Elements for the modeling of the thermal process in heating furnaces for steel forming

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Abstract. In the present paper, by "modelling of thermal process" will be understood the thermal techniques modelling, applied to the heating of steel billets in a large scale, in view of processing by forming. These technologies are correlated with the particularities of the thermal aggregates, having as main objective the reducing of energy consumptions and the optimizing of the aggregate design. When heating the steel billets in view of processing by forming, the duration and the quality of heating are influenced by the modality that the billets are receiving the thermal flow. The reception of the thermal flow depends on the heated surface exposed to the thermal radiation in compliance with their position on the hearth of the heating aggregate. The present paper intends to establish some parameters in view of optimizing the heating process. A basic point of the work is also the determination of some components of a mathematical model for the proposed heating technology. The authors have in view the complexity of the technical evolutions of the furnaces.

1 The objective of the article

The correlation between the thermal phenomena in a heating aggregate for the steel forming is very complex. We have to take this into consideration if we are expecting to obtain a good quality of heating and an energy and material reduction.

For example, the evaluation of the radiation heat exchange between the thermal isolation components may be calculated using the angular coefficient of radiation,φ, recommended by Heiligenstaedt [1], [2].

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

where B and L refers to the ratio between the geometrical dimensions of the heated billets and the thermal aggregate (e.g. $B = h/b,\ L = l/b$) (figure 1)

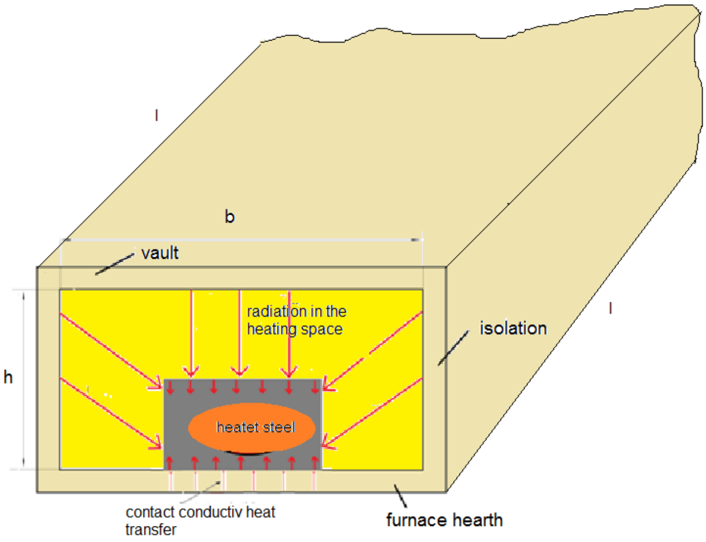
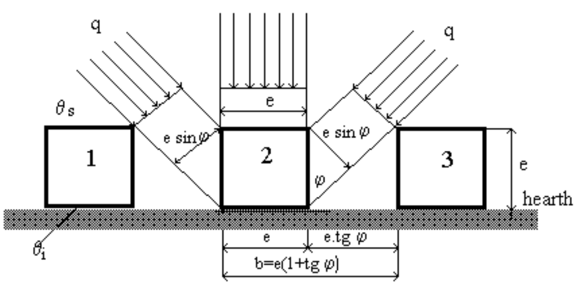
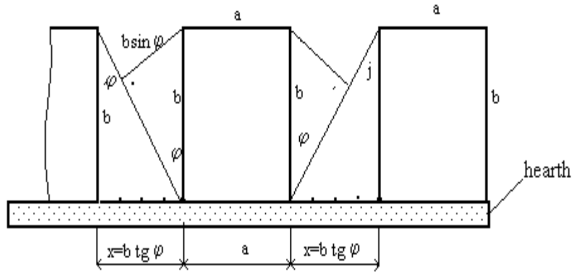


Figure 1. Heat transfer by radiation and contact conduction in the fourance with the dimanssion *b·l·h.*

2 Geometry and heat transfer

In order to analyse the heat exchange by radiation there were taken into consideration some cases for the heating furnaces. In figures 2 and 3 there are analysed the cases of the square and rectangular sections [2], [3]. In table 1 it is a presented a comparison between the two cases [3] and in table 2 it is analyzed the case of the billets with circular section.

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

 **Figure 2**. Heating of the billets with square section on the hearth of the furnace; q - thermal flow; φ - angle of radiation; θ_s – temperature of the upper surface; θ_i – temperature of the inferior surface of the billet; l – length of the billet; S – equivalent surface of heat exchange $S = e \cdot l + 2 \cdot e \cdot l \cdot sin\varphi = e \cdot l(1 + 2sin\varphi)$ (2) The difference of the temperature between the upper and inferior surface, *Δθ*, will be: $\Delta\theta = \theta_s - \theta_i = \frac{q}{\lambda} \cdot (1 + 2\sin\varphi)$ (3) λ – thermal conductivity of the steel If the billets are stuck, (as in case of the pusher-type furnace), heating by the upper face, then sin φ=0. If the billets are distanced one to each other, (*e<<e.tg φ)*, then *lim(sin* φ) *=1*. In this situation it was obtained a better uniformity of the temperature on the billet	 **Figure 3**. Heating of billets with rectangular section on the hearth of the furnace (same notation as for figure 2); $^a/_b = f$ $\boxed{S = l \cdot b \cdot (j \cdot tg\varphi + 2\sin\varphi)}$ (8) j = 2 ÷0.4, depending on the distance between the billets Examples: *x=0.5·a* : *S=l·b*·(*2*·tg φ+*e*·sin φ) x=2.5·a : *S=l·b*·(*0,4*·tg φ+*2*·sinφ) Remarks: -the maximal values of equivalent surface in the conditions of *a = ct*, there are obtained at an incidence angle of the thermal radiation of 30^0; from these, the biggest value is obtained in the case of x=2.5a, for ratio of a/b = 0.25 -the smallest values of the coefficient of optimum

section than in case of the both faces heating in the pusher-type furnace. The heating mode equivalent to the case of the both faces heating in the pusher-type furnace is obtained for the case of the walking beam furnace, when $\varphi=60^0$.

The most favourable possibility, from the thermal point of view, in the case of the heating square billets, would be when $\varphi=60^o$. Having in view the requirement to provide a high degree of furnace hearth charging, as well as the same productivity, it must be taken into consideration the case when $\varphi=45^o$. 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*",[3] 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:

$$t = \frac{X^2}{a_0} = \frac{X^2 \cdot c \cdot \rho}{\lambda} \tag{4}$$

For modelling, we propose to use the main relations, in the case of square section, presented below:

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

The specific time of internal heating:

$$t = \frac{e^2 \cdot c \cdot \rho}{\left(1 + 4\sin^2\varphi\right) \cdot \lambda} \tag{5}$$

Example: STIH for reinforcing bars

X mm	80	100	120	140	200
t min	10.6	16.7	24.0	32.8	66.8

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......60^0; 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>2.5a, 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; i=0.05); for similar values of the ratio, the value of the STIH decreases by the increase of the distance x;

-for the interval considered optimum (x=1.5a.......2a), "i" has the value (0.3....0.4) for f=(0.6....0.5), ($\varphi=45^0$) and (0.18....0.22) for f=(1.1....0.9), ($\varphi=60^0$)

-for x>2a, the STIH for the same values of the incidence angle is not very modified.

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.

For modelling, we are proposing to use the main relations, in the case of rectangular section:

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

The heating duration:

$$\tau = t \cdot \frac{\theta_f - \theta_i}{\Delta\theta} \cdot \frac{j \cdot tg^2\varphi + 4sin^2\varphi}{j \cdot tg\varphi + 2sin\varphi} \tag{9}$$

θ_f and θ_i: final and initial average temperatures of the heated material

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

$$P = \frac{m \cdot L_c \cdot \Delta\theta}{t \cdot k_2 \cdot (\theta_f - \theta_i) \cdot b \cdot f} \tag{10}$$

Following [3], some data for the relations are:

x	φ	f	j	k_1	k_2
0.5a	26	1	1	1,88	0,94
	30	1.15	2	2,15	0,77
	45	2	2	3,41	1,17

The heating duration:

$$\tau = t \cdot \frac{\theta_f - \theta_i}{\Delta \theta} \cdot \frac{1 + 4 \sin^2 \varphi}{1 + 2 \sin \varphi} \tag{6}$$

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

$$P = \frac{m \cdot n \cdot \Delta\theta}{t \cdot k_2 \cdot (\theta_f - \theta_i)} = \frac{m \cdot L_c \cdot \Delta\theta}{t \cdot k_2 \cdot (\theta_f - \theta_i) \cdot e} \tag{7}$$

where L_c is the length of the furnace

	60	3.5	2	5,19	1,75
	70	5.5	2	7,37	2,71
a	30	0.57	1	1,57	0,84
	45	1.00	1	2,41	1,25
	60	1.70	1	3,46	1,70
	70	2.75	1	4,62	2,40
1.5a	30	0.30	0.66	1,38	0,89
	45	0.60	0.66	2,07	1,68
	60	1.15	0.66	2,87	1,89
	70	1.80	0.66	3,69	2,46
2a	30	0.30	0.5	1,28	1,70
	45	0.50	0.5	1,91	1,74
	60	0.90	0.5	2,60	1,75
	70	1.40	0.5	3,25	2,21

Table 2. Heating of the billets with circular section (R-radius; l – length of the billet).

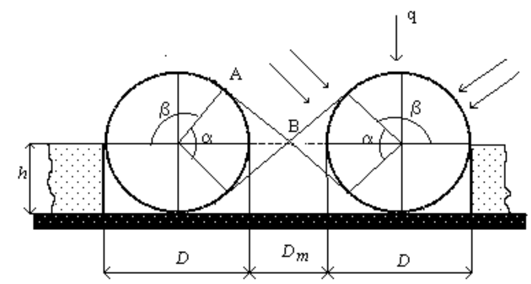


Figure 4. Heating of the billets with circular section in a roller heat furnace (a).

$$\alpha = 2\arccos[D/(D_m + D)] \tag{11}$$

$$\beta = 180 - \arccos[D/(D_m + D)] \tag{12}$$

$$S = R \cdot l \left[180 + \arccos \frac{D}{D_m + D}\right] \cdot \frac{\pi}{180} \tag{13}$$

<u>Case c)</u> In case (a), if $h=D/4$, it is obtained :

$$\alpha = 2 \arccos \frac{D}{D + D_m} \quad \text{and} \quad \beta = 210 - \arccos \frac{D}{D + D_m}$$

$$S = R \cdot l \cdot \left[210 + \arccos \frac{D}{D + D_m}\right] \cdot \frac{\pi}{180} \tag{14}$$

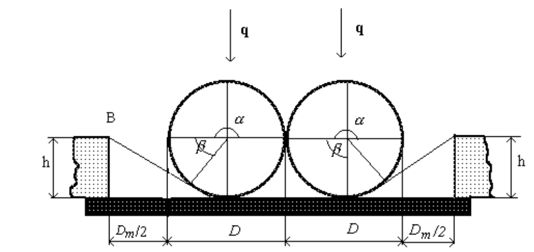


Figure 5. Heating of the billets with circular section on the hearth of the furnace (b).

$$\alpha = 180^o \qquad \beta = \arccos \frac{D}{D + D_m} \tag{15}$$

$$S = R \cdot l \cdot \left[180 + \arccos \frac{D}{D + D_m}\right] \cdot \frac{\pi}{180}$$

(16)

<u>Case d)</u> In case when the billets do not support to the border and are tangent to the middle of the hearth , the equivalent surface will be given by :

$$S = R \cdot l \left[180 + arctg \frac{D}{2(D + D_m)} + \arccos \frac{2D}{\sqrt{4(D + D_m)^2 + D^2}}\right] \cdot \frac{\pi}{180} \tag{17}$$

<u>Case e)</u> If over the two billets which support to the border ($h=0,5D$) it is placed the third one with the same diameter D , ($D \geq D_m$), the following relations for equivalent surfaces are obtained :

$$S = R \cdot l \cdot \left(180 - \arccos \frac{D + D_m}{2D}\right) \cdot \frac{\pi}{180} \tag{18}$$

- for the ingot placed above :

$$S = R \cdot l \cdot \left(180 + 2 \arccos \frac{D + D_m}{2D}\right) \cdot \frac{\pi}{180} \tag{19}$$

The general form of relations for the equivalent surface of heat exchange will be :

$$\boxed{S = k_1 \cdot R \cdot l} \tag{20}$$

The geometric surface of billets is $S_0 = 6{,}28 \cdot R \cdot l$, thus S could be written :

$$\boxed{S = 0{,}159 \cdot k_1 \cdot S_0} \tag{21}$$

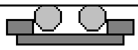
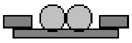
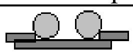
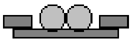
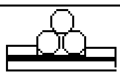
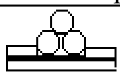
The heating time will be determined by relation:

$$\tau = \frac{\pi \cdot R \cdot \rho \cdot c \cdot \left(\theta_f - \theta_i\right)}{k_1 \cdot q} \tag{22}$$

where q is the thermal flow (kJ/m^{2}h); θ_f and θ_i: final and initial temperatures of the billet

In the table 3 are presented the values for the coefficient k_1 and for the equivalent surface of heat exchange.

Table 3. Values of the coefficient k_1 and the equivalent surface S.

Disposal mod of the billets	Ratio D_m/D	k_1	S
 case a) equ. (13)  case b) equ. (16)	D_m=4D D_m=2D D_m=1D D_m=(2/3)D D_m=0,5D	4,51 4,37 4,19 4,07 3,98	0,72S_0 0,69S_0 0,67S_0 0,65S_0 0,63S_0
 case c) equ. (14)	D_m=4D D_m=2D D_m=1D D_m=(2/3)D D_m=0,5D	5,05 4,95 4,82 4,76 4,71	0,80S_0 0,79S_0 0,77S_0 0,76S_0 0,75S_0
 case d) equ. (17)	D_m=4D D_m=2D D_m=1D D_m=(2/3)D D_m=0,5D	4,61 4,54 4,43 4,36 4,30	0,73S_0 0,72S_0 0,71S_0 0,69S_0 0,68S_0
 case e) equ.(18)	D_m=D D_m=(2/3)D D_m=0,5D	3,14 2,56 2,42	0,50S_0 0,41S_0 0,39S_0
 case e) equ.(19)	D_m=D D_m=(2/3)D D_m=0,5D	3,14 4,31 4,59	0,50S_0 0,69S_0 0,73S_0

4 Diagrams regarding the optimization of the heating

In order to select the best possibility for the billets disposal in a heating furnace we will use the criteria of the optimum distance, z (figure 6). Of course, we have to consider also the specific time of internal heating, function "i" (figure 7).

Applications for the optimization function in the case of square billets section are presented in figure 8.

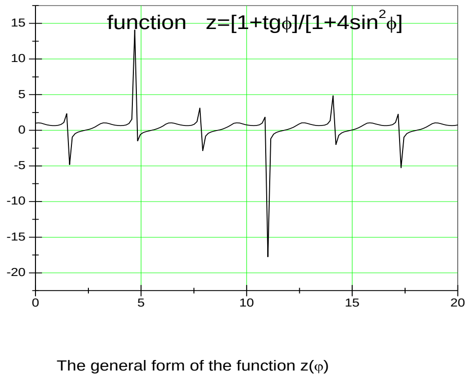


Figure 6. The graphic form of function “z”.

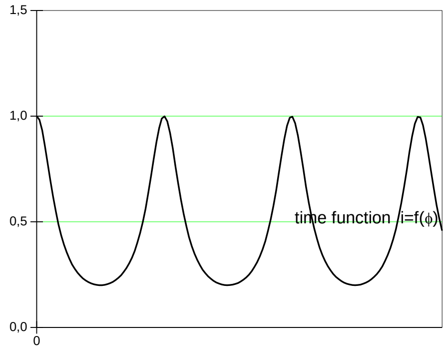


Figure 7. Function of the specific time of internal heating, i=f(φ).

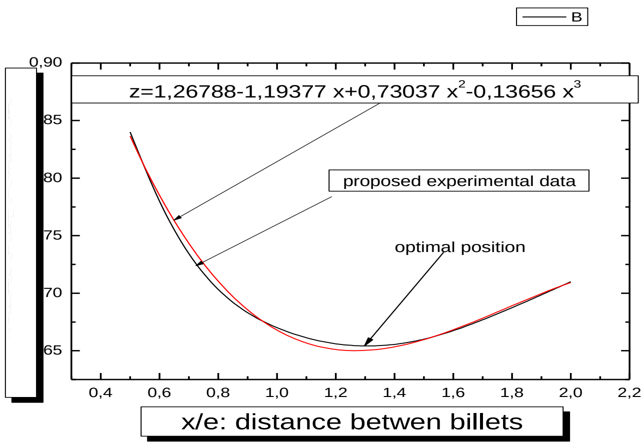


Figure 8. Optimal disposal of the square billets section in the furnace.

5 Conclusions

The coefficients regarding the disposal mode of the billets or ingots in a metallurgical heating furnace are basic to control the process of heat exchange between the flue gases, metallic material and the thermal isolation. The mathematical model can be established using the coefficient of the equivalent surface of heat exchange, the equivalent surface of heat exchange, coefficient of specific time of internal heating, criteria of optimum distance, calculation coefficient of the heating time. In case of square and rectangular section billets the optimum case (which correlates the charging mode, uniformity and time of heating with the output of the furnace) is given by the minimum value of the optimization function. In the case of circular sections, the equivalent surface of the heat exchange is established starting from the geometrical surface, using the special coefficient (k_1). The real heating time will be determined in case of rectangular sections billets by means of coefficient k_2 and in case of circular section billets by means of coefficient k1 and of equivalent surface of heat exchange.

References

[1] Heiligenstaedt W.: Thermique appliquee aux fours industriels, tom1, Dunot, Paris, 1971
[2] Constantinescu D, Carlan AB ; Particularities regarding the thermal radiation inside the heating furnaces for metal forming, METAL 2015, Brno, Editor: Tanger Ltd, Ostrava, CZ, pag.282-287 ; ISBN 978-80-87294-62-8];
[3] Constantinescu D, Aspects Regarding The Heat Transfer In Furnaces For Rolling Mills; WITpress, Heat Transfer VII, 2002, DOI: 10.2495/HT020271; ISBN 1-85312-9062; ISSN 1462-6063