Discussion of Ideal Smelting Model of Submerged-Arc Furnace

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ABSTRACT

Starting from the equivalent circuit and heat distribution in a submerged-arc furnace, it is proposed that an optimum heat distribution exists between the reaction area and furnace charge area. Based on this proposition, a simple smelting model of the submerged-arc furnace is set up. The model is constituted by the hemispherical reaction area, whose bottom is the molten metal surface (or conductive furnace bottom), the furnace charge area, whose length is electrode spacing, and the effective charge sectional area is S'. The model's rationality is briefly discussed. Subsequently, the mathematical formulae for the model's parameters are derived, e.g., pitch circle diameter, secondary current, effective depth of hearth, electrode diameter and operating resistance. The relationship between the parameter coefficient in Westly's experimental calculation and the charge physico-chemical properties obtained by simplification of the model's formulae is also derived. This simplification is achieved by further derivation of the physical significance of the analogy number in the "Analogy Method". Finally, the directive function of the smelting model in the production is also introduced.

Keywords: Reaction model, ore smelting, electric arc furnace, and parameters.

1. PREFACE

Along with the fast development of ferroalloy metallurgical techniques, ferroalloy electric arc furnaces have developed into large-scale, closed, computer-controlled production units. How to calculate exactly the parameters that fit production practices is very important. Among the three calculation methods available – Andreae's "Periphery Resistance" (the "K-factor" method), Westly's experimental calculation, and Miculinsky and Stlunsky's method – Westly's method has widespread application. The result of calculations based on Westly's method approach practical experience. However, how to determine the parameter coefficients that are used for the calculation process is the key to calculation exactitude. Starting from an analysis of equivalent electrical circuit and heat distribution, i.e., power distribution, this paper proposes that for the same product, the same metallurgical technique and the same charge conditions, i.e., physico-chemical properties and size distribution, there is on optimum power distribution relationship between the reaction area and furnace charge area. Based on this proposition: the mathematical expressions for electric furnace's main parameters are derived, the physical significance of analogy number in "Analogy Method" is defined, and the operating resistance coefficient and current coefficient in Westly's calculation are derived. This information provides the basis for future research on the relationship between furnace parameters and charge properties for both the design and the operation of the submerged-arc furnace.

2. THE ANALYSIS OF HEAT DISTRIBUTION IN A SUBMERGED-ARC FURNACE

The equivalent electric circuit between electrodes, the furnace bottom, and between electrodes is shown in Figure 1 [2].

In view of macrography, for a three-phase, three-electrode submerged-arc furnace, the electric circuit of the furnace can be summed-up by "star" and "triangular" circuits. The "star" circuit is the "star resistance, Rr" and is made up by each electrode bottom, electrode and furnace walls, the charge and furnace bottom (i.e. molten metal). For the "triangular" circuit, the changeable resistance of the charge between two electrodes is called the "triangular resistance, Rc". The two circuits are parallel, consequently, the operating resistance is: $R = \dfrac{R_c \cdot R_r}{R_c + R_r}$

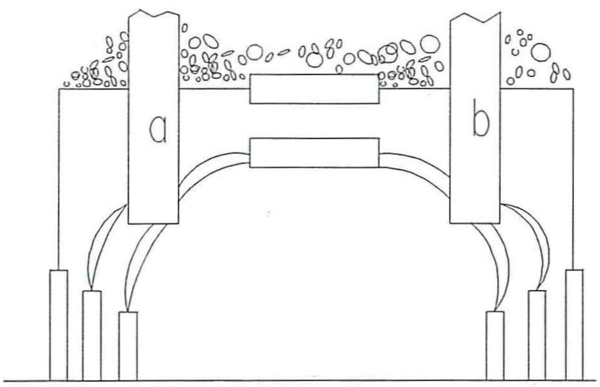

Figure 1. The Equivalent Electric Circuit of Submerged-Arc Furnace

Therefore, we may simply divide the furnace into two areas: furnace charge area with resistance Rc, and reaction area with resistance Rr. The charge resistance generates heat that smelts the charge, subsequently, the drops of smelted metal drip into reaction area where reduction is completed.

As two parallel circuits make up the smelting circuit, there is the problem of energy distribution between the two circuits. Consequently, the concept of the "Coefficient of Charge Heat Distribution, C_1" is put forward,

$Q_L =$ $C_1 \times Q_T$ (or $P_L = C_1 \times P_R$)

in which,

$C_1 =$ the coefficient of charge heat distribution, and is related to the physico-chemical property of the charge and the reaction activity of the reaction agents;
$Q_L =$ the heat received by the non-smelting charge area;
$Q_T =$ the total heat received by the furnace;
$P_L =$ the power consumed by the non-smelting charge area;
$P_R =$ the total active power consumed by the furnace.

From the electric fundamentals, we may write,

$R =$ C_1 x R_L

in which,

$R =$ Operating resistance;
$R_L =$ Charge resistance in the non-smelting charge area.

For every charge distribution, for the metallurgical techniques used to produce a particular ferroalloy, there is an optimum coefficient of charge heat distribution (C_1). For furnace operation with an optimum coefficient of charge heat distribution, the charge smelting rate is equal to the reduction rate. If the input electric energy is over-consumed during smelting of the charge, the results are: faster smelting rate, lower temperature in the reaction area, more slag and less product, lumps appear in the furnace, electrodes must be raised, increased charge surface, incomplete reduction, and increased main element content in the slag. On the other hand, if charge smelting goes too slowly, the results are: overheated product, high volatilization loss of useful elements, higher electric power consumption per ton of ferroalloy produced, reduced furnace productivity, a smaller reaction area, and an overheated and faster eroded furnace bottom.

According to reference [3], the fundamental premise for the furnace heat distribution is the separation between reaction area and furnace charge area.

In the ferrosilicon electric arc furnace, separation between reaction area and furnace charge area is maintained by the formation of a hearth at the electrode tip. If charge enters the hearth too frequently, only slag, not metal, is created.

For a production process with slag, the coke layer separates the slag from the non-smelting charge. It is very important to control thickness of the coke layer by the use of a suitably sized coke. If the coke is too small and/or the coke layer is too thin, it is difficult to maintain stable furnace operation because it is difficult to separate the reaction area from charge area. Conversely, too large a coke size leads to lower operating resistance, higher furnace temperatures and higher electric power consumption.

3. THE SMELTING MODEL OF A SUBMERGED-ARC FURNACE

3.1 Determination of the Geometric Shape for the Reaction and Furnace Charge Areas

The principle used to determine the geometric shape for the reaction area and the furnace charge areas is to take a certain isotherm as the separation line.

3.1.1 Temperature Distribution in the Submerged-arc Furnace

The charge-temperature distribution of an 11.5 MVA uncovered furnace when smelting silicon-chromium alloy; see Figure 2 [4]. In Figure 2, the shape of the isotherms is similar to the electric lines of force between electrodes, and the distribution of the isotherms is identical to that of the isopotential lines of the electric field. In the central part of the electric field the isotherms are closer together which indicates that the charge properties are different to the charge properties of the surrounding materials. In the non-slag hearth, with little heat convection and low heat conduction, the temperature of hearth's edge, 1900°C, can be assumed as the separation line.

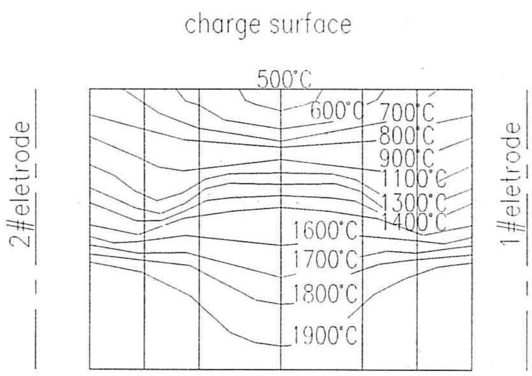

Figure 2. The Charge-Temperature Distribution of an 11.5 MVA
Silicon-Chromium Furnace

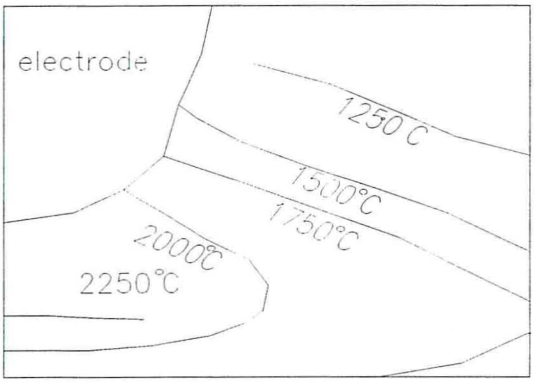

Figure 3. The Charge-Temperature Distribution of a 24 MVA
Ferrochromium-Iron Furnace

The charge-temperature distribution of a 24 MVA closed furnace when smelting ferrochromium-iron; see Figure 3.

According to reference [6], when carbon is used as reduction agent, Cr_3C_2 and Cr_7C_3 are formed at temperatures of 1096°C and 1130°C, respectively. However, net chromium begins to form at a temperature of 1775°C. From the charge temperature distribution shown in Figure 3, the 1250°C isotherm may be taken as the separation line.

From above two furnaces' charge-heat distributions, we may see that if we take a certain isothermal as the separation line between the reaction area and the charge area, then the shape of reaction area is similar to that of a hemispherical body. However, in practice, the shape of charge area is more complicated, and may differ from one furnace product to another.

3.1.2 Determination of the Geometric Shape for the Reaction Area

Ideally, the reaction area should have a large volume and small heat-radiation area; i.e., should be spherical. So the shape of the reaction area of the model may be assumed to be hemispherical, with the bottom of the hemisphere at the surface of either the smelting metal or the conductive furnace bottom; see Figure 4.

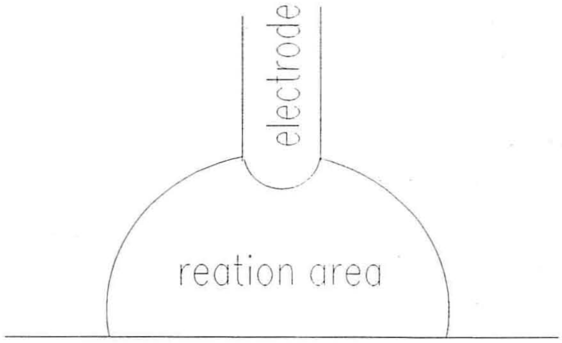

Figure 4. Schematic Diagram of the Reaction Area

The volume of the reaction area is given by the equation,

$$V_1 = \frac{\pi}{12}\left(D^3 - ad^3\right)$$

in which,

D = the diameter of bottom area;
d = the diameter of the electrode;
α = coefficient which reflects the shape of electrode tip,
(when the electrode tip is hemispherical, α = 1.0)

3.1.3 Determination of the Geometric Shape for Furnace Charge Area

The shape of the furnace charge area is more complicated. However the active volume of the furnace hearth may be assumed to be a geometrical body with critical dimensions related to the reaction area's bottom and the active depth of the hearth (H.) For a three-electrode furnace, the volume of the furnace charge area is given by the equation,

(4) $$V_L = 3 \times H \times \frac{D^2\pi}{4} - \frac{\pi D^3}{4}$$

N.B., This equation neglects the volume of the electrode that enters the charge area.

For convenience's sake, it is assumed that the charge area is represented by a geometrical body with length "L" and an active area "S'" where,

L = the horizontal distance between two electrodes;

S' = charge section active area which is vertical to electrode central line,

i.e., exclusive of "dead" charge area.

Because the electrical resistance between the electrode surface and the furnace wall belongs to the triangular circuit, it is neglected.

3.2 Power Distribution of Reaction Area and Furnace Charge Area

3.2.1 Derivation of the Mathematical Formula for Pitch Circle Diameter

For each smelting process there is an optimum power density in the reaction area. On the one hand, to a certain extent, the power density value determines the working pattern, i.e., "resistance" or "arc". On the other hand, the power density value determines the temperature distribution in reaction area. For a three-electrode furnace, the power density equation in the reaction area is,

(5) $$P_{VT} = \frac{P_f}{3V_1}$$

in which,

P_{VT} = the power density in the reaction area;

P_f = is the active power in the reaction area,

i.e., $P_f = P_R \cdot (1-C_1)$.

Substitution of equation (3) into equation (5) gives the following equation,

(6) $$D = [\frac{4(1-C_1)}{\pi P_{VT}} \cdot P_R + \alpha \cdot d^3]^{1/3}$$

According to Stlunsky's theory, the diameter of the bottom circle of the reaction area is equal to the pitch circle diameter. Only in this manner can the total charge surface (including the central part between the three-electrodes) become the active area. Otherwise, the central part of the charge will become a "dead" area and furnace production capacity will decrease. Consequently, equation (6) can be considered as the equation for the pitch circle diameter.

3.2.2 Derivation of the Mathematical Formula for the Secondary Current

The mathematical expression for the power density for three-electrode furnace charge area is given by the equation,

(7) $$P_V = \frac{P_L}{3V}$$

in which,

P_v = the power density of charge area;

P_L = is the active power consumed in

charge area,

i.e., $P_L = C_1 \cdot P_R$,

V = the volume of the charge area segment which constitutes the triangular electric resistance, i.e.,

V = $S' \cdot L$

The charge resistance between two electrodes in the charge area is given by the following equation,

(10) $$R'_L = \rho' \cdot \frac{L}{S'}$$

in which,

ρ' = the active specific resistance in charge area.

Using equations (7), (8), (9) and (10), we may derive the following equation,

(11) $$R'_L = \rho' \cdot \frac{3L^2 P_V}{C_1 P_R}$$

$$R_L = \frac{1}{3} R'_l$$

where, R'_L is the resistance of the triangular circuit, and its equivalent star resistance is given by,

$R = C_1 \cdot R_L$.

Knowing, $P_R = I^2_2 \cdot R$, and using equation (11), we may obtain equation (12),

$$I_2 = \frac{P_R}{L}\sqrt{\frac{1}{\rho' P_V}}$$

(12)

Because we know, $D \cdot \frac{\sqrt{3}}{2} = L + d$, (8) equation (12) may be rewritten,

(13) $$I_2 = \frac{P_R (\rho' P_V)^{-1/2}}{\frac{\sqrt{3}}{2}\left[\frac{4(1-C_1)}{\pi P_{VT}} P_R + 2d^3\right]^{1/3} - d}$$ (9)

3.2.3 Derivation of the Mathematical Formula for Active Hearth Depth

P_R = {Volume of reaction area × P_{VT}} + {Volume of charge area × P_V}

Neglecting effects due to electrode size, for a three-electrode furnace, from equations (3) and (6) we may obtain,

$$V_T = \frac{\pi}{4} D^3$$

$$D = \left[\frac{4(1 - C_1)}{\pi P_{VT}} P_V\right]^{1/3}$$

Substitution of the above two equations and equation (4) into equation (14), gives equation (15):

(15) $$H = \left(\frac{4}{27\pi}\right)^{1/3} \cdot \left[\left(\frac{1-C_1}{P_{VT}}\right)^{1/3} + \frac{C_1}{P_V} \cdot \left(\frac{P_{VT}}{1-C_1}\right)^{2/3}\right] \cdot P_R^{1/3}$$

3.2.4 Derivation of the Mathematical Formula for Electrode Diameter

The conductive coefficient is constant when the shape is hemispherical, and the resistance, with an homogeneous medium and infinitely great size,

$$R = \frac{\rho}{\pi d}$$

may be expressed by the equation [8],

in which,

ρ = the specific resistance of the homogeneous medium;
d = the diameter of the hemisphere.

The resistance of the reaction area for submerged-arc furnace can also be expressed by above equation. Considering that in practice, the size of reaction area is not infinitely great and the medium is not homogeneous, only the electrode tip approximates to a hemisphere. Consequently, it is necessary to invoke a "revising coefficient", k [9],

$$R_f = \frac{k}{\pi d}$$

$$R = (1 - C_1)R_f = (1 - C_1)\frac{k}{\pi d}$$

consdering $R = \frac{P_R}{I_2^2}$, *can get* :

(16) $$d = \frac{(1 - C_1)kI_2^2}{\pi P_R}$$

3.2.5 Derivation of the Mathematical Formula for Operating Resistance

From the equation $R = \frac{P_R}{I_2^2}$ and equation (12), we may derive the following equation (17) for operating resistance,

$$R = \frac{\left(\frac{\sqrt{3}}{2}\sqrt[3]{\frac{4(1-C_1)}{\pi P_{VT}}\cdot P_R + \alpha d^3} - d\right)^2 \rho' P_V}{P_R} \quad (17)$$

4. DISCUSSION

4.1 The Relationship between the Mathematical Formulae for Model Parameters and the Experimental Formulae

4.1.1 The Mathematical Formula of the Parameter Coefficient in Westly's Experimental Calculation

From the equation for pitch circle diameter, equation (6), if the electrode volume entering the reaction area is neglected, the equation may be simplified as follows,

$$D = [4(1 - C_1)/\pi P_{VT}]^{1/3} P_R^{1/3} \quad (18)$$

When neglecting the effect of electrode radius to the distance between electrode surfaces, i.e., $\frac{\sqrt{3}}{2}.D = L$, the equation for secondary current may be simplified to give,

(19) $$I_2 = \frac{2}{(3\rho' P_V)^{1/2} \cdot \left[\frac{4(1 - C_1)}{\pi P_{VT}}\right]^{1/3}} \cdot P_R^{2/3}$$

The resultant simplified equations for electrode diameter and operating resistance are,

(20) $$d = \frac{[4(1 - C_1)]^{1/3} \cdot K \cdot (\pi P_{VT})^{2/3}}{3\pi\rho' P_V} \cdot P_R^{1/3}$$

(21) $$R = \left[\frac{(3\rho' P_V)^{1/2} \cdot \left[\frac{4(1 - C_1)}{\pi P_{VT}}\right]^{1/3}}{2}\right]^2 \cdot P_R^{-1/3}$$

Using equations (19) and (20), we may obtain,

$$K^2 \cdot j = \frac{2(3\rho' P_V)^{3/2}}{P_{VT}(1 - C_1)} \qquad (22)$$

From above simplified equations we may obtain the relationship of each parameter coefficient and charge physico-chemical property in Westly's experimental calculation.

4.1.2 The Physical Significance of Analog Number in the "Analogy Method"

From equation (12) and the relationship $P_R = \sqrt{3} I_2 V_2$ we may derive the following equation,

$$\frac{U_2}{L} = \left(\frac{\rho' P_V}{3}\right)^{1/2} \qquad (23)$$

In equation (23), ρ' is related to the quantity, size and temperature distribution of the furnace charge. The concept behind the entity ρ' is the same concept as that behind the "analogy number" and the ratio of fixed carbon quantity to the metal. In fact, because the concept behind the entity ρ' is judged to be more comprehensive than the concept behind the "analogy number", it is judged that equation (23) reflects the physical significance of furnace behavior more specifically and more exactly than the "analogy number."

4.2 The Application of the Model to Production Practices

The Elkem Metals Company has presented an analysis of data for the Current Coefficient, C_L, for fifty six 75% ferrosilicon electric arc furnaces. The analysis shows the following phenomena: the average, maximum and minimum values of C_L are 10.80, 13.60, and 8.20, respectively; when using charcoal and a great quantity of wood the value of C_L tends to a minimum; when using hard coke the value of C_L tends to a maximum; when high quality quartz is used C_L tends to decrease; and when using less pure quartz, which contains more Al_2O_3 and CaO, C_L tends to increase.

To address the above phenomena, using equation (19) derived above, we may make some analyses.

The Current Coefficient, C_L, is defined as follows,

$$C_L = \frac{2}{(3\rho' P_V)^{1/2}\left[\frac{4(1 - C_1)}{\pi P_{VT}}\right]^{1/3}} \qquad (24)$$

According to equation (24), when operation is at the optimum state C_L is fixed and R_T is related to the ferroalloy produced, Therefore, $C_L \propto \frac{1}{P_V^{1/2} \cdot \rho^{1/2}}$, i.e. C_L is inversely proportional to the square root of the charge specific resistance. The smelting temperature for high purity quartz is higher than the temperature for less pure quartz, which contains Al_2O_3 and CaO, i.e., the P_v value for high purity quartz is larger. In other words, this latter analysis, based on the relationships developed in this paper, is in agreement with the data presented by Elkem.

Table 1 presents operating parameters and indices for a plant with a 12.5 MVA electric arc furnace, producing carbon ferrochromium-iron, with a pitch circle diameter from 2.50 meters to 2.65 meters.

Table 1. Comparison of Operating Parameters and Indices after changing Pitch Circle Diameter for a 12.5 MVA Carbon Ferrochromium-Iron Furnace

Pitch Circle Diameter	P_s	COSφ	η	P_R	I_2	U_2	Electric Consumption	Rate of Recovery	Coke Consumption	Coke Size	Grade of Ore
(m)	(kVA)	(-)	(-)	(kW)	(A)	(V)	(kWh/t)	(%)	(kg/t)	(mm)	(%)
2.5	11,600	0.90	0.84	8,769.6	45,000	149	2,734	93.35	354	5 – 25	44.46
2.65	12,300	0.91	0.86	9,626	45,000	158	3,210	90.60	434	5 - 40	42.50

In a second plant, with a 25 MVA electric furnace, also producing carbon ferrochromium-iron, after changing the secondary voltage from 225 volts to 210 volts – to obtain improved furnace operating indices – the coke size was changed from a 25-40 mm distribution to a 30-50 mm distribution.

Common to both of the preceding examples, for both the 12.5 MVA furnace and the 25 MVA furnace, when a particular operating parameter was changed, to guarantee a constant heat distribution coefficient C_1, thus obtaining fine operating indices, the common practice was to adjust the charge resistance.

Reference [11].also showed that by appropriately changing charge resistance, one was able to obtain

$$D=\left[\frac{4(1-C_1)}{\pi P_{VT}}\cdot P_R+\alpha\cdot d^3\right]^{1/3}$$

$$I_2=\frac{P_R\left(\frac{1}{\rho' P_V}\right)^{1/2}}{\frac{\sqrt{3}}{2}D-d}$$

$$d=(1-C_1)KP_R/\pi\rho' P_V\left(\frac{\sqrt{3}}{2}D-d\right)^2$$

$$R=\frac{\rho' P_V}{P_R}\left(\frac{\sqrt{3}}{2}D-d\right)^2$$

good operating indices. The equations derived in this paper expound the same way.

5. CONCLUSIONS

5.1 The model of submerged-arc furnace is made up of: a hemispherical reaction area; a furnace charge area of length L, where L is defined as the horizontal distance between two electrodes; and an active area, s'. First order analyses proved the rationality of the model, and the following mathematical equations for related parameters were derived,

The physical significance of analogy number in "Analogy Method" was deduced, i.e.,

$$\varphi=\frac{U_2}{L}\propto\rho'^{1/2}\cdot P_V^{1/2}$$

5.2 When neglecting the effect of the electrode diameter on a particular parameter to be calculated, the model presented in this paper may be used both to derive an expresion for the parameter coefficient in Westly's experimental calculation and to calculate the charge physico-chemical properties,

$$C_J \propto (1-C_1)^{1/3} \cdot P_{VT}^{-1/3}$$

$$C_L \propto (\rho' P_V)^{-1/2} \cdot (1-C_1)^{-1/3} \cdot P_{VT}^{1/3}$$

$$C_T \propto \left[4-\alpha C_1^3 \pi (P_{VT}-P_V)\right] \cdot P_V^{-1} \cdot C_1^{-2}$$

$$K^2 j \propto (\rho' P_V)^{3/2} \cdot \frac{1}{P_{VT}(1-C_1)}$$

$$C_{CZ} \propto \rho' P_V (1-C_1)^{2/3} \cdot P_{VT}^{2/3}$$

When charge physico-chemical properties change, the above relationships may be used to estimate and to adjust operating parameter's to obtain both fine operating indices and exact design parameters.

REFERENCES

1. "Discussion on Parameter Calculation Method of Submerged-Arc Furnace", Li Jingchun, Ferroalloy, 1996, (5), 1.

2. "Submerged-Arc Furnace", Stlunsky, p54.

3. "The Main Parameters for Design and Operation of Submerged-Arc Furnace", Translator, Di Wei, Ferroalloy, 1978, (1-2), 41

4. "Submerged-Arc Furnace", Stlunsky, p33.

5. "The Effect of the Quality of Ore to Furnace Charge and Ferrochromium Smelting", Heikki Tuovinen, Ferroalloy, 1980 (Supplement), 35.

6. "Ferroalloy Production Technique", Chief Editor: Zhou Jinhua, Science Publishing House, Beijing, 1991, p 344.

7. "Submerged-Arc Furnace", Stlunsky, p18.

8. "Discussion on Parameter's Calculation Method of Submerged-Arc Furnace", Li Jinchun, Ferroalloy, 1996, (5), 2.

9. "Discussion on Parameter Calculation Method of Submerged-Arc Furnace", Li Jingchun, Ferroalloy, 1996, (5), 2.

10. "The Main Parameters for Design and Operation of Submerged-Arc Furnace", Translator, Di Wei, Ferroalloy, 1978, (1-2), 37.

11. "Discussion on the Relationship of the Charge Specific Resistance and Power Factor and Electric Efficiency of Electric Furnace", Xiao Qianheng, Ferroalloy, 1979 (1), 24.