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, \( \varphi \), recommended by Heiligenstaedt [1], [2].

\[
\varphi = \frac{1}{2 \pi} \left( \frac{B}{\sqrt{1 + B^2}} \arcsin \frac{L}{\sqrt{1 + B^2 + L^2}} + \frac{L}{\sqrt{1 + L}} \arcsin \frac{B}{\sqrt{1 + B^2 + L^2}} \right) \tag{1}
\]

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)
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 presented a comparison between the two cases [3] and in table 2 it is analyzed the case of the billets with circular section.

![Figure 1](image1)

**Figure 1.** Heat transfer by radiation and contact conduction in the fourance with the dimensions $b \times l \times h$.

![Figure 2](image2)

**Figure 2.** Heating of the billets with square section on the hearth of the furnace; $q$ - thermal flow; $\phi$ - angle of radiation; $\theta_i$ - temperature of the upper surface; $\theta_s$ - temperature of the inferior surface of the billet; $l$ - length of the billet; $S$ - equivalent surface of heat exchange $S = e \cdot l + 2 \cdot e \cdot l \cdot \sin \phi = e \cdot l (1 + 2 \sin \phi)$ (2)

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

$$\Delta \theta = \theta_s - \theta_i = \frac{q}{\lambda} \cdot (1 + 2 \sin \phi)$$ (3)

$\lambda$ - thermal conductivity of the steel

If the billets are stuck, (as in case of the pusher-type furnace), heating by the upper face, then $\sin \phi = 0$. If the billets are distanced one to each other, ($e < 0.2 \cdot tg \phi$), then $\lim(\sin \phi) = 1$. In this situation it was obtained a better uniformity of the temperature on the billet.

![Figure 3](image3)

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

$$S = l \cdot b \cdot (j \cdot tg \phi + 2 \sin \phi)$$ (8)

$j = 2 \div 0.4$, depending on the distance between the billets

Examples:

$x=0.5 \cdot a : S=l \cdot b \cdot (2 \cdot tg \phi + e \cdot sin \phi)$

$x=2.5 \cdot a : S=l \cdot b \cdot (0.4 \cdot tg \phi + 2 \sin \phi)$

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 $30^\circ$; 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
The specific time of internal heating:

\[ t = \frac{x^2 \cdot c \cdot \rho}{(1 + 4 \sin^2 \varphi) \cdot \lambda} \]  

(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 |

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 \( \varphi = 60^\circ \).

The most favourable possibility, from the thermal point of view, in the case of the heating square billets, would be when \( \varphi = 60^\circ \). 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 \( \varphi = 45^\circ \). 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, \( X = a_o \)), reported to the thermal diffusivity, \( \"a_o\", \) suitable to the heating temperature:

\[ t = \frac{x^2}{a_o} \cdot \frac{X^2 \cdot c \cdot \rho}{\lambda} \]  

(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 | \( k_1 = 1 + 2 \sin \varphi \) |
| 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 | \( z = \frac{(1 + 2 \sin \varphi)}{(1 + 4 \sin^2 \varphi)} \) |
| specific time of internal heating | \( t = X^2 \cdot \frac{i}{a_o} \) |

The specific time of internal heating:

\[ t = \frac{x^2 \cdot c \cdot \rho}{(1 + 4 \sin^2 \varphi) \cdot \lambda} \]  

(5)

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

| X | \( \varphi \) | \( f \) | \( j \) | \( k_1 \) | \( k_2 \) |
|---|---|---|---|---|---|
| 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:

\[
\tau = t : \left( \frac{\theta_2 - \theta_1}{4 \sin \varphi} \right) \left( \frac{1+4 \sin \varphi}{1+2 \sin \varphi} \right)
\]

(6)

The productivity \( P \) can be calculated using the relation:

\[
P = \frac{m \cdot \Delta \theta}{k_c \cdot (\theta_2 - \theta_1)} = \frac{m \cdot L_c \cdot \Delta \theta}{k_c \cdot (\theta_2 - \theta_1) \cdot \varepsilon}
\]

(7)

where \( L_c \) is the length of the furnace

| Case     | Table 2. Heating of the billets with circular section (R-radius; \( l \) – length of the billet). |
|----------|------------------------------------------------------------------------------------------|
| a        | 60  | 3.5 | 2   | 5.19 | 1.75 |
|          | 70  | 5.5 | 2   | 7.37 | 2.71 |
| b        | 30  | 0.57 | 1 | 1.57 | 0.84 |
|          | 45  | 1.00 | 1 | 2.41 | 1.25 |
| c        | 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 |

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

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

\[\alpha = 2 \arccos \left( \frac{D}{D_m + D} \right)\]

(11)

\[\beta = 180 - 2 \arccos \left( \frac{D}{D_m + D} \right)\]

(12)

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

(13)

**Case c)** In case (a), if \( h = D/4 \), it is obtained:

\[\alpha = 2 \arccos \left( \frac{D}{D_m + D} \right) \quad \text{and} \quad \beta = 210 - \arccos \left( \frac{D}{D_m + D} \right)\]

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

(14)

**Case e)** 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:

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

(18)

- for the ingot placed above:

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

(19)

The general form of relations for the equivalent surface of heat exchange will be:
The geometric surface of billets is $S_0 = 6.28 R l$, thus $S$ could be written:

$$S = 0.159 \cdot k_1 \cdot S_0$$  \hspace{0.5cm} (21)

The heating time will be determined by relation:

$$\tau = \frac{\pi \cdot R \cdot \rho \cdot c \cdot (\theta_f - \theta_i)}{k_1 \cdot q}$$ \hspace{0.5cm} (22)

where $q$ is the thermal flow ($\text{kJ/m}^2\text{h}$); $\theta_f$ and $\theta_i$: 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)           | $D_m=4D$     | 4.51 | 0.72$S_0$ |
|                             | $D_m=2D$     | 4.37 | 0.69$S_0$ |
|                             | $D_m=1D$     | 4.19 | 0.67$S_0$ |
|                             | $D_m=(2/3)D$| 4.07 | 0.65$S_0$ |
|                             | $D_m=0.5D$  | 3.98 | 0.63$S_0$ |
| case b) equ. (16)           | $D_m=4D$     | 5.05 | 0.80$S_0$ |
|                             | $D_m=2D$     | 4.95 | 0.79$S_0$ |
|                             | $D_m=1D$     | 4.82 | 0.77$S_0$ |
|                             | $D_m=(2/3)D$| 4.76 | 0.76$S_0$ |
|                             | $D_m=0.5D$  | 4.71 | 0.75$S_0$ |
| case c) equ. (14)           | $D_m=4D$     | 4.61 | 0.73$S_0$ |
|                             | $D_m=2D$     | 4.54 | 0.72$S_0$ |
|                             | $D_m=1D$     | 4.43 | 0.71$S_0$ |
|                             | $D_m=(2/3)D$| 4.36 | 0.69$S_0$ |
|                             | $D_m=0.5D$  | 4.30 | 0.68$S_0$ |
| case d) equ. (17)           | $D_m=D$      | 3.14 | 0.50$S_0$ |
|                             | $D_m=(2/3)D$| 2.56 | 0.41$S_0$ |
|                             | $D_m=0.5D$  | 2.42 | 0.39$S_0$ |
| case e) equ. (18)           | $D_m=D$      | 3.14 | 0.50$S_0$ |
|                             | $D_m=(2/3)D$| 4.31 | 0.69$S_0$ |
|                             | $D_m=0.5D$  | 4.59 | 0.73$S_0$ |

### 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.
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 \( k_1 \) and of equivalent surface of heat exchange.

References
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