# PARTICULARITIES REGARDING THE THERMAL RADIATION INSIDE THE HEATING FURNACES FOR METAL FORMING

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**Abstract**

During the thermal processes in metallurgy, it is important in many cases to know the exactly particularities of heat transfer in a complex system. In the case of steel semi-finished products heating, the most of the models refers to the heat exchange by convection and radiation or to the heat transfer by conductivity inside the material. The heat transfer by radiation has two important components: the value of the heated surface by radiation and the values of the radiation coefficient. The aim of this analysis is to establish the basic relations for a model in order to evaluate the parameters of the heat transfer and energy consumption in the case of some metallurgical heating furnaces. The article refers also to "the equivalent surface of heat transfer" (a new term proposed by the authors), connected to the modality of billets disposal in various types of heating furnaces. Starting from the considerations regarding the burning process of the fuels, there were established relations between the heat exchange coefficients, energy and metallic material saving. We are considering that it is an important difference between various types of continuous operating furnaces: while in the pusher-type furnace the billets may be disposed only one near the other, without free spaces between them, the walking-beam furnace or the rotary hearth furnace allows the disposal of the billets at the required distances. Modifying this distance, it is the possibility of acting upon: the billets stationary time in the furnace, the temperature distribution in the section of the billets and the oxidation and decarburization decrease. Saving energy and metal consumption due to the oxidation process means to have a cleaner environment.

**Keywords:** Heat transfer, plastic deformation, billet, mathematical model, furnace

## 1. THE OBJECTIVES OF THE ARTICLE

When a billet or an ingot is heated in view of forming, we have to take into consideration the main phenomena which occur in the thermal space. In **Fig. 1** there are presented the phenomena we have to take into consideration.

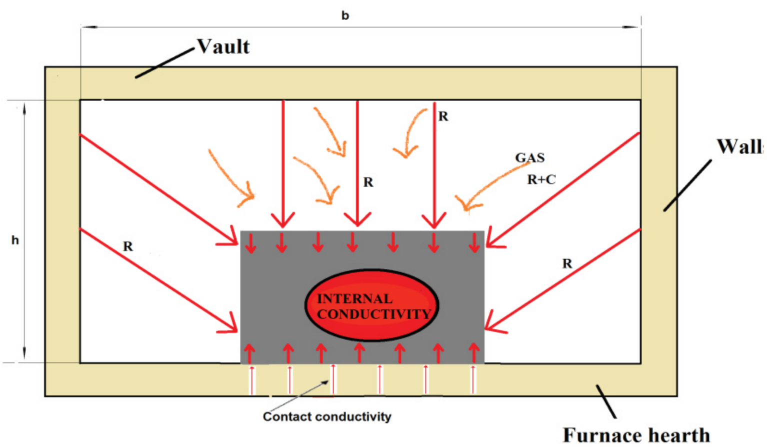


**Fig. 1** The main thermal phenomena which occur in the furnace thermal space; GAS R+C: radiation and convection due to the flow gases; R: radiation from the thermal isolation; contact conductivity includes the effect of the steel oxides

The interaction between the heat exchange phenomena is very complex and we have to take this into consideration if we are expecting to obtain a good quality of heating and an energy reduction. The material saving will influence the decrease of the industrial *ecological footprint*.

## 2. THE RADIATION HEAT EXCHANGE BETWEEN THE FURNACE THERMAL ISOLATION AND THE STEEL BILLET

The computation of the radiation heat exchange between the thermal isolation components may be calculated using the angular coefficient of radiation, $\varphi$, recommended by Heiligenstaedt [1].

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

For the equation (1), it is noted: h - height of the heating space; b - width and l - length of the heating space; $B = h/b$ and $L = l/b$ (**Fig. 1**). In the case of heat exchange between the thermal isolation and the billets, the coefficient $\varphi$ is [2]:

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

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

$$Q_{pm} = \alpha_{pm} \cdot \varepsilon_{pm} \cdot S \cdot (\theta_p - \theta_s) \quad (3)$$

$\theta_s$: temperature of the metallic billet at the surface, °C (**Fig. 2**)
S: heated surface of the metallic material (billets); here it is necessary to calculate the *„equivalent surface of heat exchange“*, m$^2$ [3]
$\theta_p$: temperature of the thermal isolation inside the furnace, °C
$\alpha_{pm}$: radiation heat exchange coefficient between the thermal isolation and the billet, $kJ \cdot m^{-2} \cdot h^{-1} \cdot K^{-1}$
$\varepsilon_{pm}$ : thermal emissivity coefficient for metal and refractory isolation

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 to the quantity of the energy that the metal could receive from the flue gases, if the temperature of the gases is equal with the temperature of the thermal isolation:

$$Q_{abs} = \alpha_{gpm} \cdot \varepsilon_p \cdot S \cdot (\theta_p - \theta_s) \quad (4)$$

$\alpha_{gpm}$: coefficient of the heat exchange from the gases to the metallic material, if it is considered that the temperature of the gases is equal with the temperature of the thermal isolation, $kJ \cdot m^{-2} \cdot h^{-1} \cdot K^{-1}$
$\varepsilon_p$: coefficient of the thermal emissivity of the isolation

The real value of $Q_{pm}$ is:

$$Q_{pm} = S(\alpha_{pm} \cdot \varepsilon_{pm} - \alpha_{gpm} \cdot \varepsilon_p) \cdot (\theta_p - \theta_s) \quad (5)$$

It is possible to write:

$$S_p \cdot (\alpha_{gp} \cdot \varepsilon_p + \alpha_c) \cdot (\theta_g - \theta_p) = S \cdot (\alpha_{pm} \cdot \varepsilon_{pm} - \alpha_{gpm} \cdot \varepsilon_p) \cdot (\theta_p - \theta_s) + S_p \cdot q_{ex} \quad (6)$$

$S_p$: surface of the thermal isolation
$\theta_{ga}$: temperature of the flue gases on the exit of the furnace, °C
$\alpha_{gp}$: coefficient of the radiation heat exchange between the gases and the thermal isolation, $kJ \cdot m^{-2} \cdot h^{-1} \cdot K^{-1}$
$\varepsilon_p$: coefficient of the thermal emissivity of the isolation (refractory material)
$\alpha_c$ : coefficient of convection heat exchange between the gases and the thermal isolation, $kJ \cdot m^{-2} \cdot h^{-1} \cdot K^{-1}$
$\theta_g$: temperature of the flue gases, °C
$q_{ex}$: thermal flow through the furnace isolation, $kJ \cdot m^{-2} \cdot h^{-1}$

If it is noted the ratio between the „equivalent surface of heat exchange" and the surface of the thermal isolation, $\sigma = S/S_p$, the equation (6) will be:

$$\theta_g \cdot (\alpha_{gp} \cdot \varepsilon_p + \alpha_c) = \theta_p \cdot (\alpha_{gp} \cdot \varepsilon_p + \alpha_c + \sigma \cdot \alpha_{pm} \cdot \varepsilon_{pm} - \sigma \cdot \alpha_{gpm} \cdot \varepsilon_p) - \theta_s \cdot \sigma (\alpha_{pm} \cdot \varepsilon_{pm} - \alpha_{gpm} \cdot \varepsilon_p) + q_{ex} \quad (7)$$

It is clear that together with the value of the emission coefficients, the *equivalent surface of heat exchange* has also an important impact on the value of the heat transmitted to the metallic body (billet).

## 3. RADIATION HEATING SURFACE OF THE STEEL BILLETS

In order to analyse the radiation surface of the billets (the equivalent surface of heat transfer), there were taken into consideration some frequent cases for the heating furnaces [3]. In **Figs. 2 and 3** there are presented the cases of the square and rectangular sections. In **Table 1** it is a comparison between the two cases.

**Table 1** Comparison between the evaluation of the equivalent surface of heat transfer for the square and rectangular sections of the billets

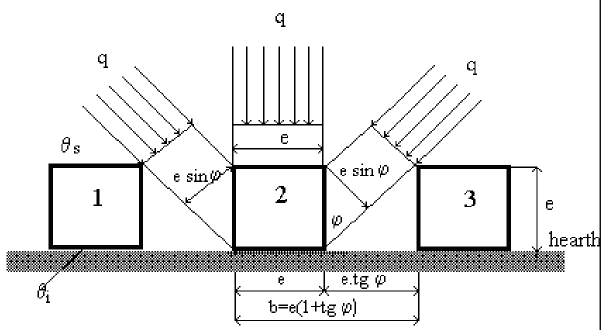


**Fig. 2** Heating of the billets with square section on the hearth of the furnace; q - thermal flow; $\varphi$ - angle of radiation; $\theta_s$ - temperature of the upper surface; $\theta_i$ - temperature of the inferior surface of the billet; *l* - length of the billet

$$S = e \cdot l + 2 \cdot e \cdot l \cdot sin\varphi = e \cdot l(1 + 2sin\varphi) \quad (8)$$

The difference of the temperature between the hot and cold surface, $\Delta\theta$, will be:

$$\Delta\theta = \theta_s - \theta_i = \frac{q}{\lambda} \cdot (1 + 2\sin\varphi) \quad (9)$$

$\lambda$ - thermal conductivity of the steel

If the billets are stuck, as in case of the pusher-type furnace with heating by the upper face, then sin $\varphi$ = 0.
If the billets are distanced one to each other, ($e$<<$e$.tg $\varphi$), then lim(sin $\varphi$) =1. In this situation it was obtained a better uniformity of the temperature on the billet section than in case of the both faces heating in the pusher-type furnace. The heating mode equivalent to the situation of the both faces heating in the pusher-type furnace is obtained for the case of the walking beam furnace, when $\varphi$ = 60°.
The most favourable situation from the thermal point of view, in the case of the heating square billets, would be when $\varphi$ = 60°. Having in view the requirement to provide a high degree of furnace hearth charging, as well as the

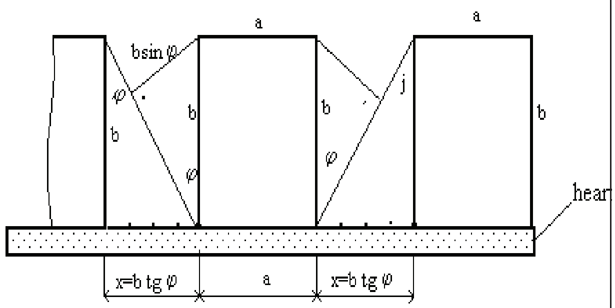


**Fig. 3** Heating of billets with rectangular section on the hearth of the furnace (same notation as for 2); $a/b = f$

$$S = l \cdot b \cdot (j \cdot tg\,\varphi + 2\sin\varphi) \quad (14)$$

*j* = 2 ÷0.4, depending on the distance between the billets

Examples:
$x$=0.5·$a$ : $S$=$l$·$b$·(2·tg $\varphi$+$e$·sin $\varphi$)
x=2.5·a : $S$=$l$·$b$·(0.4·tg $\varphi$+2·sin$\varphi$)

Analyzing the obtained data, we can remark:
- the maximal values of equivalent surface in the conditions of $a$ = $ct$, there are obtained at an incidence angle of the thermal radiation of 30°; from these, the biggest value is obtained in the case of $x$ = 2.5$a$, for ratio of $a/b$ = 0.25
-the smallest values of the coefficient of optimum distance, z, are obtained for a distance between billets of x = 1.5a........2a and for the values of the incidence angle of thermal radiation of 45......60°; in these conditions, the optimum value of the ratio between the section sides of billet must be 0.6.......1.2; at the distance of $x$ > 2.5$a$, the coefficient „z" may be considered constant.
- the specific time of heating is first of all influenced by the shape of the billet section: the minimum value is obtained for flat billets ($f$ = 5.5; $l$ = 0.05 ); for similar values of the

same productivity, it must be taken into consideration the case when φ = 45°. This represents, on the basis of established data, practically the optimum supposed situation from the point of view of the heating uniformity, the heating time and furnace productivity.
To analyze easier the heating mode of the billets, it will be introduced the notion "specific time of internal heating - STIH", representing the necessary time to heat a billet with effective thickness (which corresponds to the geometric thickness and is different from the thermal thickness which is reported to the Biot criteria; in the case of square section billets, $X = e$), reported to the thermal diffusivity, "$a_0$", suitable to the heating temperature:

$$t = \frac{X^2}{a_0} = \frac{X^2 \cdot c \cdot \rho}{\lambda} \qquad (10)$$

For modelling the heat transfer by radiation, we propose to use the main relations (**Table 1.1**), in the case of square section.

**Table 1.1** Functions for modelling the heat transfer by radiation for the square section billets

| | |
|---|---|
| function of equivalent surface of heat exchange | $k_1 = 1 + 2sin\varphi$ |
| function of heating duration | $k_2 = \frac{(1+4\sin^2\varphi)}{(1+2\sin\varphi)}$ |
| function of the specific time of internal heating | $i = \frac{1}{(1+4\sin^2\varphi)}$ |
| criteria of optimum distance between billets | $z = \frac{(1+tg\varphi)}{(1+4\sin^2\varphi)}$ |
| specific time of internal heating | $t = X^2 \cdot \frac{i}{a_0}$ |

The specific time of internal heating:

$$t = \frac{e^2 \cdot c \cdot \rho}{(1+4\sin^2\varphi)\cdot\lambda} \qquad (11)$$

The heating duration:

$$\tau = t \cdot \frac{\theta_f - \theta_i}{\Delta\theta} \cdot \frac{1+4\sin^2\varphi}{1+2\sin\varphi} \qquad (12)$$

The productivity $P$ can be calculated using the relation:

$$P = \frac{m \cdot n \cdot \Delta\theta}{t \cdot k_2 \cdot (\theta_f - \theta_i)} = \frac{m \cdot L_c \cdot \Delta\theta}{t \cdot k_2 \cdot (\theta_f - \theta_i) \cdot e} \qquad (13)$$

where $L_c$ is the length of the furnace

ratio, the value of the STIH decreases by the increase of the distance *x*;
- for the interval considered optimum ($x$ = 1.5*a*.......2*a* ), i has the value (0.3....0.4) for *f* =(0.6....0.5 ), (*φ* = 45°) and ( 0.18....0.22 ) for *f* = (1.1....0.9 ), (*φ* = 60°)
-for $x > 2a$, the STIH for the same values of the incidence angle is not very modified.
For modelling the heat transfer by radiation, we proposed to use the main relations presented in **Table 1.2** for the case of rectangular section:
*STIH* - represents the time necessary to heat a billet with effective thickness (which corresponds to the geometric thickness and is different from the *thermal thickness* which is reported to the Biot criteria; in this case, the section $X = b$), reported to the thermal diffusivity "$a_0$", suitable to the heating temperature is the same as in the equation (10).
For modelling the heat transfer by radiation, we are proposing to use the main relations (**Table 1.2**), in the case of rectangular section.

**Table 1.2** Functions for modelling the heat transfer by radiation for the rectangular section billets

| | |
|---|---|
| function of equivalent surface of heat exchange | $k_1 = j \cdot tg\varphi + 2 \cdot \sin\varphi$ |
| function of heating duration | $k_2 = \frac{j \cdot tg^2\varphi + 4\sin^2\varphi}{j \cdot tg\varphi + 2\sin\varphi} = \frac{1}{k_1 \cdot i}$ |
| function of the specific time of internal heating | $i = \frac{1}{j \cdot tg^2\varphi + 4\sin^2\varphi}$ |
| criteria of optimum distance between billets | $z = \frac{b \cdot (f + tg\varphi)}{j \cdot tg^2\varphi + 4\sin^2\varphi} = b \cdot (f + tg\varphi) \cdot i$ |
| specific time of internal heating | $t = X^2 \cdot \frac{i}{a_0}$ |

The heating duration:

$$\tau = t \cdot \frac{\theta_f - \theta_i}{\Delta\theta} \cdot \frac{j \cdot tg^2\varphi + 4sin^2\varphi}{j \cdot tg\varphi + 2sin\varphi} \qquad (15)$$

$\theta_f$ and $\theta_i$: final and initial average temperatures of the heated material

The productivity $P$ will be calculated in this case using the relation:

$$P = \frac{m \cdot L_c \cdot \Delta\theta}{t \cdot k_2 \cdot (\theta_f - \theta_i) \cdot b \cdot f} \qquad (16)$$

## 4. HEAT EXCHANGE BY CONVECTION AND RADIATION OF THE FLUE GASES

The equation (7) correlates the temperature of the flue gases, the temperature of the thermal isolation and the temperature of the billets ($\theta_s$). However, the establishing of the values of the heat exchange coefficients put yet some dificulties.
The thermal flow sent to the metallic material (billets) includes:

- radiation thermal flow from the thermal isolation

$$q_{pm} = (\alpha_{pm} \cdot \varepsilon_{pm} - \alpha_{gp} \cdot \varepsilon_p)(\theta_p - \theta_s) \quad [\text{kJ} \cdot \text{m}^{-2} \cdot \text{h}^{-1}] \tag{17}$$

- radiation and convection thermal flow from the flue gases

$$q_{gm} = (\alpha_{gm} \cdot \varepsilon_m + \alpha_c)(\theta_g - \theta_s) \tag{18}$$

- the conductive thermal flow from the furnaces hearth to the heated metal (it is important especialy at the beginning of the heating process) [4], when the billet or the ingot is introduced in the thermal space of the aggregate (**Fig. 1**).

The total thermal flow received by the billets is:

$$q = q_{pm} + q_{gm} + q_{vm} \tag{19}$$

There were obtained the following expressions regarding the complex heat exchange by radiation and convection in the analysed furnace:

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

$$\alpha_1 = \frac{\alpha_{gm} \cdot \varepsilon_m + \alpha_c}{\alpha_{gp} \cdot \varepsilon_p + \alpha_c} \cdot \left( \alpha_{gp} \cdot \varepsilon_p + \alpha_c + \sigma \cdot \alpha_{pm} \cdot \varepsilon_{pm} - \sigma \cdot \alpha_{gm} \cdot \varepsilon_p + \frac{q_{ex}}{\theta_p - \theta_s} \right) [\text{kJ} \cdot \text{m}^{-2} \cdot \text{h}^{-1} \cdot \text{K}^{-1}] \tag{20}$$

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

$$\alpha_2 = \frac{\alpha_{pm} \cdot \varepsilon_{pm} - \alpha_{gpm} \cdot \varepsilon_p}{\alpha_{gp} \cdot \varepsilon_p + \alpha_c + \sigma \cdot (\alpha_{pm} \cdot \varepsilon_{pm} - \alpha_{gpm} \cdot \varepsilon_p)} \cdot \left( \alpha_{gp} \cdot \varepsilon_p + \alpha_c - \frac{q_{ex}}{\theta_g - \theta_s} \right) + \alpha_{gm} \cdot \varepsilon_m + \alpha_c [\text{kJ} \cdot \text{m}^{-2} \cdot \text{h}^{-1} \cdot \text{K}^{-1}] \tag{21}$$

3) The heat transfer coefficient between the furnace hearth and the billet:

$$\kappa = \frac{k_3}{2\sqrt{\tau}} \left\{ \frac{e^{n^2}}{n} [1 - \Phi(n)] - \frac{1}{n} + \frac{2}{\sqrt{\pi}} \right\} \tag{22}$$

where:

$\Phi(n) = \frac{2}{\sqrt{\pi}} n \left( 1 - \frac{n^2}{3 \cdot 1!} + \frac{n^4}{5 \cdot 2!} - \frac{n^6}{7 \cdot 3!} + \ldots \right)$ and $k_3 = \frac{\lambda_3}{\sqrt{a_3}} = \sqrt{\lambda_3 \cdot c_3 \cdot \rho_3}$ (refers to the hearth properties) [5, 6]

## 5. THE OXIDATION PROCESS AND THE OUTPUT OF THE FURNACE

In the case of the heating process in furnaces using the combustion, the source of energy can be analysed from two points of view:

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

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

The presence of the oxides layers on the surface of the billets or ingots influences the transfer of the heat by contact conduction. In **Fig. 4** are presented the values of the thermal conductivity of the ferrous oxides [4]. The values of the thermal conductivity of the oxides, together with the value of the thermal conductivity of the refractory material of the hearth, influences the transfer coefficient, κ (equation 22).

The values of the thermal flow, q, which determinates the value of Δθ [**Fig. 1** and equations (13) and (16)] and by this the furnace's output are presented in the **Fig. 5.**

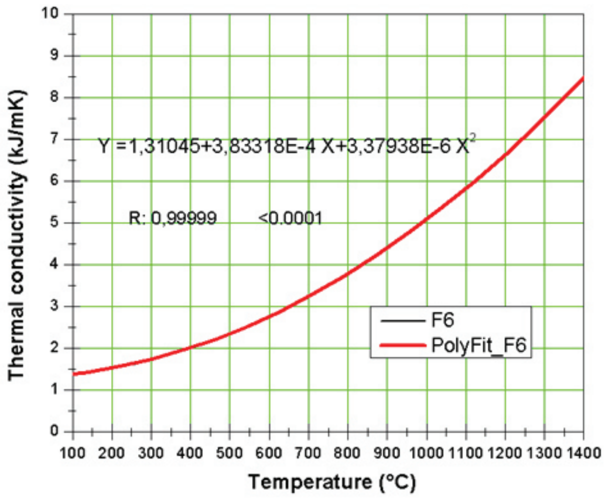


**Fig. 4** Values of the thermal conductivity for ferrous oxides obtained using experimental data

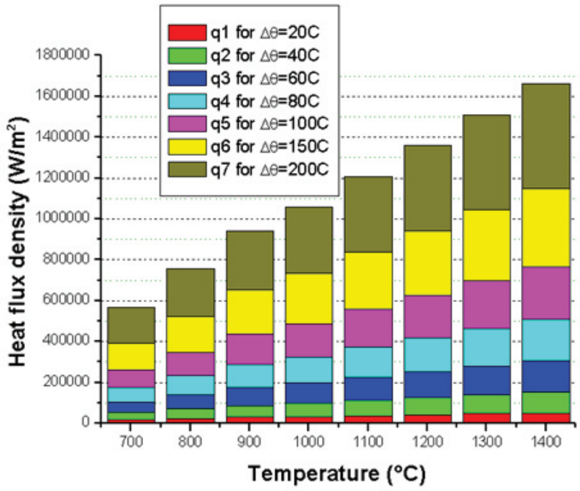


**Fig. 5** Thermal flow, statistics (function of Δθ, thermal conductivity and temperature of the refractory hearth

## 6. CONCLUSIONS AND DISCUSSIONS

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. By the 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 billet or ingot. The coefficients $\alpha_1$, $\alpha_2$, κ, as well as the function $\Phi(n)$ and the disposal mode of the billets or ingots are at the basis of the control process of heat exchange between the flue gases, metallic material and the thermal isolation.

For the next steps of studies we have in view to establish some correlations between the heating technology, the energy consumption and the ecological footprint of the thermal aggregates on the environment.

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