\bar{\bar{J}}_1$	$10^{3,75}VW^{0,25}m^{1,5}$	0,395	0,393	0,393	0,393	0,393	0,392	0,392
9	C_{fix}	$mol\ C/mol\ SiO_2$	2,04	2,05	2,04	2,07	2,07	2,05	2,06
10	Efficiency, FeSi75	$kg/24h$	49495	48520	48198	47786	47602	47220	46560
11	Elect. consump. indicator, E	MWh/Mg	8,027	8,160	8,219	8,275	8,352	8,449	8,538
12	Indicat. of quartz. consump.	kg/Mg	1789,0	1782,5	1821,3	1823,5	1831,7	1861,9	1867,6
13	Quartzite consumption	kg/MWh	222,90	220,61	220,93	220,81	220,55	220,52	220,11
14	Dust	kg/Mg	171,42	163,54	205,11	201,58	213,56	247,52	252,88
15	Yield Si	%	90,55	90,86	88,87	88,73	88,31	86,84	86,32
16	Yield Mg	%	42,35	43,07	32,21	28,27	28,39	21,55	16,37

TABLE 2

Grouping and mean values of furnace parameters during the period of furnace operation with active power $P_R \approx 15.0$ MW, FeSi75, the 20 MVA furnace with 3 electrodes of $d = 1.2$ m

Nº	Parameter	P_R (daily average)	>16	>16	>16	>16	>16	>16	>16
		MWh/Mg		>8,1	>8,2	>8,25	>8,3	>8,4	>8,5
		MWh/Mg	<=8,1	<=8,200	<=8,250	<=8,300	<=8,400	<=8,5	
1	Number of data, N		15	14	15	14	14	6	13
2	Active power, $\overline{\overline{P_R}}$	MW	15,074	15,064	15,028	15,067	15,060	14,992	14,969
3	Reactive power, $\overline{\overline{P_X}}$	$MVar$	9,038	8,999	9,086	9,145	9,139	9,198	9,151
4	Phase current, $\overline{\overline{I}}$	kA	60,61	60,53	60,56	60,76	60,54	60,69	60,47
5	Phase voltage, $\overline{\overline{U}}$	V	83,41	83,44	83,37	83,32	83,75	83,11	83,30
6	Parameter of Kelly, $\overline{\overline{k}}$	$10^{-3}\Omega$	4,863	4,881	4,856	4,837	4,876	4,820	4,849
7	Parameter of Westly, $\overline{\overline{C_3}}$	$10^{-1}AW^{-2/3}$	10,332	10,323	10,347	10,363	10,319	10,392	10,363
8	Parameter of Jacarda, $\overline{\overline{j_1}}$	$10^{3,75}VW^{0,25}m^{1,5}$	0,357	0,357	0,357	0,357	0,359	0,355	0,356
9	C_{fix}	$mol\ C/mol\ SiO_2$	2,05	2,03	2,04	2,04	2,04	2,03	2,00
10	Efficiency, FeSi75	$kg/24h$	45361,3	44951,0	43948,0	43812,1	43267,1	42585,0	41874,7
11	Elect. consump. indicator, E	MWh/Mg	7,981	8,033	8,168	8,241	8,303	8,363	8,504
12	Indicat. of quartz. consump.	kg/Mg	1753,92	1773,10	1788,42	1788,02	1846,91	1838,63	1868,15
13	Quartzite consumption	kg/MWh	219,74	220,70	220,11	219,35	219,95	219,93	219,89
14	Dust	kg/Mg	132,29	172,49	165,02	164,03	230,75	226,76	263,51
15	Yield Si	%	92,15	90,15	90,38	90,83	87,53	87,95	86,02
16	Yield Mg	%	47,94	33,68	35,75	42,99	23,68	29,46	13,41

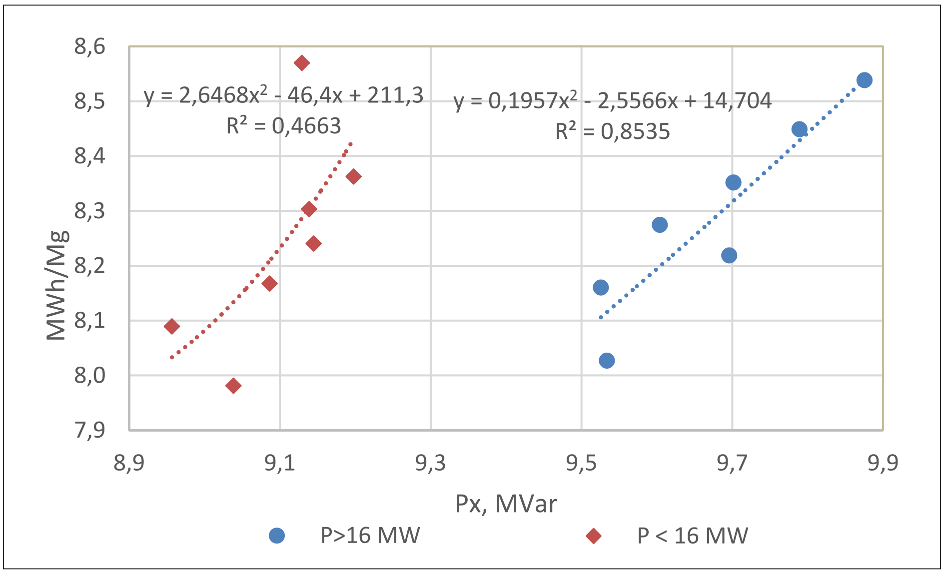


Fig. 1. Relations between mean reactive power P_x and the electricity consumption indicator E in the process of FeSi75 ferrosilicon smelting, determined based on Table 1 and Table 2 data for the furnace active power of, respectively, 16.5 and 15.0 MW

the submerged arc furnace in the ferrosilicon smelting process and they are controlled by the automated electrode load control system. They are maintained at the pre-defined level despite disturbances of the power system and other disturbances during the ferrosilicon smelting process that are not directly measured. These disturbances are related to raw material supplying, uneven melting and placement of charge material in the furnace bath, gas blows, metal tapping etc. Temperature conditions of the reaction zones are strongly influenced by the fraction of carbon C_{fix} in the charge mixture, chemical and physical properties of reducers as well as position of the electrode tips in the furnace and resulting distribution of heat, generated due to current flow, in the furnace working space. In addition, position of the electrodes in the furnace depends on their 'burning out' and slipping

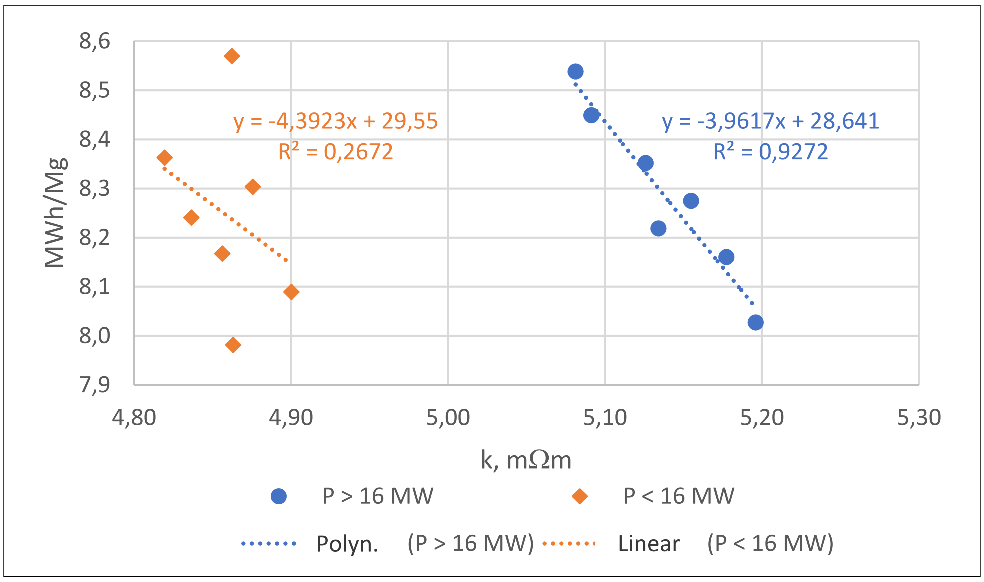


Fig. 2. Relations between the *k* parameter and the electricity consumption indicator *E* in the process of FeSi75 ferrosilicon smelting, determined based on Table 1 and Table 2 data for the furnace active power of, respectively, 16.5 and 15.0 MW

process. Alterations of reducer fraction in the charge mixture as well as uncontrolled changes of the chemical composition and physical properties of reducers (conductivity, granulation) affect the furnace bath resistance and resulting reactive power alterations. Therefore, reactive power reflects metallurgical conditions of the process, such as the carbon balance, position of electrodes and temperature conditions of the reaction zones. In addition to the electrode position, observation of reactive power by the furnace operators is one of the most important signals for decisions regarding adjustment of the reducer fraction in the charge mixture.

"Sensitivity" of reactive power to the metallurgical conditions of ferrosilicon smelting process is confirmed by regression formulas determined for the whole set of statistical data regarding $N = 192$ days of the 20 MVA furnace operations based on daily mean values:

$$W = 3311.012 \cdot P_R - 692.326 \cdot P_X, \text{ kg} \qquad (8)$$
$$R^2 = 0.9996$$

$$E = 0.98275P_R - 0.10775P_R P_X + 0.09889P_x^2, \text{ MWh/Mg} \qquad (9)$$
$$R^2 = 0.9995$$

Factors contributing to higher resistance of the furnace bath (a higher *k* value) and resulting lower reactive power P_x show

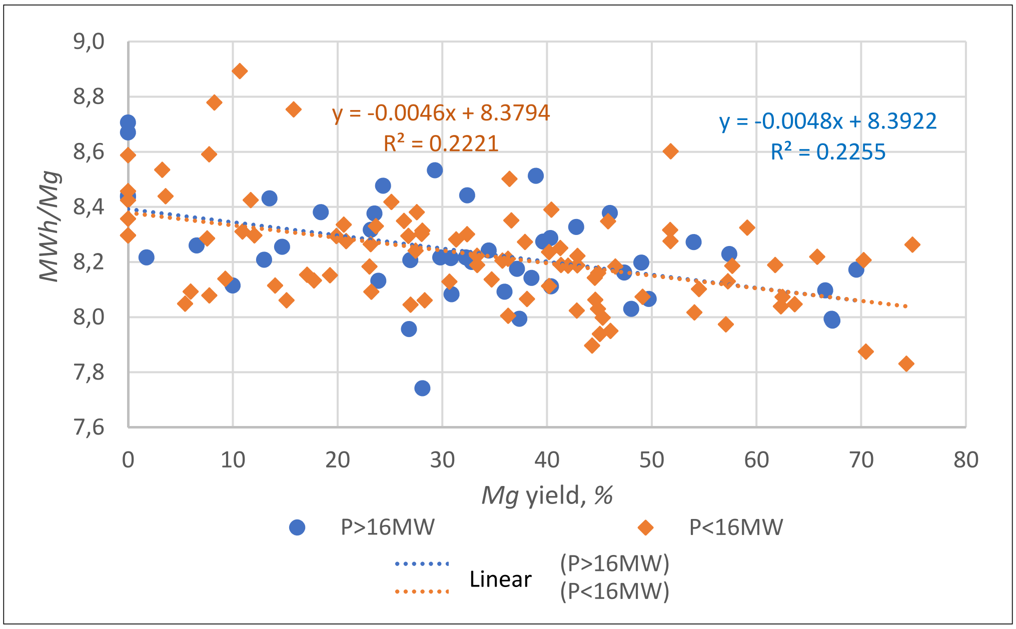


Fig. 3. Relation between magnesium yield and the electricity consumption indicator in the FeSi75 ferrosilicon smelting process, determined based on the population of $N = 191$ days of 20 MVA furnace operation with the power of 16.5 and 15.0 MW

a favourable effect on the process, which is demonstrated by deeper electrode positions and better conditions of the condensation reaction (2) of gaseous SiO in the upper zones of the furnace. Similarly to the SiO condensation process, lower temperatures of the upper zones result in better condensation of magnesium vapours, which is confirmed in Fig. 3. Due to high magnesium vapour pressures, this element is very sensitive to temperature conditions in the reaction zones. Too high temperatures of the furnace upper reaction zones result in a small Mg yield in the metal.

4. Summary

For a given electrode diameter *d*, there is a certain limit value of the submerged arc furnace active power. When this value is exceeded, the furnace capacity in the process of ferrosilicon smelting does not increase but the energy loss is higher and the technical and economic indicators become worse. The statistical analysis shows that, in addition to basic electrical parameters (e.g. active power and electrical load of the electrodes), the ferrosilicon smelting output is significantly influenced by such parameters as the furnace reactive power and bath resistance. These parameters are strictly related to the position of electrodes and temperature conditions in the reaction zones. Factors contributing to higher resistance of the furnace bath (a higher *k* value) and resulting lower reactive power show a favourable effect on the process. These parameters can be used in algorithms of controlling metallurgical process conditions, such as balancing the amounts of carbon in the reaction zones and identification of electrode tip positions. A proper process of FeSi75 ferrosilicon smelting in the submerged arc furnace can result in the electricity consumption indicator of 8 MWh/Mg.

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REFERENCES

[1] A. Schei, J.K. Tuset, H. Tveit, Production of High Silicon Alloys. Trondheim: Tapir (1998).

[2] V.L. Zubov, M.I. Gasik, Electrometallurgy of Ferrosilicon. Physical Chemistry and Technology. Dnenpropetrovsk: System Technologies Publ. (2002) (rus).

[3] B.M. Struński, Rasczety rudo-termiczeskich pieczi. Izdatielstwo Metallurgia, Moskwa (1982).

[4] M. Gasik, [red.]: Handbook of Ferroalloys Theory and Technology. Waltham: Elsevier Ltd. (Butterworth-Heinemann), (2013).

[5] B. Panic, Influence of the bed type on the flow resistance change during the two-phase (gas plus powder) flow through the descending packed bed. Archives of Metallurgy and Materials **59** (2), 795-800 (2014).

[6] O.S. Klevan, Removal of C and SiC from Si and FeSi during ladle refining and solidification. PhD Thesis. Trondheim: The Norwegian University of Science and Technology, Department of Metallurgy, 1997.

[7] T. Merder, J. Pieprzyca, M. Warzecha, P. Warzecha, Application of high flow rate gas in the process of argon blowing through steel. Archives of Metallurgy and Materials **62** (2), 905-910 (2017).

[8] B. Machulec, S. Gil, W. Bialik, Equilibrium model of the ferrosiliucon process in the submerged arc furnace. 27th International Conference on Metallurgy and Materials, METAL 2018, Conference Proceedings, Brno, Czech Republic, 122-127 (2018).

[9] D. Senapati, E.V.S. Uma Maheswar, C.R. Ray, Ferro silicon operation at IMFA – a critical analysis. International Ferro-Alloys Congress Infacon XI, New Delhi, India, 371-380 (2007).

[10] M. Golewski, Programowanie w języku R. Analiza danych, obliczenia, symulacje, Warszawa: PWN, 2016.