STUDY REGARDING THE THERMAL PROPERTIES OF THE IRON OXIDES AND THEIR APPLICATION IN THE PROCESS OF THE HEAT TRANSFER FROM THE FURNACE HEARTH TO THE INGOT

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The iron oxides resulted from thermal processes have an important role in the analysis of the heat transfer particularities and in finding new methods of reducing the energy consumptions. Searching the specialty literature, there are not enough data regarding the thermal properties of the iron oxides. This is the main reason the authors have sampled the iron oxides and analyzed them in laboratory.

The experimental values of the thermal properties of the iron oxides were then applied in a mathematical model in order to obtain a new parameter, the 'global coefficient of heat transfer', from the furnace hearth to the inferior surface of the steel ingot.

Keywords: iron oxides, heat transfer, properties, experimental data

1. Introduction

During thermal processes in metallurgy, it is important in many cases to know the exactly particularities of the heat transfer, in a complex system formed by materials with different properties. It may be included the heating in view of forming, thermal isolation structures or the complex material structures. [1]

In the case of steel ingots heating, it can be taken into consideration the heat exchange by convection and radiation, or the heat transfer inside the material, by conductivity. The system may be composed by metal (the ingot), the metallic oxide (iron oxides), which may result from the previously thermal processes and the ceramic material (hearth of the aggregate) [2] (Fig. 1).

While the hearth temperature is higher than the ingot temperature, the sense of the thermal flow will be from the hearth to the ingot. It can be written [3], [4]:

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$$Q_{3-1} = \frac{\lambda_2}{\delta}(\theta_{2-3} - \theta_{1-2}) = r_t(\theta_{2-3} - \theta_{1-2}) \quad (1)$$

$$q_{3-1} = k(\theta_v - \theta_s) \quad (2)$$

λ_2: thermal conductivity of the oxides;
δ: thickness of the oxide layer;
r_t: thermal resistivity;
k: global coefficient of heat transfer from the hearth to the ingot.
It results:

$$r_t = k \cdot \frac{\theta_v - \theta_s}{\theta_{2-3} - \theta_{1-2}} \quad (3)$$

Because $(\theta_v - \theta_s) > (\theta_{2-3} - \theta_{1-2}), it\ results\ that\ r_t > k.$

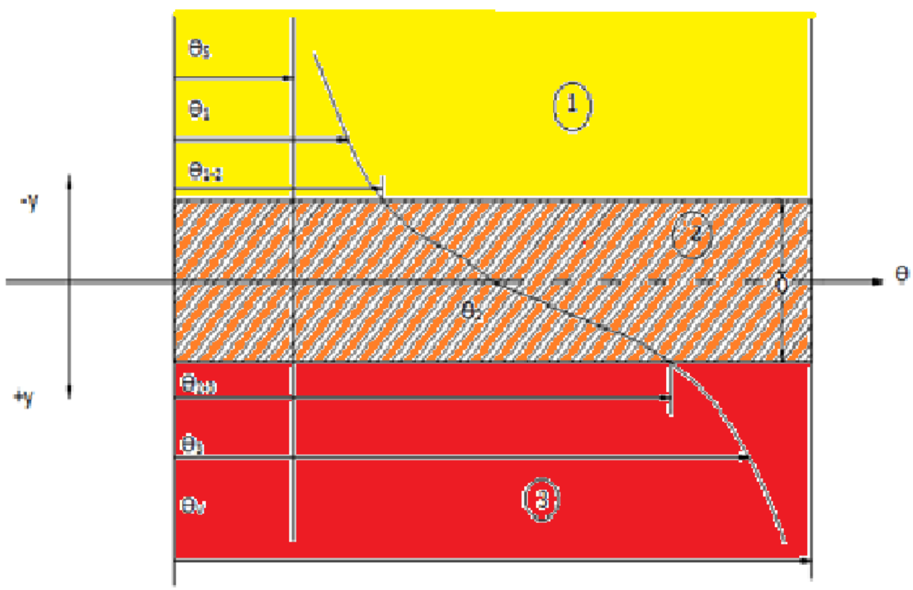

Fig. 1. The temperature in the system ingot-oxide-hearth *(Source: D. Constantinescu et al, 2013, [4])*

2. The thermal properties of the iron oxides

Having such an important role in the heating of the steel ingots, it is necessary to obtain data regarding the thermal properties of the iron oxides.

2.1 Chemical composition and structure of the iron oxides

On the purpose of determine the chemical composition of the iron oxides, the used method was the diffraction on powders, with the diffractometer X –

X'Pert PRO MPD, PANalytical. After the laboratory analyses, there were obtained the results presented in Figs. 2 and 3.

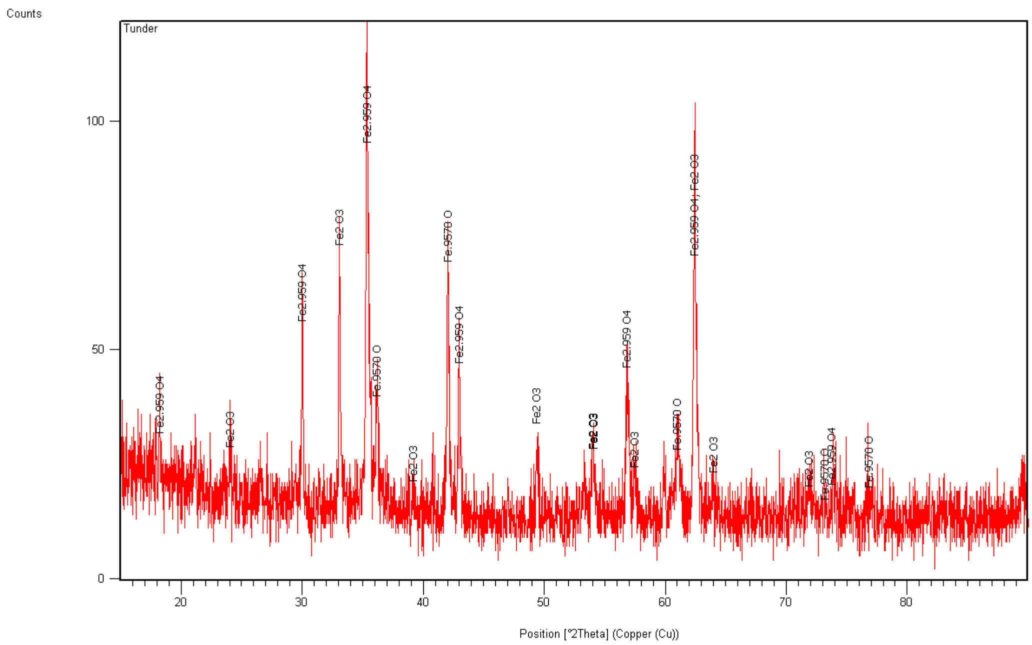

Fig. 2. Iron oxides diffractograme for FeO+Fe_2O_3+Fe_3O_4 *(Source: D. Constantinescu et al, 2013, [4])*

No.	Visible	Ref. Code	Compound N…	Chemical Formula	Score	Scale …	SemiQua
1	☐	01-086-1347	magnetite high	Fe2.959 O4	40	1.184	49
2	☐	01-074-1881	Wustite, syn	Fe.9570 O	33	0.430	19
3	☐	01-072-0469	iron(III) oxide	Fe2 O3	28	0.492	32

Fig. 3. Iron oxides chemical composition and ratio *(Source: D. Constantinescu et al, 2013, [4])*

2.2 The thermal conductivity and thermal capacity of the iron oxides

Analyzing the theoretical data of thermal conductivity (from specialty literature), there were deduced the values until the temperature of 1400^{0}C, using the polynomial regression (Fig. 4) [5].

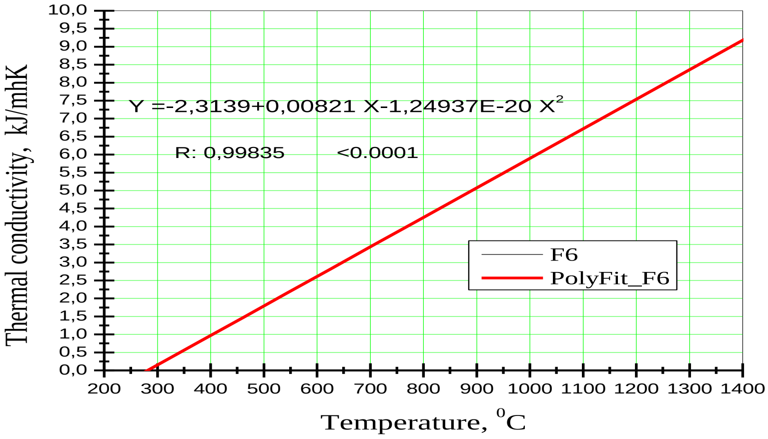

Fig. 4. Theoretical thermal conductivity for $FeO+Fe_2O_3+Fe_3O_4$, deduced by polynomial regression *(Source: D. Constantinescu et al, 2013, [4])*

According to the theoretical data, it results that te value of the thermal conductivity on 280^0C temperature is zero, but this is not corresponding to reality. Therefore, it intervened the need to perform some experimental analysis, to may establish the values of the iron oxides thermal conductivity (Fig. 5).

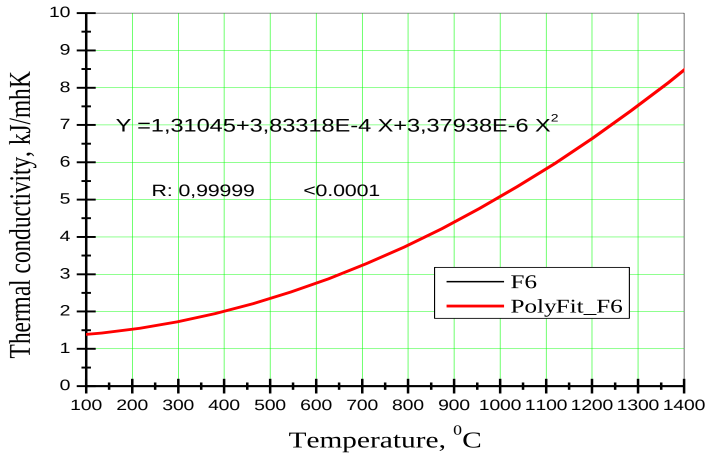

Fig. 5. Experimental thermal conductivity for $FeO+Fe_2O_3+Fe_3O_4$ *(Source: D. Constantinescu et al, 2013, [4])*

In Fig. 6, there are presented some data for the thermal capacity and the thermal conductivity of the iron oxides, using data from the technical literature. [6], [7]

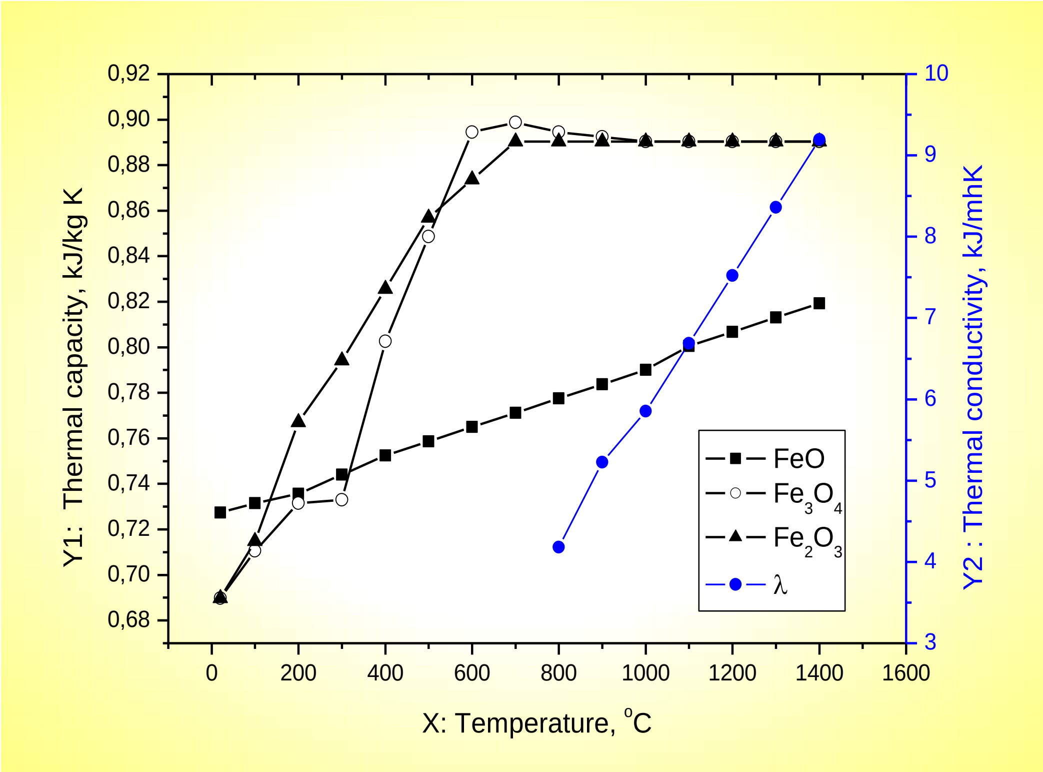

Fig. 6. Thermal capacity and conductivity of the oxide layer, using theoretical data *(Source: D. Constantinescu, 2011, [8])*

2.3 The thermal resistivity of the iron oxides

The thermal resistivity is the inverse of the thermal conductivity. It was determinated by calculus, depending of the thickness of the iron oxides layer (which was considered from 1 to 10mm) and temperature (from 700 to 1400^{0}C).

In table 1, there are presented values of the thermal resistivity, using theoretical thermal conductivity data, depending of the iron oxides layer thickness and in Fig. 7, it is the graphic representation of the thermal resistivity.

Table 1

Values of the thermal resistivity, using theoretical data, W/m^{2}K *(Source: D. Constantinescu et al, 2013, [4])*

	Thickness of the iron oxides layer									
Temperature ^{0}C	δ_1 1mm	δ_2 2mm	δ_3 3mm	δ_4 4mm	δ_5 5mm	δ_6 6mm	δ_7 7mm	δ_8 8mm	δ_9 9mm	δ_{10} 10mm
700	871	435	290	218	174	145	124	109	97	87
800	1161	581	387	290	232	194	166	145	129	116
900	1451	726	484	363	290	242	207	181	161	145
1000	1626	813	542	406	325	271	232	203	181	163
1100	1858	929	619	464	372	310	265	232	206	186
1200	2090	1045	697	523	418	348	299	261	232	209
1300	2322	1161	774	581	464	387	332	290	258	232
1400	2554	1277	851	639	511	426	365	319	284	255

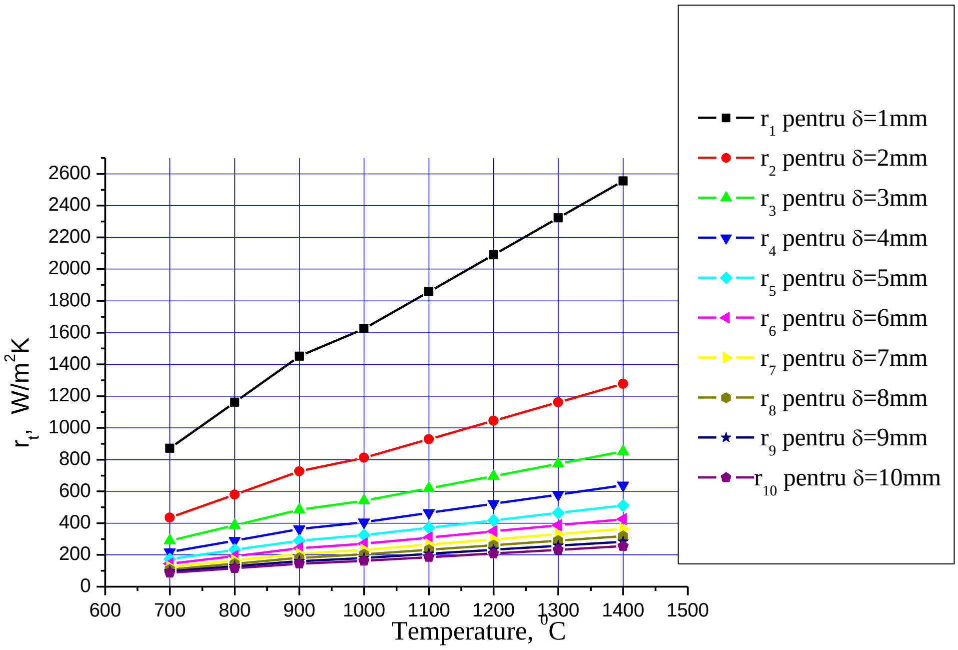

Fig. 7. Thermal resistivity of the iron oxides layer, using theoretical data *(Source: D. Constantinescu et al, 2013, [4])*

In table 2, there are presented values of the thermal resistivity, using experimental thermal conductivity data, depending of the iron oxides layer thickness and in Fig. 8, it is the graphic representation of the thermal resistivity.

Table 2

Values of the thermal resistivity, using theoretical data, W/m^{2}K

	Thickness of the iron oxides layer									
Temperature ^{0}C	δ_1 1mm	δ_2 2mm	δ_3 3mm	δ_4 4mm	δ_5 5mm	δ_6 6mm	δ_7 7mm	δ_8 8mm	δ_9 9mm	δ_{10} 10mm
700	890	445	296	222	178	148	127	111	98	89
800	1030	515	343	257	206	171	147	128	114	103
900	1210	605	403	302	242	201	172	151	134	121
1000	1400	700	466	350	280	233	200	175	155	140
1100	1610	805	536	402	322	268	230	201	178	161
1200	1848	920	613	460	368	306	262	230	204	184
1300	2080	1040	693	520	416	346	297	260	231	208
1400	2330	1165	776	582	466	388	332	291	258	233

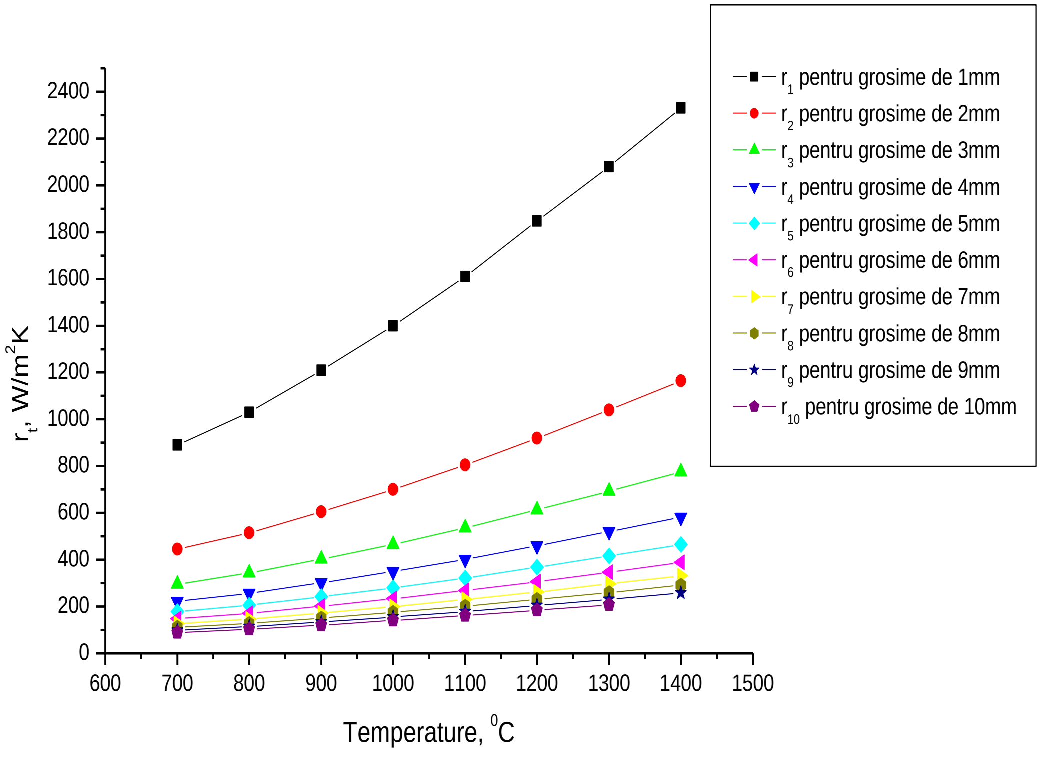

Fig. 8. Thermal resistivity of the iron oxides layer, using experimental data

3. The evaluation of the global coefficient of heat transfer

If it is considered that on the contact surface between the furnace hearth and the steel ingot, the sense of the thermal flow will be from the hearth to the ingot (Fig. 1), than:

$$\frac{\vartheta\theta_1}{\vartheta\tau} = a_1 \frac{\vartheta^2\theta_1}{\vartheta y^2} \quad \text{(for the steel ingot)} \tag{4}$$

$$\frac{\vartheta\theta_2}{\vartheta\tau} = a_2 \frac{\vartheta^2\theta_2}{\vartheta y^2} \quad \text{(for the iron oxides layer)} \tag{5}$$

$$\frac{\vartheta\theta_3}{\vartheta\tau} = a_3 \frac{\vartheta^2\theta_3}{\vartheta y^2} \quad \text{(for the furnace hearth)} \tag{6}$$

θ_1, θ_2, θ_3: temperatures of the three components of the system;

τ: time;

$a=\lambda/c\rho$: thermal diffusivity.

The temperature in the middle of the oxide layer is presented in eq. 7:

$$\theta_{2(y=\delta/2)} = \theta_m = \frac{\theta_S + \theta_v}{2} = const. \tag{7}$$

The temperature fluctuation in the oxide layer is transferred almost linear:

$$\frac{\vartheta\theta_2}{\vartheta y} = \frac{2(\theta_{2-3} - \theta_m)}{\delta} \tag{8}$$

The heat transferred from the hearth, by a surface element, dS, in the time $d\tau$, in the point y=0 is presented in equation 9.

$$d^2Q = \lambda_2 \frac{\vartheta\theta_2}{\vartheta y} dSd\tau = r_t(\theta_{2-3} - \theta_m)dSd\tau \tag{9}$$

Replacing, it is obtained:

$$r_t = \frac{2\lambda_2}{\delta} \qquad (10)$$

The relative coefficient of heat transfer is noted with χ (equation 11):

$$\chi = \frac{r_t}{\lambda_3} = \frac{2\lambda_2}{\delta \cdot \lambda_3} \qquad (11)$$

To calculate the relative coefficient of heat transfer it was chosen as refractory material of the furnace hearth, the chamotte.

In Fig. 9 it is presented the relative coefficient of heat transfer, χ, calculated using the theoretical values of thermal resistivity, depending on the thickness of the oxide layer (which fluctuates between 1 and 10mm), in the temperature interval 700-1400^{0}C.

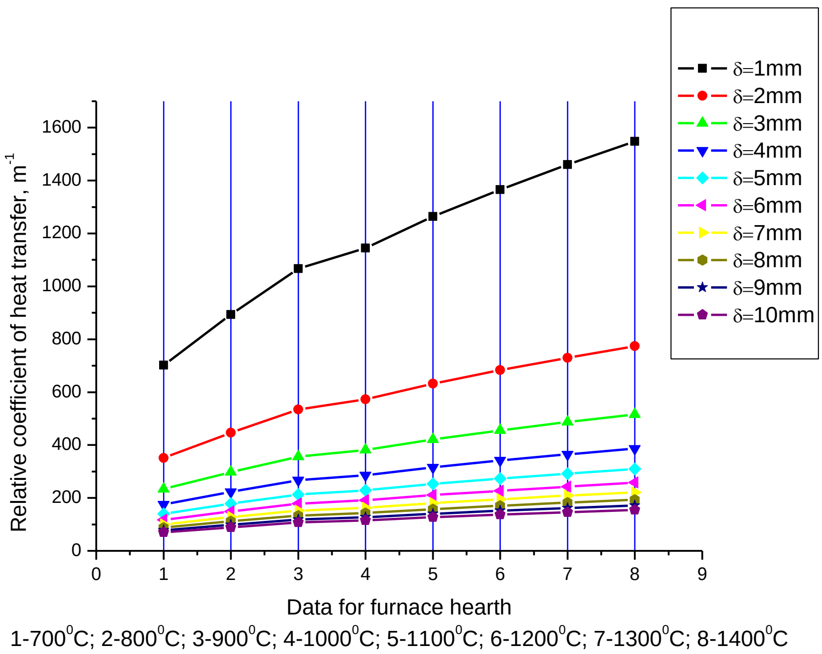

Fig. 9. Relative coefficient of heat transfer (using theoretical data of thermal resistivity)

In Fig. 10 it is presented the relative coefficient of heat transfer, χ, calculated using experimental values of thermal resistivity, depending on the thickness of the oxide layer (which fluctuates between 1 and 10mm), in the temperature interval 700-1400^{0}C.

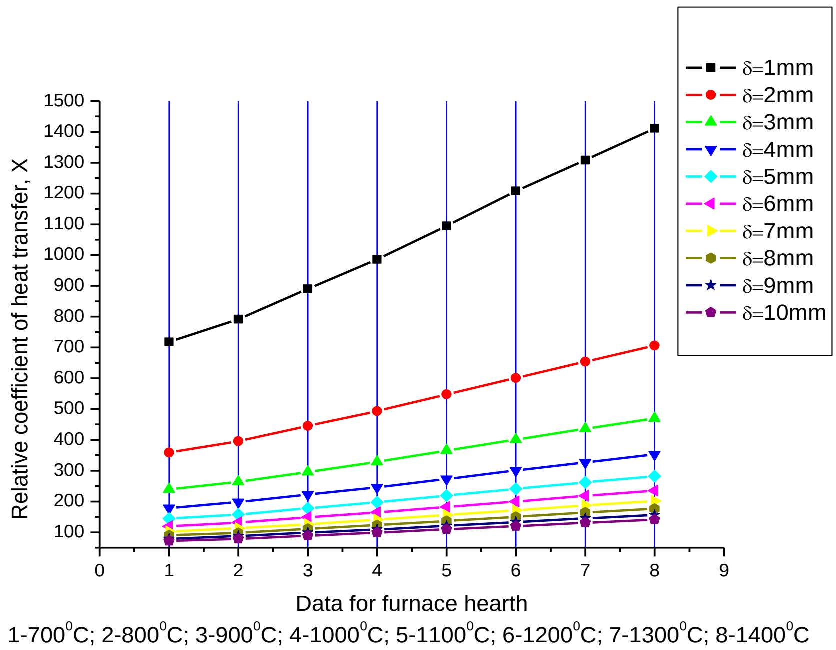

Fig. 10. Relative coefficient of heat transfer (using experimental data of thermal resistivity)

Applying a function proposed by P. Frank and R. Mises, [9] the form of the function for the analysed case will be:

$$\theta_{2-3} = \theta_m + (\theta_v - \theta_m) \cdot e^{a_3 \cdot \tau \cdot \chi^2} \cdot \left[1 - \Phi\left(\sqrt{a_3 \cdot \tau \cdot \chi^2}\right)\right] \cdot dS d\tau \tag{12}$$

where Φ is the symbol for Gauss function (equation 13).

$$\Phi(\xi) = \frac{2}{\sqrt{\pi}} \int_0^{\xi} e^{\eta^2} d\eta \tag{13}$$

$$d^2 Q = \frac{\lambda_2}{\delta} (\theta_v - \theta_S) \cdot e^{C \cdot \tau} \left[1 - \Phi\left(\sqrt{C \cdot \tau}\right)\right] dS d\tau \tag{14}$$

$$\frac{dQ}{dS} = \frac{\lambda_2}{\delta} (\theta_v - \theta_S) \int_o^{\tau_c} e^{C \cdot \tau} \left[1 - \Phi\left(\sqrt{C \cdot \tau}\right)\right] d\tau \tag{15}$$

Comparing (2) with (15), the global coefficient of heat transfer will be defined:

$$\frac{dQ}{dS} = k(\theta_v - \theta_s)\cdot\tau_c \tag{16}$$

$$k = \frac{\lambda_2}{\delta\cdot\tau_c}\int_0^{\tau_C} e^{C\cdot\tau}\left[1-\Phi\left(\sqrt{C\cdot\tau}\right)\right]d\tau \tag{17}$$

$$b_3 = \frac{\lambda_3}{\sqrt{a_3}} = \sqrt{\lambda_3\cdot c_3\cdot\rho_3}$$ (coefficient of heat penetration) (18)

The final form of the coefficient k is presented in equation 19.

$$\boxed{k_0 = \frac{b_3}{\sqrt{\pi\cdot\tau_c}} = \sqrt{\frac{\lambda_3\cdot c_3\cdot\rho_3}{\pi\cdot\tau_c}}}\ [Jm^{-2}K^{-1}] \tag{19}$$

In Fig. 11 it is presented the global coefficient of heat transfer, calculated for a chamotte furnace hearth, depending on the stationary time of the steel ingot on the hearth (which fluctuates between 10 and 100 hours).

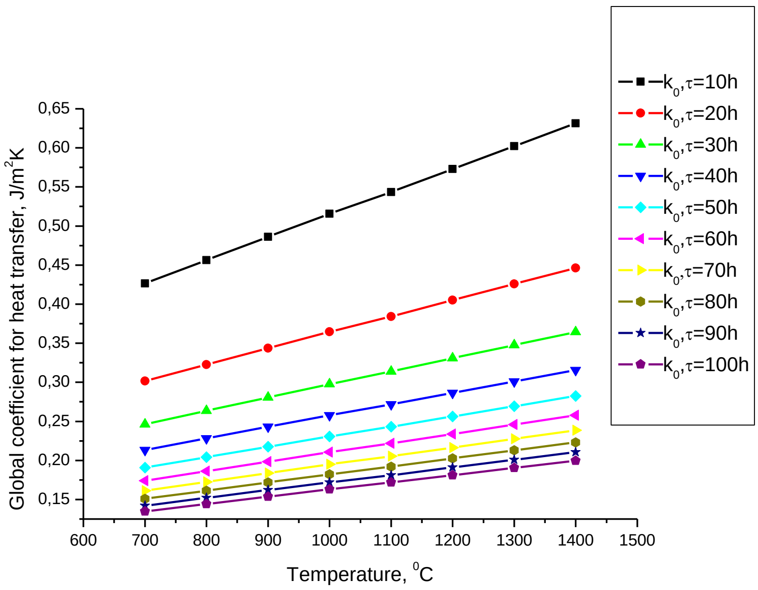

Fig. 11. Global coefficient of heat transfer (using as refractory material for hearth the chamotte)

Therefore, the global coeficient of the heat transfer, k, is dependent only on the coefficient of heat penetration, b_3 and the stationary time of the steel ingot on the furnace hearth. Along with the increasing of the contact duration, τ_c, the coefficient of heat transfer, k, is decreasing.

4. Conclusions

Because in the technical literature are not too many data regarding the thermal properties of the iron oxides, the authors have sampled it and analyzed in laboratory. The main goal was to compare the theoretical with the experimental data, but also to apply it in mathematical models, in order to determine new methods of reducing the energy consumptions.

The analyzed mathematical model has in view the establishing of the global coefficient of heat transfer, k, from the furnace hearth to the inferior surface of the steel ingot.

The thermal sense of the coefficient k is similar with the global coefficient of heat transfer by radiation and convection, from the burned gases to the free surfaces of the ingot.

The k coefficient depends of the thermal parameters of the hearth material and steel ingot, separated from the hearth with a metallic oxide layer.

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