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OPTIMIZATION OF THE REFRACTORY LINING FOR FERROMANGANESE PRODUCTION FURNACE

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ABSTRACT

The methods of decreasing the lining corrosion rate by controlling the temperature mode are analyzed. It is shown that selection of a proper combination of refractory material layers would allow a noticeable decreasing the lining corrosion rate at interaction with liquid metal, but this also would increase heat losses due to convective and radiation heat transfer. A proper algorithm is suggested to reach the optimal solution by optimization of the lining layer thickness and composition.

KEYWORDS: furnace, lining, thermal mode, temperature distribution, ferromanganese, corrosion

INTRODUCTION

Medium- and low-carbon ferromangaese is produced by the silicothermal process in ore reduction electric furnaces by reducing manganese from low-phosphorus slags by ferrosilicomanganese applying a three-stage scheme: manganese concentrate dephosphoration; smelting of processed silicomanganese; smelting of ferromanganese or metallic manganese [1–3]. According to the Ukrainian standard (DSTU 3547–97), ferromanganese, depending on the grade, has the following composition: 85–95 % Mn, <0.2 or <2.0 % C, <1.8 or < 3.0 % Si, <0.07 or <0.40 % P. Electric furnaces for smelting of such ferromanganese (Figure 1) have a magnesite lining, which is expected to provide a sufficiently long-term resistance to corrosion from molten Mn–Si–Fe ferroalloy and MnO–SiO_2–CaO slag [1–4]. The corrosion and destruction of a magnesite lining may be very significant if the slag has an elevated content of alkali metals (NA_2O + K_2O). These additives are used in the process in order to decrease the slag viscosity, especially at low temperatures, but their negative effect on the lining resistance can be much greater than the expected advantage due to control of the slag viscosity [5].

An improvement in the lining resistance can be solved by changing its composition (replacement of refractory materials by other), which changes the total thermal resistance of the heat insulating layer depending on the combination of thermal conductivity and layer geometry.

In [6], the temperature along the central axis of the furnace was calculated and the potential ability for reducing the lining corrosion rate was shown. The temperature distribution was estimated for a dense magnesite lining and when replacing a part of the lower layer with a magnesium-carbon brick having higher thermal conductivity. The idea consisted in reducing the temperature of the upper layer to its level close to the liquidus temperature of the ferro-alloy of the known composition and accordingly to delayering of the kinetics of the reaction of metal components with magnesite. The end results mentioned in [6] prove the potential ability for almost 5 times increase in the lining resistance, but due to greater heat losses. A significant disadvantage of these calculations is the inconsistency of parameters. They did not present any specific data on the heat flux, and the values of parameters differ between the text and figures. Our attempts to reproduce these results by using the same lining composition and geometry for such limiting conditions were not successful. In order to check these calculations and develop a justified concept of furnace lining, in this research the disadvantages of the method [6] were analyzed and the algorithm for evaluating the thermal parameters of lining of the furnace for smelting a middle and low-carbon ferromanganese.

FURNACE MODEL AND COMPLIANCE WITH PARAMETERS

The first model of electric furnace for smelting of a medium-carbon ferromanganese was taken from [6] with parameters (Table 1), to which the main values of properties of refractory materials were added [3, 7, 8]. Other parameters were the same as in [6], except for those (the same materials or temperature) that differed beteen each other. Some of the mentioned values were optimized in [6] but without explanation of the exact way how it was done, which does not allow checking the calculations properly.

An additional analysis was conducted to justify the main variable parameters of the furnace thermal mode. The casing-air heat transfer coefficient α_c was taken into account as the function of the casing tem-

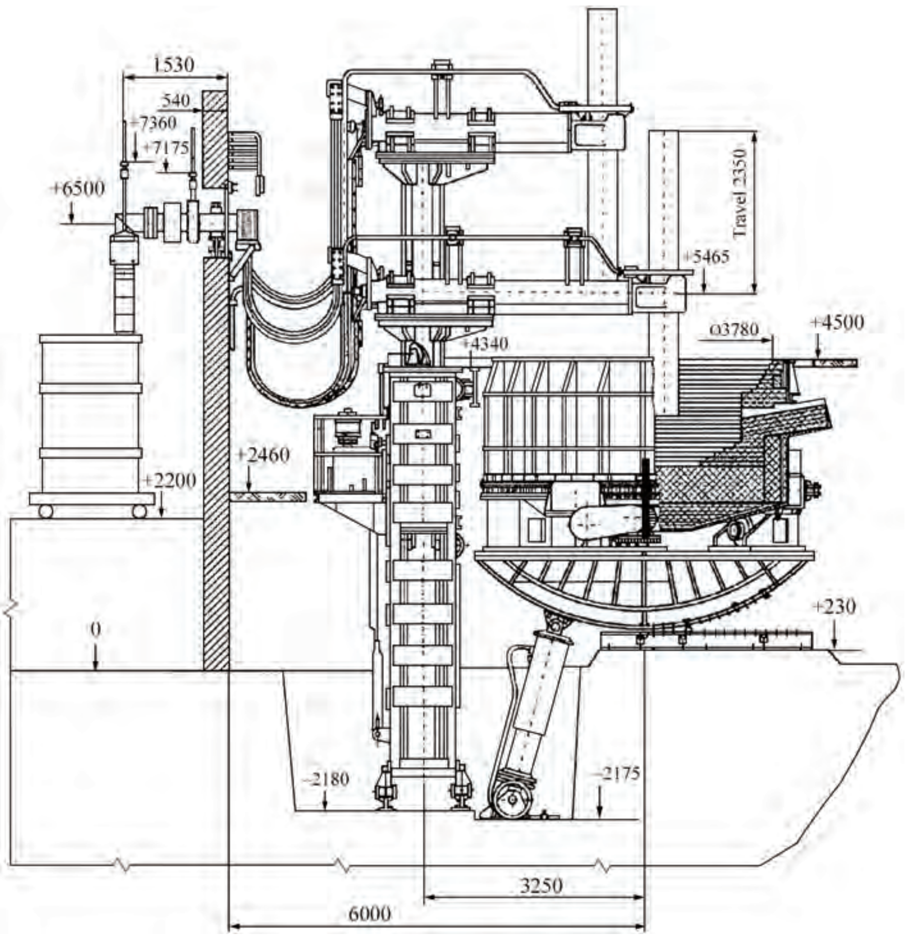

Figure 1. Typical furnace for smelting ferromanganese by silicothermal process [1, 3, 4]

perature $\alpha_c = 7.7743 + 0.0061t_c$ including natural convection and radiation heat exchange [8]. The overall Fourier metal-environment (air) heat transfer equation has the following appearance:

$$q = \frac{t_m - t_0}{\dfrac{1}{\alpha_m} + R_{th} + \dfrac{1}{\alpha_c}}; \quad R_{th} = \sum \frac{H_i}{\lambda_i}, \qquad (1)$$

where q is the total heat flux through the lining along the central axis; t_m and t_0 are the temperatures of metal and surrounding air (~ 30 °C), respectively; α_m and α_c are the metal-lining and casing-air heat transfer coefficients, respectively; R_{th} is the total thermal resistance of the lining; H_i is the height of each lining layer; λ_i is the thermal conductivity of the layer material. To check the results [6], the total heat flux (1) can be evaluated according to data of Table 1: $q = (t_m - t_{cm})\cdot\alpha_m$ = (1350–1262)·18 = 1584 W/m^2, which is a constant at a stationary furnace operation. However, according to [6], for the magnesite height H = 0.585 m at its thermal conductivity λ = 10 W/m·K, the heat flux (1)

Table 1. Parameters of furnace and lining

Index	Work [6]*	Data of [3, 7, 8] and this work
Thermal conductivity of materials, W/m·K:		
● magnesite-carbon brick	25	25
● sintered magnesite	5 (Figure 4), 10, 11 (Text)	10
● sintered dolomite	–	5.8
● fireclay brick	–	1.2
Temperature across the central axis of furnace, °C:		
● outer casing (t_c)	196 (Figure 3), 150 (Text)	Variable
● casing in contact with metal (t_{cm})	1262 (Figure 3)	–»–
● metal melt (t_m)	1350	1350
● metal liquidus (80 % Mn, 0.80 % Si)	1180	1180
Other parameters, W/m^2·K:		
● metal–casing heat transfer (α_m)	18	Depends on the Nusselt number
● casing-air heat transfer (α_c)	–	Depends on the temperature
*In [6], for the same parameters different data in the figures and in the text are shown.		

should be equal to $q = (t_{cm} - t_c)/(H/\lambda) = (1262–196)/(0.585/10) = 18220$ W/m², i.e. almost 10 times higher than the value based on $\alpha_m = 18$ W/m²·K. If the value $q = 18220$ W/m² is considered correct, then the metal-lining heat transfer coefficient α_m should be equal to ~207 and not 18 W/m²·K. At such a high heat flux and the casing temperature $t_c = 196$ °C, the heat transfer coefficient α_c should be ~103 W/m²·K, which is impossible in the case of natural convection and radiation [8]. For a lower heat flux of 1584 W/m², the thermal resistance of magnesite should be (1262–196)/1584 = 0.673 m²·K /W, which at the magnesite layer height $H = 0.585$ m [6] corresponds to its effective thermal conductivity $\lambda = 0.585 /0.673 = 0.87$ W/m·K. This is much lower than the values 5 and 10–11 W/m·K given in [6] and lower than the data 4–5 W/m·K in the reference book [8]. Accepting the thermal conductivity of magnesite being $\lambda \sim 5$ W/m·K, this leads to the non-physical values of the heat exchange coefficients and the much higher casing temperature for the same lining geometry. Thus, data of [6] are inconsistent and prevent the correct evaluation of the furnace lining thermal mode.

CALCULATION OF TEMPERATURE MODE

To obtain the correct values of the furnace thermal mode, in this work at first the parameters were taken, the values of which are undoubted: metal temperature, lining geometry and thermal conductivity of refractory materials (Table 1). The thermal flux should be self-consistent with the known heat transfer coefficients, so at the above heat flux of ~1584 W/m², the furnace-environment heat transfer coefficient α_c will amount to ~9.54 W/m²·K, which is closer to 8.97 W/m²·K (at $t_c = 196$ °C) for natural convection with a radiation component according to [8]. In this case, the metal-lining heat transfer coefficient α_m is really closer to 18 than to 207 W/m²·K. However, at $\alpha_c \sim 10$ W/m²·K and $\alpha_m \sim 18$ W/m²·K, it is impossible to obtain the same temperatures as given in [6] if a part of a magnesite lining ($\lambda = 5$ W/m·K) is replaced by magnesium and carbon ($\lambda = 25$ W/m·K). This leads to either non-physical values of heat flux and heat transfer coefficients, or temperatures.

Thus, the correct method for calculation of lining properties and structure should be based on the self-consistent initial conditions (metal and casing temperature, thermal conductivity of refractory materials, correct heat transfer coefficients). Heat transfer coefficients can be changed if the free surface of the casing is exposed to forced convection with compressed air or water.

EVALUATION OF CORROSION RESISTANCE OF LINING

It is known that resistance of a dense lining in contact with the molten metal can be estimated through its chemical degradation, since the contribution of the infiltration component is much smaller. For a porous lining, the situation can be inverse, where infiltration with the liquid metal reaches lower horizons [3, 6, 9]. Using a method similar to that taken in [6], the rate of chemical degradation of the lining (v, cm/h) during its contact with a middle-carbon ferromanganese can be estimated as follows:

$$v = 0.332\,\mathrm{Re}^{1/2}\,\mathrm{Sc}^{1/3}\left(\frac{D_i}{L}\right)\frac{\rho_{\mathrm{Me}}}{\rho_{\mathrm{MgO}}}\left(\frac{100}{\%\,x}\right), \qquad (2)$$

where Re is the Reynolds number [6, 8] for the motion (convection) of metal near the bottom-plate; Sc is the Schmidt number [6, 8]; D_i is the diffusion coefficient of active mental components (in this case mostly for silicon); L is the characteristic length of the furnace; ρ_{Me} is the density of metal at a temperature t_m; ρ_{MgO} is the lining density (magnesite); % x is the magnesite fraction that can be dissolved by metal (taken in 5 %). Choosing the value of the parameters, it can be evaluated that the expected corrosion rate of magnesite (2) at $t_{xm} = 1262$ °C (the temperature at the lower point of the bottom-plate in contact with metal) will amount to ~0.275 cm/h at 0.80 % Si in the ferromanganese. A significant decrease in corrosion can be achieved by reducing the contact temperature of metal to the liquidus line (~1180 °C for ferromaganese 85 % Mn, 1 % C, 0.80 % Si) when diffusion processes and kinetics of the reactions is slowing down.

The task consists in finding such a combination of layers of refractory materials that would provide the temperature of the highest magnesite layer of 1180 °C, when the lining corrosion will be calculated at ~0.20 cm/h (approximately 30 % lower) under other identical conditions. This can be reached by two lining zones made of fireclay and magnesite/dolomite (Table 2). At the lining temperature being 1180 °C and metal being 1350 °C, the expected heat flux will be (1350–1180)·18 = 3060 W/m², which is ~2 times higher than in the initial case for the temperature $t_{cm} = 1262$ °C (Table 1), but ~ 5 times lower than in the lining of magnesium and carbon material according to [6]. The results of the calculations are shown in Table 2 (it should be noted that for the furnace (Figure 1), the total lining height is greater than in [6].

Thus, it can be stated that the results of [6] are unbalanced and have differences between the data in figures and in the text. Replacement of a refractory material with another having a higher thermal conductivity (by 3–5 times) can never lead to a lower casing temperature at an elevated heat flux. It is probable that in the experiments of [6], an intense forced cooling of the casing was used for the furnace, but this was not shown clearly.

The overall optimization algorithm for the lining can be used in a rather simple way: the temperature of the upper layer of the lining should be maintained close to the liqui-

Table 2. Lining parameters in different variants

Index	Work [6]		Data of this work	
Height of layers of materials, m:				
● sintered magnesite	0.585	0.285	0.983	–
● sintered dolomite	–	–	–	0.906
● magnesium-carbon brick	–	0.30	–	–
● fireclay brick	–	–	0.067	0.144
Temperature across the central axis of the furnace, °C:				
● outer casing (t_c)	196	950*	340	
● casing in contact with metal (t_{cm})	1262	1180	1180	

*Calculated by the heat transfer equation (1); in [6] 150 °C is shown.

dus temperature of the metal, which will allow delayering the rate of corrosion processes regardless of their mechanisms [6, 9]. Based on the known temperature of the metal, its liquidus temperature and heat transfer coefficients, the total heat flux is first estimated through the lining and the corresponding thermal resistance and the casing temperature, then the combination of layers of refractory materials is calculated, which will be optimal for these conditions. If the casing temperature is higher than the optimum, forced cooling can be attracted and the possibility of efficient disposal of thermal losses can be evaluated.

CONCLUSIONS

1. The thermal mode of the furnace for ferromanganese production is important not only for the melting process, but also for the lining stability. The corrosion of a magnesite lining depends on the content of silicon in ferromanganese, temperature and convection of the metal, geometry and composition of the lining.

2. The analysis showed that the data of [6] regarding thermal mode of the lining operation exhibit inconsistence between the values of heat flux, heat transfer coefficients and limit temperatures. New calculations in this work showed that there should be a considered approach to replacing lining layers with other having higher thermal conductivity in order to prevent a high casing temperature and a possible freezing of the metal.

3. A convenient algorithm for optimization of the layers height and the composition of refractory lining materials was proposed to reduce the corrosion rate by maintaining the temperature of the upper layer of the lining close to the liquidus temperature of the metal of a particular composition.

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