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Bolesław Machulec, Wojciech Bialik

THERMAL AND ELECTRICAL SIMILARITY OF REACTION ZONES IN THE FERROSILICON SUBMERGED ARC FURNACES

Due to various electrical properties and diverse mechanisms of heat generation, differences in current characteristics for the upper and lower zones of the ferrosilicon furnace are observed. These differences are neglected in similarity criteria by Andreae and Struński-Westly (k, c_3), applied in theory and practice for a long time for ferrosilicon smelting processes. It has been demonstrated that the parameter c_3 is useful for determination of current characteristics concerning the furnace upper zones where heat is directly generated in the charge material due to resistance heating. It cannot be used for assessment of thermal conditions in gas chambers of the arc where heat is generated as a result of radiation from the arc. For determination of current characteristics of gas chambers, Jaccard's parameter J_1 is suitable. Do date, it has not been widely used in theory and practice of ferrosilicon smelting. The paper controverts the opinion of Jaccard who negates usefulness of the parameter c_3 for selection of electrical parameters with respect to ferrosilicon furnaces. The parameter c_3 characterises thermal and electrical similarity of the ferrosilicon furnace upper zones while the parameter J_1 refers to thermal and electrical conditions of the arc gas chambers.

Key words: *ferrosilicon, submerged arc furnace, reaction zones, parameter c_3, parameter J_1*

1. Introduction. Electrodes submerged in the charge material, which mediate electrical current delivery to the working space of the ferrosilicon furnace, belong to one of the most important its internal structural components [1-3]. Electrodes form the reaction zones the size of which depend on their diameter. These are areas of current flow, heat generation and continuous charge movement. Considering the mechanism of heat generation in physicochemical and electrical models of a ferrosilicon furnace bath, two zones are distinguished (Fig. 1): the charge zone (zone 1) where heat is generated due to resistance heating and the area within the arc chamber (zone 2) where heat is a result of arc heating. Relations between geometric, electrical and thermal parameters of the ferrosilicon furnace reaction zones are complex and difficult to determine. Therefore, the electrical parameters of furnaces are assessed based on the theory of physical similarity [4] as well as on data obtained for the furnaces of good production results.

In almost all publications, selection of ferrosilicon furnace electrical parameters is based on the electrical and thermal similarity criteria k, c_3 by Andrea and Struński-Westly [1-3, 5]:

$$k = R\pi d,\ \Omega \cdot m \tag{2}$$

$$c_3 = I \cdot P_u^{-2/3},\ A \cdot W^{-2/3} \tag{3}$$

where:

R - furnace resistance, Ω,

d - electrode diameter, m

P_u - furnace useful active power, W, $P_u = P_a \cdot \eta$,

P_a - furnace active power, W,

η - coefficient for the furnace electrical efficiency related to loss due to heavy current line resistance, $\eta \cong 0.90 \div 0.95$ [5]

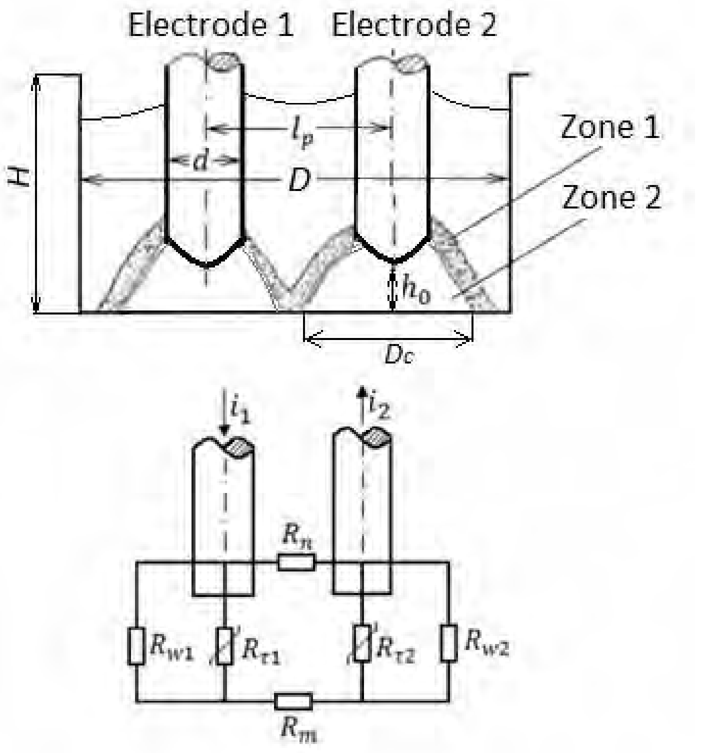

Fig. 1. Cross-section of two electrodes in the ferrosilicon furnace working space and the equivalent circuit of a furnace section [5,6]

Symbols:

Zone 1 - resistance heating zone,
Zone 2 - arc heating zone,
d, D, l_p, h_0 - geometric parameters of the furnace bath,
D_C - diameter of the arc gas chamber,
i_1, i_2 - phase currents,
R_{w1}, R_{w2} - equivalent resistances in the path of current flow through the charge,
$R_{\tau 1}$, $R_{\tau 2}$ - arc resistances,
R_n, R_m - equivalent resistances for the current flow between the electrodes through the charge material and the liquid metal bath, respectively.

Published in 1976, Westly's equation [7] gained recognition and is applied in practice. It was determined by means of statistical analysis using a relatively large collection of furnaces with various power levels and experimentally established optimal electrical parameters. An analogical equation had been published earlier in 1972 by Struński [5] based on laboratory investigations using an electrolytic model of a furnace. Similarity criteria k, c_3 apply to the whole working space of the furnace and neglect significant differences in current flow conditions as well as mechanisms of heat generation in zones 1 and 2. In zone 1, heat is mainly generated due to resistance heating directly in the charge material. With small amounts of liquid phase, convective heat transfer is limited and thermal conductivity of the charge material in the furnace is small whereby there is no conditions for equalization of temperature. At a given point of the reaction zone, temperature is mostly determined by volume power density q_{γ} and thermodynamic processes related to the course of chemical reactions. Different conditions are observed in zones where heat is generated as a result of arc radiation. In the arc gas chambers, heat transfer is mainly driven by radiation and convection. Therefore, to meet condition (1), different thermal similarity criteria for the upper and lower reaction zones of the ferrosilicon furnace are required (Fig. 1):

Zone 1:

$$q_V = const \tag{4}$$

Zone 2:

$$q_S = const \tag{5}$$

where:

q_V - volume power density in the reaction zones of furnaces, W/m^3,

q_S - power density at the electrode cross-section, W/m^2

2. Criteria of thermal and electrical similarity in zone 1. Assuming the electrode diameter *d* as the linear value and using the principles of geometric similarity [4], equations (2), (4) can be applied to determine useful active power of the electrode, P_{1u}, by means of volume power density q_V, as follows:

$$P_{1u} = \frac{1}{C_1} \cdot k_{1L}^3 \cdot q_V \cdot d^3 = \frac{1}{C_1} \cdot k_{1L}^3 \cdot q_V \cdot \left(\frac{k}{\pi \cdot R}\right)^3 \tag{6}$$

where:

C_1 – fraction of energy generated due to current flow in zone 1, directly in the charge material, $0 < C_1 < 1$,$q_1 = C_1 \cdot P_{1u}$,W,

q_1 – heat flux generated in zone 1 ,W,

k_{1L} – geometric similarity criterion.

Equation (6) can be used to obtain:

$$R = a \cdot P_{1u}^{-1/3}, \text{ - bath resistance, } \Omega \tag{7}$$

$$I = (P_{1u}/R)^{1/2} = b \cdot P_{1u}^{2/3} \text{ - phase current, } A, \tag{8}$$

$$U = I \cdot R = c \cdot P_{1u}^{1/3} \text{ - phase voltage, V} \tag{9}$$

where:

$a = \frac{k_{1L}}{\pi \cdot C_1^{1/3}} \cdot k \cdot q_V^{1/3}$,$\Omega \cdot W^{1/3}$

$b = a^{-1/2}$, $A \cdot W^{-2/3}$

$c = a^{1/2}$,$V \cdot W^{-1/3}$

Constants a, b, c characterise thermal and electrical similarity of the charge zones (zones 1) of ferrosilicon furnaces with various geometrical parameters. It should be noted that Westly’s equation (3) directly results from the equation (8) when the electrode load symmetry is assumed,

$$P_{1u} = P_u/3, W.$$

In practice, a useful parameter that characterises thermal properties of ferrosilicon furnace reaction zones is current density at the electrode cross-section j. Based on the equations (2), (7), (8), the following can be obtained:

$$j = \frac{4I}{\pi \cdot d^2} = \frac{4\pi \cdot a^{3/2}}{k^2} ,A/m^2 \tag{10}$$

The operating active power of the furnace should be adjusted to the electrode diameter d. This relation can be determined based on the equations (6), as follows:

$$d = A_1 \cdot P_a^{\frac{1}{3}} \tag{11}$$

where:

$$A_1 = \frac{1}{k_{1L}} \left(\frac{C_1 \eta}{3 q_V}\right)^{1/3} \text{ - constant, } m \cdot W^{-1/3}$$

This is confirmed by a statistical relation in the form of a regression equation [2]:

$$d = 4{,}8344 \cdot P_a^{0.3257} ,10^{-3} m \tag{12}$$

Assuming the electrode diameter d as the base value, other geometric parameters of the furnace *L* can be determined with the use of geometric similarity criteria k_L :

$$L = k_{1L} \cdot A_1 \cdot P_a^{1/3} \tag{13}$$

In practice, for selection of electrical parameters of submerged arc furnaces, the following equation is widely used [9]:

$$U = cP_u^n \text{ ,} V \tag{14}$$

where:

c – a constant typical of a given technological process, $V \cdot W^{-1/n}$

n – an exponent.

According to equation (9), the exponent value for non-slag processes (FeSi, FeSiCr) is $n = 1/3$. For slag processes (FeCr, FeSiMn), its value amounts to $n = 1/4$. This is related to the effect of slag on equalization of temperature in zones 1 as a result of convection.

3. Thermal and electrical similarity criteria in zone 2. In the arc gas chambers, heat is generated due to arc radiation. Moreover, there are different current flow conditions than those in zones 1. Current flow occurs in plasma [13] and heat is transferred into the gas chamber mainly due to arc radiation as well as, to a lesser extent, convection. According to Newton's law [14], heat transferred by means of radiation and convection is proportional to the heat-emitting surface. Thus, surface power density (5) should be assumed so that temperature conditions in the gas chambers of arcs in furnaces with various geometrical parameters meet the similarity criterion (1). Therefore, the useful active power P_{1u} can be expressed using the power density at the electrode cross-section q_S, as follows:

$$P_{1u} = \frac{1}{C_2} \cdot k_{2L}^2 \cdot q_S \cdot d^2 \text{ ,} W \tag{15}$$

The following equation results from the (15):

$$d = \left(\frac{C_2}{q_S}\right)^{1/2} \cdot {P_{1u}}^{1/2} \text{ ,} m \tag{16}$$

where:

k_{2L} - geometric similarity criterion.

C_2 - fraction of power generated in zone 2 due to arc radiation,

$$q_2 = C_2 \cdot P_{1u}, \quad W$$

$$C_1 + C_2 = 1$$

Electrical properties of the arc gas chamber are different from those of the charge material in zones 1 or in the electrolytic model of furnace bath by Struński [5]. Thus, the arc resistance R_{arc} does not meet Andreae's equation (2) or the equation (3) by Struński-Westly. To determine electrical arc resistance R_{arc}, it was assumed that electrical conductivity of a high-power arc is an approximately linear temperature function [13]. Assuming that the arc temperature is proportional to the power density at the electrode cross-section q_S, conductance and resistivity of the arc can be determined as follows:

$$\sigma_{arc} = D' \cdot \frac{P_{1u}}{d^2} \text{ ,} S/m \tag{17}$$

$$\rho_{arc} = \frac{1}{\sigma_{arc}} = D \cdot \frac{d^2}{P_{1u}} \text{ ,} \Omega \cdot m \tag{18}$$

where:

$$D \text{ - constant, } \Omega \cdot W/m$$

$$D' = 1/D, \; S \cdot m/W$$

Applying dimensionless scales of geometric similarity based on the equations (16), (18), the following can be expressed:

$$\frac{U^2}{P_{1u}} = R_{arc} = \frac{\rho_{arc} \cdot h_0}{S_{arc}} \overset{(18)}{\triangleq} \frac{D}{k_{2L}} \cdot \frac{d^2}{P_{1u} \cdot d} \overset{(16)}{\triangleq} \frac{D \cdot \left(\frac{c_2}{q_S}\right)^{-1/2}}{k_{2L} \cdot P_{1u}} \cdot d^2 \cdot P_{1u}{}^{-1/2}$$

This results in:

$$U = J_0 \cdot d \cdot P_{1a}^{-1/4} \text{ ,} V \tag{19}$$

where:

$$J_0 = \eta^4 \left(\frac{D' \cdot (c_2/q_S)^{1/2}}{k_{2L}}\right)^{1/2} \text{ ,} V \cdot W^{\frac{1}{4}}/m$$

Moreover, based on the equations (11), (13), (16), the following is obtained:

$$d \cdot \sqrt{l_p} = A_1 \cdot P_a^{\frac{1}{3}} \cdot \left(k_{2L} \cdot A_1 \cdot P_a^{\frac{1}{3}}\right)^{\frac{1}{2}} \overset{(16)}{\triangleq} \sqrt{3} \cdot k_{2L}^{1/2} A_1^{\frac{3}{2}} \cdot \left(\frac{c_2}{\eta \cdot q_S}\right)^{1/2} \cdot d$$

and based on the (19),

$$U = J_1 \cdot d\sqrt{l_p} \cdot P_{1a}^{-1/4} \tag{20}$$

where:

$$J_1 = \frac{J_0}{\sqrt{3} \cdot A_1 A_2^{1/2} \cdot \eta^{1/2} \cdot k_{2L} \cdot q_S^{1/2}} \text{ ,} V \cdot W^{1/4}/m^{3/2}$$

The parameters J_0, J_1 determine conditions of thermal and electrical similarity in the arc gas chambers; the same parameter for zones 1 is c_3 by Struński-Westly. The parameters J_0, J_1 were proposed by Luis R. Jaccard, instead of Westly's parameter c_3 [11, 12]. In his publications, Jaccard negates usefulness of the parameter c_3 for selection of electrical parameters in submerged arc furnaces, which also applies to ferrosilicon furnaces. He came to this conclusion while observing submerged arc furnaces intended for cassiterite smelting [11]. This process markedly differs from ferrosilicon smelting but Jaccard's concept and point of view can be applied to the arc gas chambers. Like for criteria (5), he assumes that to ensure proper temperature conditions of reaction zones, the phase active power P_{1a} should be proportional to the surface of reaction zone with the diameter D_c (Fig. 1).

4. Current characteristics and heat balancing in reaction zones. Adequate fractions of heat fluxes q_1, q_2, generated due to flow of current in the upper and lower reactions zones, should be in accordance with the heat balance of physical and chemical processes that occur there under conditions ensuring maximum efficiency of the reduction process and the highest *Si* yield. The furnace active power and fractions of heat fluxes q_1, q_2, generated due to current flow, should be adjusted to its geometrical parameters as well as to physical and chemical processes that occur in reaction zones. Important factors are electrical parameters of the furnace and electrode positions. Proper thermal and temperature conditions of reaction zones have a significant effect on the process efficiency as well as its technical and economical indicators.

Current characteristics for the upper and lower reaction zones in the ferrosilicon furnace differ due to various electrical properties of zones 1 and 2 as well as diverse mechanisms of heat generation. Characteristics for the upper zones of ferrosilicon furnace can be determined by means of the parameter c_3 and the equation (3) by Struński-Westly, as follows:

$$P_a = \frac{1}{\eta} \cdot \left(\frac{I}{c_3}\right)^{3/2} \text{, } W \tag{21}$$

In a similar manner current characteristics for the lower reaction zones can be determined by means of the parameter J_1 and the equation (20) by Luis R. Jaccard:

$$P_a = 3 \cdot \left(I \cdot J_1 \cdot d \cdot \sqrt{l_p}\right)^{4/5},\ W \tag{22}$$

Sample current characteristics for the upper and lower reaction zones of the 20 MVA ferrosilicon furnace are presented in Fig. 2. To determine similarity criteria, averaged values of technological furnace parameters were used with respect to its adequately selected "perfect" operation periods when average daily electrical energy consumption amounted to approximately 8.000 MWh/t (Table 1). Amounts of heat generated in the upper and lower reaction zones are balanced at the intersection point of both characteristics lines (Fig. 2). For the investigated furnace, this corresponds to the following electrical parameters (I^*, P_a^*): $I^* \cong 63.0\ kA$, $P_a^* \cong 16.7\ MW$. According to Westly's theory [8], these parameters correspond to the balance of heat fluxes q_1, q_2 generated within the furnace working space, which means optimal thermal and temperature conditions of the physical and chemical processes in the reaction zones. In practice, there is an occasional need to operate furnace at $P_a \neq P_a^*$. In this case, the thermal balance between reaction zones in the ferrosilicon furnace is not possible. This may apply to e.g. power limitations during energy "peak load" hours ($P_a < P_a^*$) or when the electrode diameter is too small in relation to the power of transformer and the furnace operates at too high power values ($P_a > P_a^*$). In both cases, during selection of the furnace electrical parameters, current characteristics that ensure more beneficial temperature conditions for condensation of gaseous oxide *SiO* in the upper zone charge material under given conditions are recommended [1-3,10]. This means characteristics that correspond to a lower active power of the furnace under given conditions. Fig. 2 shows that these are Westly's characteristic (21) for $P_a < P_a^*$ and Jaccard's characteristic (22) for $P_a > P_a^*$. The present paper controverts the opinion of Jaccard [11,12] who negates usefulness of the parameter c_3 for selection of electrical parameters for the ferrosilicon submerged arc furnaces. This may only refer to cases when the operating active power of the furnace is too high for its geometric parameters ($P_a > P_a^*$). In industry practice, such cases are quite rare and may only concern furnaces of old design and improperly selected geometrical parameters.

5. Summary. For given geometric parameters of the furnace, optimal temperature conditions of the reaction zones depend on strictly defined electrical parameters. This means optimal electrode positions in the furnace and minimisation of raw material and energy consumption indicators. Due to various electrical properties and diverse mechanisms of heat generation, differences in current characteristics for the upper and lower reaction zones of the ferrosilicon furnace are observed. Westly's parameter c_3 is useful for determination of current characteristics concerning the furnace upper zones where heat is directly generated in the charge material due to resistance heating, while Jaccard's parameter J_1 is suitable for determination of current characteristics in reactions zones where heat generation is a result of arc radiation. The parameters c_3 i J_1 characterise similarity of thermal and electrical conditions of the reaction zones. This means that for furnaces of various geometric parameters, the c_3 and J_1 values should be approximately equal to adequate values for a "model" furnace that features good production results. This conclusion is opposite to Jaccard's opinion who entirely negates usefulness of Westly's parameter c_3 for the ferrosilicon smelting process.

Table 1

Technical data and averaged parameter values during “perfect” operation periods of a 20 MVA FeSi75 ferrosilicon smelting furnace

Parameter	**Unit**	**Data**
1	2	3
Geometruc parameters		
Electrode diameter, d	m	1,2
Electrode spacing, l_p	m	2,685
High of the bath, H	m	2,5
Electrical parameters		
Active power, P_a	MW	16,669
Ppower factor, $cos\phi$		0,849
Electrical efficiency, η		0,94
Phase voltage, U	V	88,357
Phase current, I	kA	62,939
Daily energy consumption	MWh	400,07
Production results		
Daily metal output (pure), w	t/24h	49,537
Volume indicater, $w/(3 \cdot 24 \cdot d^3)$	t/(m^{3}h)	0,398
Electricity consumption index, E	MWh/t	8,079
Similarity criteria		
Current density, $j = 4 \cdot I/(\pi \cdot d^2)$	10^4A/m^2	5,565
Volume power density, P_{1u}/d^3	MW/m^3	3,020
Furnace resistance, $R = P_{1u}/I^2$	$10^{-3}\Omega$	1,317
Parameter Andrea, $k = R \cdot \pi \cdot d$	$10^{-3}\Omega$m	4,966
Parameter Westly, $c_3 = I \cdot P_u^{-2/3}$	10^{-1}AW$^{-2/3}$	10,058
Parametr*, $J_0 = U \cdot P_{1a}^{0,25}/d$	$10^{2,75} VW^{1/4}/m$	6,357
Parametr*, $J_1 = U \cdot {P_{1a}}^{0,25}/(d \cdot l^{0,5})$	$10^{3,75} VW^{1/4}/m^{1,5}$	0,388
Zużycie surowców:		
Daily quartzite consumption, Q	kg/24h	85736
Quartzite consumption index	kg/t	1730,8
Quatrzite consumption per 1MWh	kg/MWh	214,3
Quartzite stream index, Q/(3*24*d^3)	kg/(m^{3}h)	689,1
Si yield	%	94,44

* J_0, J_1 - applied units proposed by Luis R. Jaccard [11,12], (V, kV, cm)

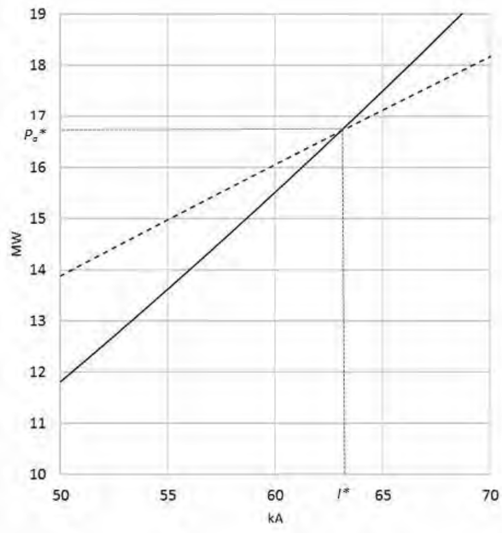

Fig. 2. Current characteristics for the upper and lower reaction zones of a 20 MVA ferrosilicon furnace with electrodes of diameters $d = 1.2\ m$. The continuous line – Westly’s characteristics (zone 1), dashed line - Jaccard’s characteristics (zone 2). Values of the parameters c_3, J_1 are presented in Table 1, $(I^* \cong 63\ kA,\ P_a^* \cong 16.7\ MW)$.

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