ANNALS OF FACULTY ENGINEERING HUNEDOARA
– INTERNATIONAL JOURNAL OF ENGINEERING
Tome X (Year 2012) – FASCICULE 1 (ISSN 1584 – 2665)

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ENERGY AND METAL SAVING IN THE HEATING FOURNACES MEANS A CLEANER ENVIRONMENT

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ABSTRACT: *As a major consumer of energy the steel producers are always mentioned as interesting field of investigations. The aim of this paper is to establish the basic relations for a model in order to help to evaluate the parameters of the heat transfer and energy consumption in the case of some metallurgical heating furnaces for billets reheating. Starting from considerations about the burning process of the fuels, the paper establishes connections between the heat exchange coefficients, energy and metallic material saving. Saving energy and lost metal due to the oxidation process, means to have a cleaner environment. A new disposing system of the burners inside the furnace can lead to saving energy and metal. The paper offer also a model to calculate the temperature in the furnace (temperature of the flue gases) taking in consideration the global heat exchange, the technological temperature of the billet in order to evaluate the thermal energy looses.*
KEYWORDS: *oxidation, heating, energy, furnace, thermal regime, clean environment*

INTRODUCTION – OXIDATION AND HEATING PROCESS

In the case of the heating process in furnaces using the combustion in view of rolling of the cast billets, the source of energy can be analyzed from tow points of view:

a) as component which can reduce the material looses due to the oxidation process

b) as component which assure the technological conditions for the heating process

In order to analyze the source of energy as component influencing the steel oxidation process one can use the partial pressures (p) of $H_2O_{(gas)}$, H_2 CO_2 and CO in the flue gases. So, it is obtained the K_a coefficient:

$$K_a = \frac{p_{H_2O}/p_{H_2}}{p_{CO_2}/p_{CO}} = \frac{K_H}{K_C} \qquad (1)$$

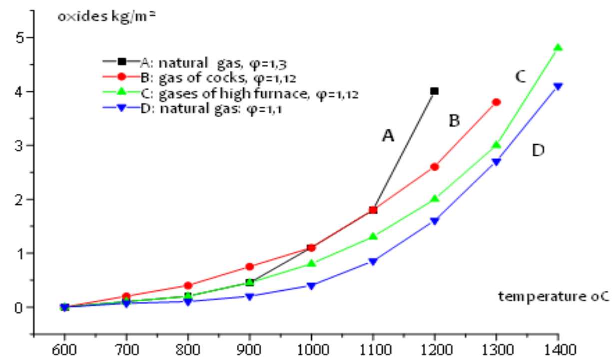

Figure 1 : Dependence of the quantity of the iron oxides, during the heating process of the non alloyed steels on the fuel, temperature and air excess coefficient, φ

In the figure 1 there are presented the influence of type of the fuel, the furnace temperature and the air coefficient φ, on the quantity of the oxides.

In order to analyze how to influence the heat exchange and to assure the thermal technological conditions, one start from the equation of heat exchange between the flue gaze, the furnace thermal isolation and the metallic material. It is necessary to considerate that the heat exchange is simultaneously by radiation and convection. So, the thermal energy, Q_{gp}, received by the furnace isolation from the flue gases is:

$$Q_{gp} = S \cdot \alpha_{gp} \cdot \varepsilon_p \cdot (\theta_g - \theta_p) + S \cdot \alpha_c \cdot (\theta_g - \theta_p) \quad [kJ/h] \qquad (2)$$

where: S - internal surface of the thermal isolation, m^2; θ_g- temperature of the flue gases, ^oC; θ_p- temperature of the thermal isolation, inside the furnace, ^oC; α_{gp}- radiation heat exchange coefficient between the gases and the thermal isolation, $kJ \cdot m^{-2} \cdot h^{-1} \cdot K^{-1}$; α_c - convection heat exchange coefficient between the gases and the thermal isolation, $kJ \cdot m^{-2} \cdot h^{-1} \cdot K^{-1}$; ε_p- emission coefficient of the thermal isolation.

In the same time:

$$Q_{gp} = Q_{pm} + S \cdot q_{ex} \qquad [kJ/h] \qquad (3)$$

where: Q_{pm} - thermal energy from the isolation of the furnace to the heated billets, $kJ \cdot h^{-1}$; q_{ex} - thermal flow thru the furnace's isolation , $kJ \cdot m^{-2} \cdot h^{-1}$

The computation of the heat exchange by radiation between the thermal isolation components can be calculated using the angular coefficient of radiation, [1].

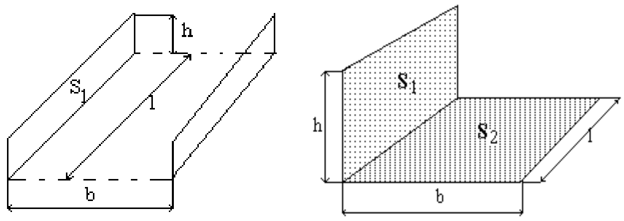

Figure 2: dimensions referring to the continuous furnaces in order to establish the coefficient φ [B=h/b ; L=l/b]

In the case of heating pushing type furnaces and walking type furnaces, [1; 2], it was obtained (4), (figure 2):

$$\beta = \frac{1}{\pi}\left[\frac{1}{B \cdot L} \cdot \ln\frac{(1+B^2)(1+L^2)}{1+B^2+L^2} - \frac{2}{B} arctg(L) - \frac{2}{L} arctg(B) + \frac{2}{L}\sqrt{1+L^2}\, arctg\frac{B}{\sqrt{1+L^2}} + \frac{2}{B}\sqrt{1+B^2}\, arctg\frac{L}{\sqrt{1+B^2}}\right] \qquad (4)$$

In the case of heat exchange between the thermal isolation (figure 3) and the billets, the coefficient β is [2]:

$$\beta = \frac{1}{2\pi}\left(\frac{B}{\sqrt{1+B^2}} \cdot \arcsin\frac{L}{\sqrt{1+B^2+L^2}} + \frac{L}{\sqrt{1+L}} \cdot \arcsin\frac{B}{\sqrt{1+B^2+L^2}}\right) \qquad (5)$$

ENERGY SOURCE AND MATERIAL LOSSES DURING THE HEATING PROCESS

Starting from the equation (1) it can be observed that it is necessary to calculate the quantity of oxygen, resulted from the fuel and from the combustion air:

$$O_x = O_{2c} + 0{,}21 \cdot v_{oa} \cdot \lambda = CO_2 + 0{,}5CO + 0{,}5H_2O$$

where: v_{oa} - specific air volume, necessary for the reaction with $1m^3$ of fuel, $m^3_{N(air)} \cdot m^{-3}_{N(fuel)}$; CO_2- in flue gazes; λ - coefficient of air excess.

It is obtained:

$$H_2O = 2O_x - C\frac{0{,}5 + K_c}{1 + K_c}$$

where: $C = CO + CO_2$

Analyzing the oxidation phenomena of the steel in the case of the must usual fuel (the natural gas), it can be deduced that the oxidation process is very fast for the temperatures up to 800°C. In order to reduce the oxidation process, the theoretic burning temperature must be under 1360°C. If the heating temperature of the steel in view of rolling must be 1200…1250°C, this case is not economic from energetic point of view.

The calculation of the temperature of the source of energy starting only from the equation (1) is valid if the oxygen content of the air combustion and of the fuel together can assure the transformation in CO of the carbon resulted from the dissociation of the carbides. If the air excess coefficient is too small to assure this transformation, the flue gases will include particles of black pigment.

Due to the law values of the equilibrium constant $K=(p_{CO2}/p^2_{CO})= 10^{-2} \div 10^{-4}$, for the Bell-Boudoir reaction (CO_2+C $\Leftrightarrow$ 2CO), the presence of the black particles in the flue gazes is of low importance in the case when the coefficient of air excess is over the normal values resulted from the chemical reactions.

METHODOLOGY – THE HEATING FURNACE TEMPERATURE AND STEEL OXIDATION

The theoretical output η_t, indicate the efficiency of the use of the energetic sources (the fuel).

If in the furnace is introduced a quantity of thermal energy, resulted from the fuel combustion:

$$Q^t_{cb} = Q_{cb} \cdot \eta_t + v_{ga} \cdot \theta_{ga} \cdot c_p \qquad (6)$$

where: v_{ga} - volume of the flue gases related to a thermal unit of the fuel (for example to 1000kJ), [$Nm^3/10^3Kj$]; θ_{ga}- temperature of the flue gases at the exit from the furnace, °C; c_p - thermal capacity of the flue gases, $kJ \cdot m^{-3}_N \cdot K^{-1}$.

If Q_{cb}, is a unit of the fuel, it can be written:

$$v_{ga} \cdot \theta_{ga} \cdot c_p = v_{ot} \cdot \theta_{ga} \cdot c_p + (\varphi_a - 1) \cdot v_{oa} \cdot \theta_{ga} \cdot c_a \qquad (7)$$

where: v_{ot}- theoretical volume of the flue gases related to the thermal unit of the fuel, [$Nm^3/10^3kJ$]; v_{oa}- theoretical volume of air combustion related to the thermal unit of the fuel, [$m^3_N/10^3$ kJ]; c_a - air combustion thermal capacity, $kJ \cdot m^{-3}_N \cdot K^{-1}$.

If the fuel and the air combustion are heated and the real air combustion volume is $\varphi_a \cdot v_{oa}$, it results:

$$\eta_t = 1 + \varphi_a \cdot v_{oa} \cdot \frac{\theta_a \cdot c_a}{Q_{cb}} + \frac{\theta_{cb} \cdot c_{cb}}{H_i} - \frac{v_{ot} \cdot \theta_{ga} \cdot c_p}{Q_{cb}} - (\varphi_a - 1) \cdot v_{oa} \cdot \frac{\theta_{ga} \cdot c_a}{Q_{cb}} \quad (8)$$

The equation (8) establishes a correlation between the theoretical output, the nature of the fuel and the air excess coefficient [by the factor $(\varphi_a - 1) \cdot v_{oa} \cdot \frac{\theta_{ga} \cdot c_a}{Q_{cb}}$].

Else, the oxidation process of the metal can be controlled by the air excess coefficient.

If it is defined "the factor of the fuel":

$$K_{cb} = 1 + \frac{\theta_{cb} \cdot c_{cb}}{H_i} \quad (9)$$

it is obtained:

$$\eta_t = K_{cb} + \frac{1}{Q_{cb}}\left(\lambda_a \cdot v_{oa} \cdot \theta_a \cdot c_a - v_{ot} \cdot \theta_{ga} \cdot c_p - (\varphi_a - 1) \cdot v_{oa} \cdot \theta_{ga} \cdot c_a\right) \quad (10)$$

The equations (8) and (10) can be used to choose the thermal source (gas fuel) in correlation with the preheating degree of the fuel and the air combustion and with the coefficient of air combustion excess which control the oxidation process in the heating furnace.

HEAT EXCHANGE COEFFICIENTS AND THE THERMAL PROCESS IN THE HEATING FURNACE

If all the thermal energy radiated by the isolation, Q_{pm}, is receipted by the heated metal, it is possible to write:

$$Q_{pm} = \alpha_{pm} \cdot \varepsilon_{pm} \cdot s \cdot (\theta_p - \theta_m) \quad (11)$$

where: θ_m- temperature of the metal, ^oC; α_{pm}- heat exchange coefficient by radiation between the thermal isolation and the metal, $kJ \cdot m^{-2} \cdot h^{-1} \cdot K^{-1}$; s - heated surface of the metallic material (billets), (reception surface, S_2, in fig. 3), m^2

But, a part of this radiation is absorbed by the flue gases. The absorption process depends on the partial pressure of CO_2 and H_2O. The absorbed thermal energy by radiation, Q_{abs}, is equal with the quantity of energy which the metal could receive from the flue gases if the temperature of the gases is equal with the temperature of the thermal isolation:

$$Q_{abs} = \alpha_{gpm} \cdot \varepsilon_p \cdot s \cdot (\theta_p - \theta_m) \quad (12)$$

where: α_{gpm} - heat exchange coefficient from the gases to the metallic material, if it is considerate that the temperature of the gases is the same with the temperature of the thermal isolation, $kJ \cdot m^{-2} \cdot h^{-1} \cdot K^{-1}$

So, the real value of Q_{pm} is:

$$Q_{pm} = s(\alpha_{pm} \cdot \varepsilon_{pm} - \alpha_{gpm} \cdot \varepsilon_p) \cdot (\theta_p - \theta_m) \quad (13)$$

Replacing, it is obtained:

$$S \cdot (\alpha_{gp} \cdot \varepsilon_p + \alpha_c) \cdot (\theta_g - \theta_p) = s \cdot (\alpha_{pm} \cdot \varepsilon_{pm} - \alpha_{gpm} \cdot \varepsilon_p) \cdot (\theta_p - \theta_m) + S \cdot q_{ex} \quad (14)$$

If $\sigma = s/S$, equation (14) will be:

$$\begin{aligned}\theta_g \cdot (\alpha_{gp} \cdot \varepsilon_p + \alpha_c) = \theta_p \cdot (\alpha_{gp} \cdot \varepsilon_p + \alpha_c + \sigma \cdot \alpha_{pm} \cdot \varepsilon_{pm} - \sigma \cdot \alpha_{gpm} \cdot \varepsilon_p) - \\ - \theta_m \cdot \sigma(\alpha_{pm} \cdot \varepsilon_{pm} - \alpha_{gpm} \cdot \varepsilon_p) + q_{ex}\end{aligned} \quad (15)$$

Equation (15) correlates the temperature of the flue gases, temperature of the thermal isolation and the temperature of the billets (θ_m). But, the establishing of the values of the heat exchange coefficients is yet difficult.

The thermal flow sanded to the metallic material (billets) includes:

- *radiation thermal flow from the thermal isolation*

$$q_{pm} = (\alpha_{pm} \cdot \varepsilon_{pm} - \alpha_{gp} \cdot \varepsilon_p)(\theta_p - \theta_m) \quad [kJ \cdot m^{-2} \cdot h^{-1}] \quad (16)$$

- *radiation and convection thermal flow from the flue gases*

$$q_{gm} = (\alpha_{gm} \cdot \varepsilon_m + \alpha_c)(\theta_g - \theta_m) \quad (17)$$

The total thermal flow received by the billets is:

$$q = q_{pm} + q_{gm} \quad (18)$$

Starting from the equation (15), it is noted:

$$\left(\theta_p-\theta_m\right)+\left(\theta_g-\theta_p\right)=\left(\theta_g-\theta_m\right) \tag{19}$$

Then, the coefficient of the global heat exchange can be calculated:

$$\left(\alpha_{gp}\cdot\varepsilon_p+\alpha_c\right)\cdot\left[\left(\theta_g-\theta_m\right)-\left(\theta_p-\theta_m\right)\right]=\sigma\left(\alpha_{pm}\cdot\varepsilon_{pm}-\alpha_{gpm}\cdot\varepsilon_p\right)\left(\theta_p-\theta_m\right)+q_{ex}$$

$$\left(\theta_p-\theta_m\right)\cdot\left[\sigma\left(\alpha_{pm}\cdot\varepsilon_{pm}-\alpha_{gpm}\cdot\varepsilon_p\right)+\left(\alpha_{gp}\cdot\varepsilon_p+\alpha_c\right)\right]+q_{ex}=\left(\theta_g-\theta_m\right)\left(\alpha_{gp}\cdot\varepsilon_p+\alpha_c\right) \tag{20}$$

Replacing the expressions of the thermal flows, it is obtained:

$$q=\left(\alpha_{pm}\cdot\varepsilon_m-\alpha_{gm}\cdot\varepsilon_p\right)\cdot\left(\theta_p-\theta_m\right)+\left(\alpha_{gm}\cdot\varepsilon_m+\alpha_c\right)\cdot\left(\theta_g-\theta_m\right) \tag{21}$$

Eliminating (θ_p-θ_m) and (θ_g-θ_m) from the last two expressions, there are obtained the following expressions regarding the complex heat exchange in the analysed furnace:

1. The heat exchange coefficient between the thermal isolation and the billets:

$$\alpha_1=\frac{\alpha_{gm}\cdot\varepsilon_m+\alpha_c}{\alpha_{gp}\cdot\varepsilon_p+\alpha_c}\cdot\left(\alpha_{gp}\cdot\varepsilon_p+\alpha_c+\sigma\cdot\alpha_{pm}\cdot\varepsilon_{pm}-\sigma\cdot\alpha_{gm}\cdot\varepsilon_p+\frac{q_{ex}}{\theta_p-\theta_m}\right)\ [kJ\cdot m^{-2}\cdot h^{-1}\cdot K^{-1}] \tag{22}$$

2. The heat exchange coefficient between the flue gases and the billets:

$$\alpha_2=\frac{\alpha_{pm}\cdot\varepsilon_{pm}-\alpha_{gpm}\cdot\varepsilon_p}{\alpha_{gp}\cdot\varepsilon_p+\alpha_c+\sigma\cdot\left(\alpha_{pm}\cdot\varepsilon_{pm}-\alpha_{gpm}\cdot\varepsilon_p\right)}\cdot\left(\alpha_{gp}\cdot\varepsilon_p+\alpha_c-\frac{q_{ex}}{\theta_g-\theta_m}\right)+\alpha_{gm}\cdot\varepsilon_m+\alpha_c\ [kJ\cdot m^{-2}\cdot h^{-1}\cdot K^{-1}] \tag{23}$$

RESULTS, DISCUSSIONS, ANALYZIS

A general solution to modeling the thermal regime

Using the ratio $\sigma = s/S$, it can be deduced the temperature of the flue gases:

$$\theta_g=\theta_p\frac{\alpha_{gp}\cdot\varepsilon_p+\alpha_c+\sigma\cdot\alpha_{pm}\cdot\varepsilon_{pm}-\sigma\cdot\alpha_{gpm}\cdot\varepsilon_p}{\alpha_{gp}\cdot\varepsilon_p+\alpha_c}-\theta_m\cdot\sigma\cdot\frac{\alpha_{pm}\cdot\varepsilon_{pm}-\alpha_{gpm}\cdot\varepsilon_p}{\alpha_{gp}\cdot\varepsilon_p+\alpha_c}+\frac{q_{ex}}{\alpha_{gp}\cdot\varepsilon_p+\alpha_c} \tag{24}$$

In the case when heating the billets in view of rolling there are used, in the most of the cases, natural gas, high furnace gas and cocks gas (fig.1). In this case the values of the emissive coefficients are:

$$\varepsilon_p=0,77\ldots0,8 \qquad \varepsilon_m=0,8\ldots0,88 \qquad \varepsilon_{pm}=\frac{1}{\frac{1}{\varepsilon_m}+\sigma\left(\frac{1}{\varepsilon_p}-1\right)}=0,8\ldots0,81 \tag{25}$$

In these conditions it is obtained in (23):

$$\alpha_p=\frac{0,8\cdot\left[\alpha_{gp}+\alpha_c+\sigma\left(\alpha_{pm}-\alpha_{gpm}\right)\right]}{0,8\cdot\alpha_{gp}+\alpha_c}\quad [kJ\cdot m^{-2}\cdot h^{-1}\cdot K^{-1}] \tag{26}$$

$$\alpha_m=\sigma\frac{0,8\left(\alpha_{pm}-\alpha_{gpm}\right)}{0,8\cdot\alpha_{gp}+\alpha_c}\quad [kJ\cdot m^{-2}\cdot h^{-1}\cdot K^{-1}] \tag{27}$$

So, the temperature of the flue gases will be:

$$\theta_g=\alpha_p\cdot\theta_p+\alpha_m\cdot\theta_m+\frac{q_{ex}}{0,8\cdot\alpha_{gp}+\alpha_c}\quad [^\circ C] \tag{28}$$

where the conduction thermal flow is:

$$q_{ex}=\frac{\theta_p-\theta_{pex}}{\sum_{i=1}^{n}\frac{\delta_i}{\lambda_i}}\quad [kJ\cdot m^{-2}\cdot h^{-1}] \tag{29}$$

where θ_{pex}- temperature of the outside of the thermal isolation layer, °C

Using practical data from [3], [4], [5], [6], for the steels, thermal isolation materials and chemical composition of the flue gases, there where established the values for the coefficients α_{gp}, α_{pm}, α_{gpm} (figures 4 and 5).

In the equation (25) the temperature of the billets is considerate as "known data" from the technological conditions. So, it is necessary to establish the values for θ_p.

In order to follow, it is necessary to use the equations (20) and (23). For the beginning it is considerate that θ_g=θ_p, in order to establish the necessary data for the equation (23) (figures 4 and 5).

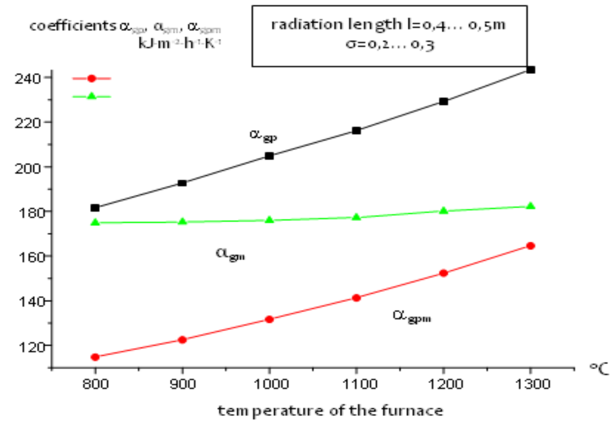

Figure 4: Variation of the coefficients α_{gp}, α_{gm} and α_{gpm} depending on the temperature of the furnace, thermal radiation's length and the ratio σ

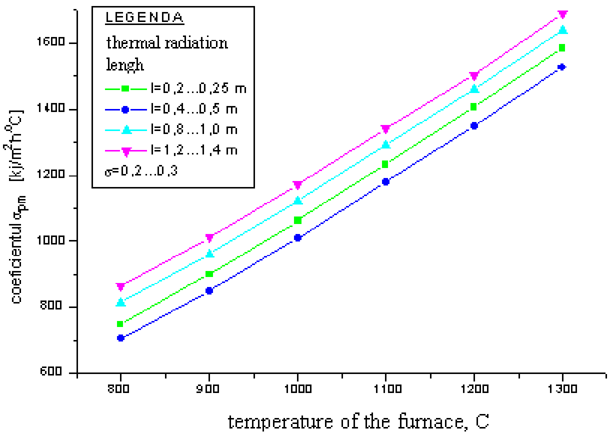

Figure 5: Variation of the coefficient α_{pm} depending on the temperature of the furnace, thermal radiation's length and the ratio σ

The exact value of the temperature of the thermal isolation (inside the furnace) will be:

$$\theta_p = \theta_m - \frac{q_{ex}}{\sigma \cdot \left(\alpha_{pm} \cdot \varepsilon_{pm} - \alpha_{gpm} \cdot \varepsilon_p\right)} \quad [^\circ C] \qquad (30)$$

Equation (30) can be in correlation with the particularities of a kind of furnace. For example, in the case of a rotary type furnace for circular billets it can be established the dependence of the flue gases at the exit from the furnace (θ_g), furnace's productivity (P) and the disposal mode of the burners [7]. It can be deduced using the equation (28):

$$\theta_g = \alpha_p \cdot \theta_p + \alpha_m \cdot \theta_m + \frac{Q_p}{0{,}8 \cdot \alpha_{gp} + \alpha_c} = \frac{A}{y} - B \cdot y + C \quad [^\circ C] \qquad (31)$$

where: Q_p- total looses due to the heat conduction in the furnace's isolation

$$A = \frac{Q_p}{\pi (D+d) \cdot V_g \cdot c_p} \qquad B = \frac{4 \cdot P \cdot c_m \cdot (\theta_2 - \theta_1)}{\pi \cdot K \cdot b \cdot (D+d)} \qquad (32)$$

where: D, d: dimensions of the circular furnace, m; θ_1, θ_2- final and initial temperature of the billets, °C; V_g: flue gases debit, $m^3 \cdot h^{-1}$; K: coefficient of the furnace, depending on the design, dimensions, output and working temperature [7]

CONCLUSIONS

- ◊ The quantity of the metallic material lost by oxidation during the reheating of the billets depends on the chemistry of the atmosphere in the heating furnace, on the temperature and on the duration of the thermal process.
- ◊ During the reheating process, the soaking duration of the billets at the high temperature must have a minimum value. This is recommended from the points of view of oxidation a decarburising process and for energy saving too. In practice, in most of the cases, the soaking duration of the billets is too long and the temperature is too high. It is necessary to impose that the plastic deformation temperature (the rolling beginning temperature) are reached by the billets moment of the defournement or just a few minutes before. On the other hand, the deformation temperature must be minimum admitted for the category of steel.
- ◊ To reduce the oxidation and decarburising process an important action regards the control of chemical composition of the flue gases. This is possible by the control of the air combustion excess coefficient and the designee of the heating furnace.
- ◊ Using the proposed general solutions for the remodelling of the thermal regime it can be obtained a better control of the temperatures in each heating zone of the furnace and to correlate it with the necessary temperatures of the billets. It is also possible to control the temperature of the thermal isolation, and by this to save thermal energy.
- ◊ Using the above established equations it is possible to control the flue gases temperature in each heating zone of the furnace in correlation with the temperature of the metallic material. It is possible also to control the temperature of the thermal isolation and by this to save important quantities of thermal energy.

◊ *The coefficients α_p, α_m, α_{gpm} are at the basis of the control process of heat exchange between the flue gases, metallic material and the thermal isolation. The values of this coefficients are established in the present work*

◊ *The basics of the general solution to modeling the thermal regime allowed establishing the disposal mode of the burners in connection with the design of the furnace and the necessary output. The design of the furnace can be also changed having in view the thermal and the dynamic particularities of the flow gases.*

REFERENCES

[1.] Heiligenstaedt, W.: Thermique appliquee aux fours industriels, tom1, Dunot, Paris, 1971

[2.] Constantinescu, D : Cercetări privind îmbunătățirea parametrilor de funcționare ai agregatelor tehnologice de încălzire a materialelor metalice supuse deformării prin laminare, tesis, UPB, 621.771.06 (043)

[3.] Rosier , Ch.: Etude sur la valeur d'usage des combustibles; CIT, 6/1990

[4.] Schack, A. : Strömungverhältnisse und Wärmebilanz neuzeitlicher Tieföfen; in Wärmestelle der Vereins Deutscher Eisenhütteleute nr.435

[5.] Constantinescu, D., Nicolae, A., Predescu, C., Sohaciu, M. : Termotehnica metalurgică, Printech, Bucuresti, 2003

[6.] Constantinescu, D.: A model of the dynamic of the burned gazes in heating furnaces for rolling mills; 4th International Symposium of Croatian Metallurgical Society, June 2000, in "Metalurgija - Metallurgy" vol.39, nr.3/2000 p. 216.

[7.] Constantinescu, D., Mazankova, M.: Heat exchange and metall saving in the fournaces for billets reheating in view of rolling; pag.53, Metal 2003, Hradec nad Moravici, Czech Republic, May 2003

[8.] Constantinescu, D., Sîrbu, E., Smical, I. Equipment for Metallurgical Processing and the Environment; Metalurgia International, Special Issue nr.2, February 2009 pag.63, ISSN 1582-2214

[9.] Constantinescu, D.,. Application of the mathematical modeling to the dynamic design of the thermal space of the furnaces for rolling mills; METAL2007, 16th Metallurgical and Material Conference, Hradec nad Moravici, Czech Republic, May 2007, pag.51, ISBN 978-80-86840-33-8, http://www.metal2007.com

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