INVESTIGATION OF HEATING TIME OF A BUNDLE OF STEEL BARS

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ABSTRACT

The paper deals with the problem of determining the heating time of a bundle of flat steel bars. To describe a mathematical model of transient heat transfer the energy balance method was used. The most important element is to determine the effective thermal conductivity coefficient using the electrical analogy. The simulations of heating were performed for increasing temperature of furnace. The results show that using different sizes and bundle arrangement the heating time can be reduced by 5–15%. The analysed problem is important from the practical point of view because it allows for optimization of heat treatment processes of steel bars.

Key words: steel porous charge, effective thermal conductivity, heat treatment, heating time

INTRODUCTION

Heat treatment is important process in steel bars production. It allows to change the material properties by changing its structure. The most popular heated charges are cylindrical bundles, which are an example of steel porous charge widely used in industry (Musiał, 2013; Kolmasiak & Wyleciał, 2018). The model of cylindrical bundle of flat steel bars, considered in the present paper, is shown on Figure 1.

The geometry of the charge (length of bars is bigger than their transverse dimensions) determines that during heating the heat transfer processes occur in the radial direction. The section of the bundle is not homogenous – solid phase is not continuous and the gaps between the bars are filled with gas. Therefore heat transfer process is complex and consists of conduction within gas, conduction the bars, contact conduction and radiation. To simplify the model of heat transfer in such a bundle the effective thermal conductivity (k_{ef}) is used. It is a parameter which is widely used in the theory of nonhomogeneous (Bagdasaryan, 2014; Kula & Wodzyński, 2020) and porous media (Kaviany, 1995; van Antwerpen, du Toit & Rousseau, 2010; Wyczółkowski & Benduch, 2014). The effective therml conductivity simplifies the description of transient heat transfer in analysed bundle (Sahay & Krishnan, 2007).
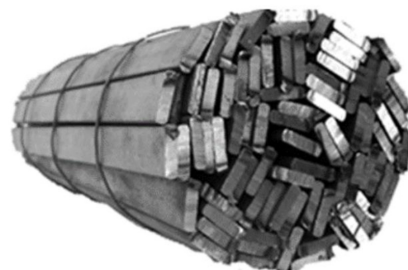

Fig. 1. A model of cylindrical bundle of flat steel bars (own photo)

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In the manuscript authors investigate the influence of contact conduction between adjacent bars on the heating time of the bundle. To describe the contact conduction in the bundle quantitatively thermal contact resistance (R_{ct}) was applied. The values of the this coefficient where determined experimentally.

MATERIAL AND METHODS

In the paper the considered material of the bars was low-alloy steel with carbon content of 0.2%. In calculations three arrangement of bars were considered: horizontal, vertical and mixed (Fig. 2).
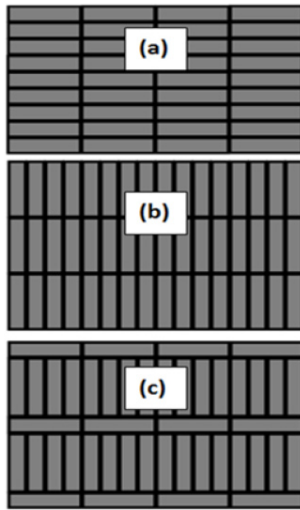

Fig. 2. Samples of flat bars with: horizontal (a), vertical (b) and mixed (c) arrangement (own elaboration)

Due to the dimensions of the charge it can be assumed that it is axially symmetric problem by assuming that heat transfer occur only in the radial direction, at a uniform heat flux (q_0) on the whole circumference. Hence, geometry of the charge is defined by the radius of the heated bundle $r_0 = 0.25$ m. For the purposes of the numerical solution, the area of the bundle is divided into n cylindrical elements with the width of $\Delta r = r_0/n$ (where $n = 18$). In the middle of each element there is a node, for which a temperature is established. The radius of the m-th node is described with the dependency:

$$r_m = r_0 - (m - 0.5)\Delta r. \tag{1}$$

In order to solve a transient heat conduction problem, energy balance method has been used, according to which the rate of heat conduction to the m-th element from the adjacent elements (Q_{jm}) is equal to the change in the energy content of an element during time interval ($\Delta\tau$). Using the explicit approach, it can be represented with the following dependency (Cengel, 2007):

$$\rho c_p \phi V_m \frac{t_m^{i+1} - t_m^i}{\Delta\tau} = \sum_j Q_{jm}^i, \tag{2}$$

where:

ρ, c_p – density and specific heat of steel,
φ – bundle porosity ($\varphi = 0.05$),
$t_m^{i+1} - t_m^i$ – temperature change of the m-th node during the time interval $\Delta\tau$,
V_m – volume of the m-th element:

$$V_m = 2\pi r_m \Delta r. \tag{3}$$

In the solution it has been assumed that the specific heat of steel in the temperature function changes according to the following dependency:

$$c_p = 0.41t + 468. \tag{4}$$

Equation (4) has been established based on literature data (Raźnjević, 1966).

The heat transferred into the m-th element from adjacent elements amounts to:

$$\sum_j Q_{j,m}^i = \frac{1}{R_{m-1,m}^i}\left(t_{m-1}^i - t_m^i\right) + \frac{1}{R_{m,m+1}^i}\left(t_{m+1}^i - t_m^i\right), \tag{5}$$

where:

$$R_{m-1,m}^i = \frac{\ln\left(r_{m-1,m} / r_m\right)}{2\pi k_{ef\,m}^i}, \quad R_{m,m+1}^i = \frac{\ln\left(r_i / r_{i+1}\right)}{2\pi k_{ef\,m}^i}. \tag{6}$$

The boundary condition used in the solution is heat transfer rate which flows in to the charge (Q_o). It has two components: a convection one and a radiation one:

$$Q_0^i = 2\pi r_0 \left(h^i (t_F^i - t_0^i) + \varepsilon\, \sigma \left(\left(T_F^i \right)^4 - \left(T_0^i \right)^4 \right) \right), \qquad (7)$$

where:
h – convection heat transfer coefficient,
ε – surface emissivity ($\varepsilon = 0.7$),
σ – Stefan-Boltzmann constant,
T_F, T_o – thermodynamic temperatures of the furnace and bundle surface.

The bundle was considered under conditions when the furnace temperature is rising up to the final value in the function of time as follows:

$$T_F = 20 + 0.173\tau, \qquad (8)$$

where time (τ) is expressed in seconds. Upon reaching the final value, for the rest of the process temperature (T_F) is kept constantly at this level. The final value of the furnace temperatue was assumed as 750°C.

The values of thermal contact resistance (R_{ct}), minimal and maximal, were obtained experimentally and used to determine the effective thermal conductivity of the bundle (Kolmasiak, Wyleciał, Bagdasaryan & Gała, 2021). The mean values of effective thermal conductivity for 12 considered cases (two bar sizes, three arrangement and two values of R_{ct}) are shown in Tables 1 and 2.

RESULTS

Obtained results has been shown in the form of figures and tables. Figures 3–8 present the results of computations of bundle heating process for investigated cases. The diagrams show the temperature of chosen points of the section in the time function. Chosen points are: t_o – the surface of the charge, $t_1 - 2/3r_o$, $t_2 - 1/3r_o$, t_3 – the axis of the charge. Diagrams marked with the letter (a) relate to resistance $R_{ct\text{-min}}$; diagrams marked with the letter (b) relate to resistance $R_{ct\text{-max}}$.

Table 1. Mean values of effective thermal conductivity (k_{ef}) for 5 × 20 mm size bars (own elaboration)

| Parameter [W·m⁻¹·K⁻¹] | Steel bars arrangement | | | | | |
| | horizontal | | vertical | | mixed | |
	$R_{ct\text{-min}}$	$R_{ct\text{-max}}$	$R_{ct\text{-min}}$	$R_{ct\text{-max}}$	$R_{ct\text{-min}}$	$R_{ct\text{-max}}$
k_{ef}	2.01	1.19	6.95	4.35	4.66	2.84

Table 2. Mean values of effective thermal conductivity (k_{ef}) for 10 × 40 mm size bars (own elaboration)

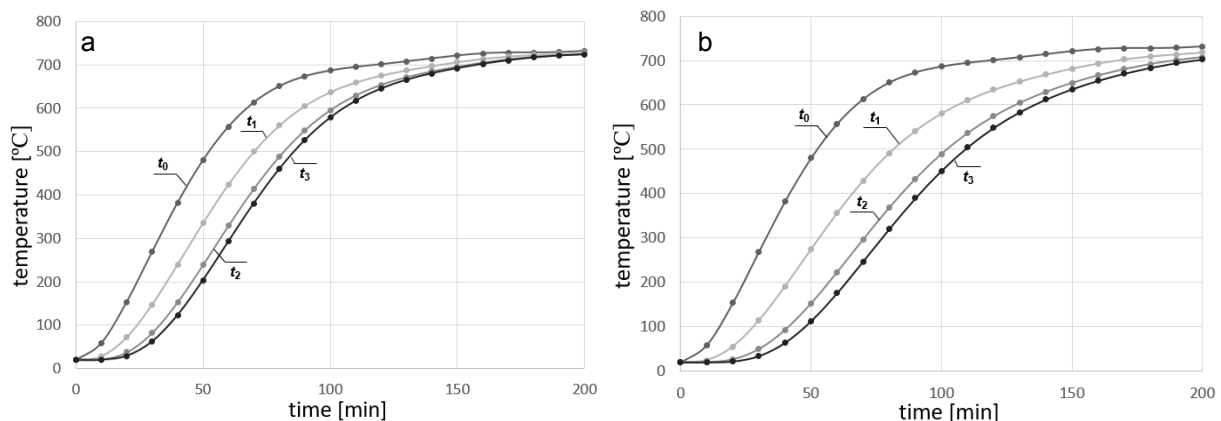| Parameter [W·m⁻¹·K⁻¹] | Steel bars arrangement | | | | | |
| | horizontal | | vertical | | mixed | |
	$R_{ct\text{-min}}$	$R_{ct\text{-max}}$	$R_{ct\text{-min}}$	$R_{ct\text{-max}}$	$R_{ct\text{-min}}$	$R_{ct\text{-max}}$
k_{ef}	3.82	2.31	11.8	7.81	8.32	5.29

Fig. 3. Temperature change in the time function in chosen points of section for 5 × 20 bars with horizontal arrangement: (a) results for $R_{ct\text{-min}}$; (b) results for $R_{ct\text{-max}}$ (own elaboration)

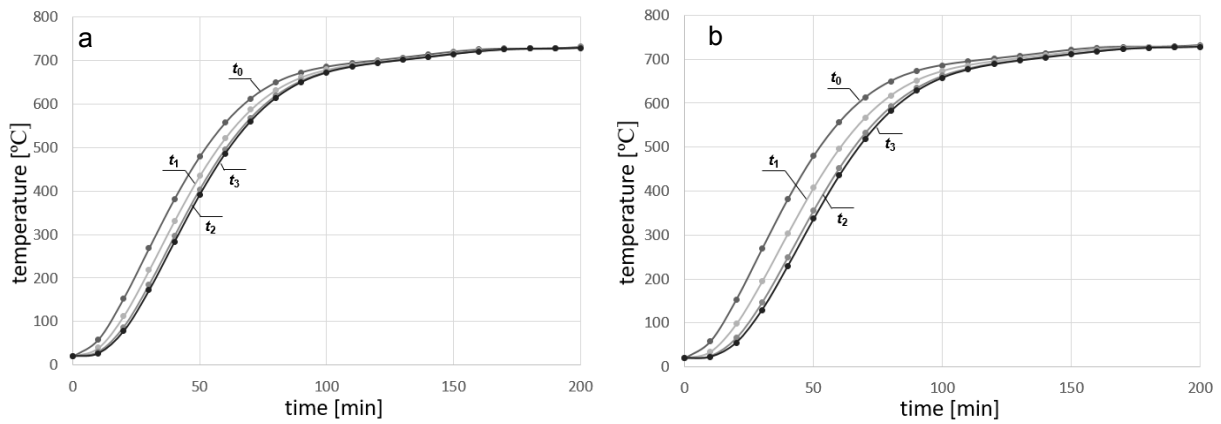**Fig. 4.** Temperature change in the time function in chosen points of section for 5 × 20 bars with vertical arrangement: (a) results for $R_{ct\text{-min}}$; (b) results for $R_{ct\text{-max}}$ (own elaboration)
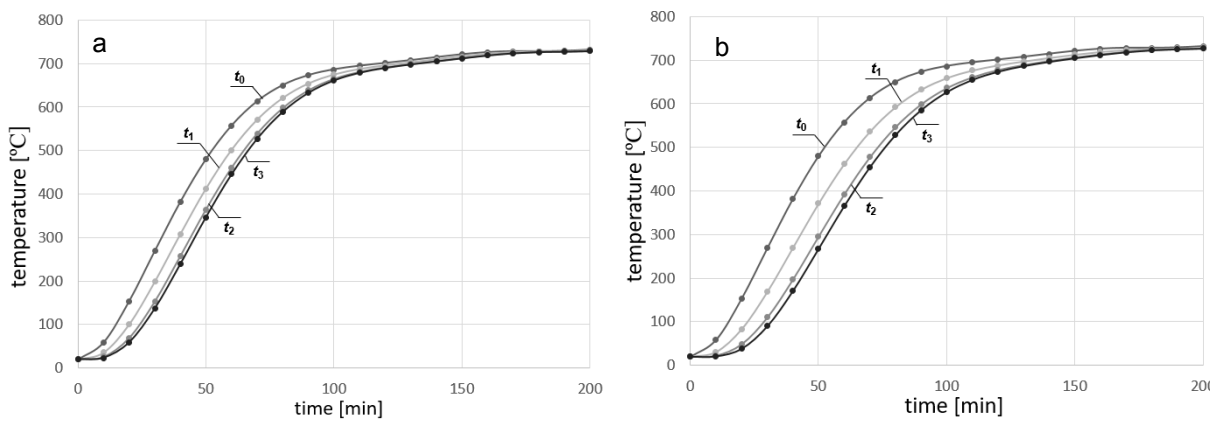

Fig. 5. Temperature change in the time function in chosen points of section for 5 × 20 bars with mixed arrangement: (a) results for $R_{ct\text{-min}}$; (b) results for $R_{ct\text{-max}}$ (own elaboration)
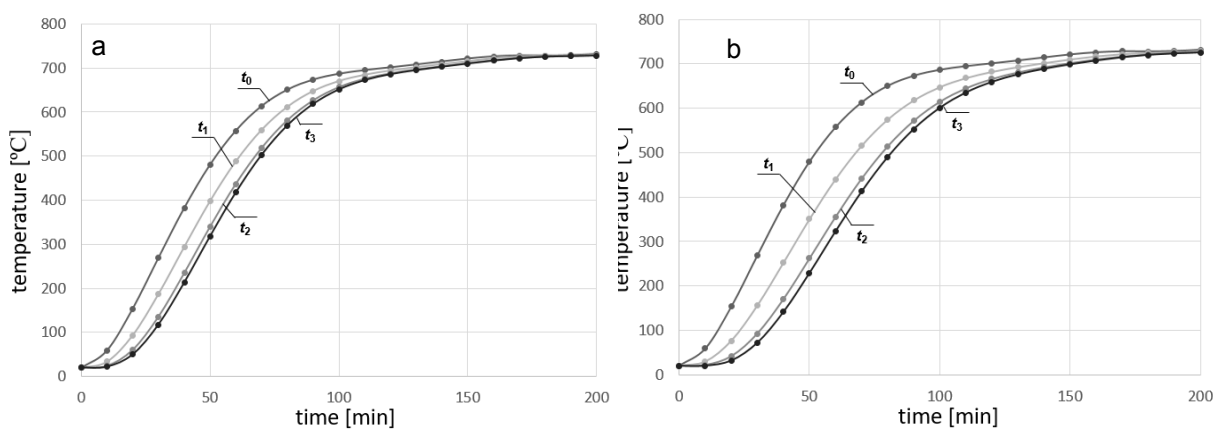

Fig. 6. Temperature change in the time function in chosen points of section for 10 × 40 bars with horizontal arrangement: (a) results for $R_{ct\text{-min}}$; (b) results for $R_{ct\text{-max}}$ (own elaboration)
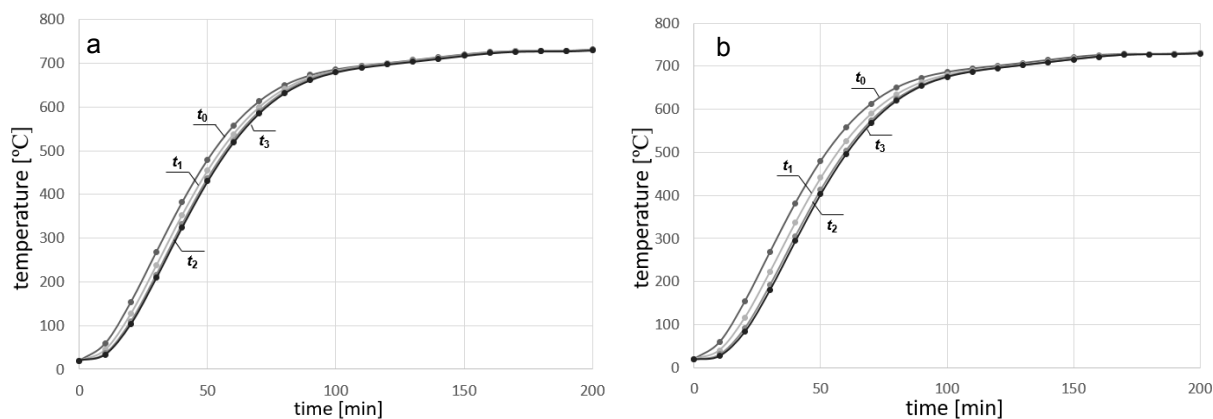
Fig. 7. Temperature change in the time function in chosen points of section for 10×40 bars with vertical arrangement: (a) results for $R_{ct\text{-min}}$; (b) results for $R_{ct\text{-max}}$ (own elaboration)
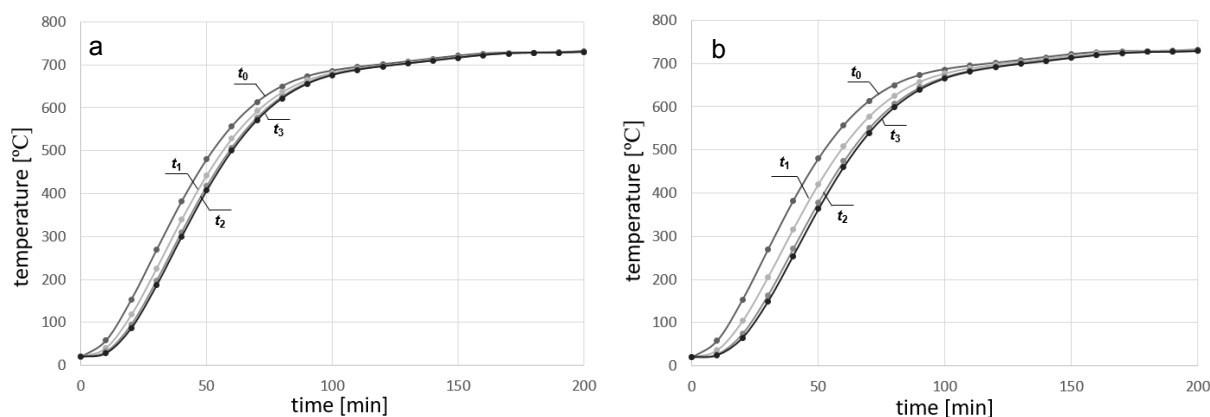

Fig. 8. Temperature change in the time function in chosen points of section for 10×40 bars with mixed arrangement: (a) results for $R_{ct\text{-min}}$; (b) results for $R_{ct\text{-max}}$ (own elaboration)

During the analysis it was important to determine the time necessary to reach 720°C in the axis of the charge. Table 3 shows the results for the investigated samples (H – horizontal arrangement, V – vertical arrangement, M – mixed arrangement) taking into account $R_{ct\text{-min}}$ and $R_{ct\text{-max}}$ (denoted by $\tau_{\min}$ and $\tau_{\max}$ respectively). To show the difference quantitavely $\Delta\tau$ was calculated by the equation:

$$\Delta\tau = \frac{\tau_{\max} - \tau_{\min}}{\tau_{\max}} 100\%. \qquad (9)$$

Table 3. The results of heating time up to reaching 720°C in the axis of the charge (own elaboration)

Sample	$\tau_{\min}$ [min]	$\tau_{\max}$ [min]	$\Delta\tau$ [%]
5×20 H	189	223	15
5×20 V	158	165	4
5×20 M	163	172	5
10×40 H	166	181	8
10×40 V	155	159	3
10×40 M	157	161	2

CONCLUSIONS

In the present paper the heating times of a bundle of steel bars in chosen arrangements were calculated. As it is shown it is possible to reduce heating time even by 15% thanks to certain arrangement. Other factor that has an influence on decreasing of the heating time is increasing of the force, which is used during preparing the bundle. Investigation of other factors (such as the force used during preparing the bundle or accuracy of bar arrangement) having influence on heating time will be the next stage of authors' works.

Authors' contributions

Conceptualisation: R.W., S.A. and V.B.; methodology: R.W.; validation: S.A. and V.B.; formal analysis: R.W. and S.A.; investigation: V.B.; writing – original draft preparation: V.B. and S.A.; writing – review and editing: S.A. and R.W.; visualisation: V.B.; supervision: S.A. and R.W.; project administration: S.A.

All authors have read and agreed to the published version of the manuscript.

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BADANIE CZASU NAGRZEWANIA WIĄZKI PRĘTÓW STALOWYCH

STRESZCZENIE

Praca przedstawia zagadnienia związane z wyznaczaniem czasu nagrzewania w wiązce płaskich prętów stalowych. Do opisu matematycznego modelu niestacjonarnego przewodzenia ciepła wykorzystano metodę bilansu energetycznego. Kluczowym elementem zadania było wyznaczenie efektywnego współczynnika przewodzenia ciepła, wykorzystując analogie elektryczne. Symulacje nagrzewania wiązki prętów przeprowadzono w przypadku rosnącej temperatury pieca. Wyniki pokazują, że wraz ze zmianą rozmiarów oraz ułożenia prętów w wiązce czas nagrzewania można zredukować o 5–40%. Rozpatrywane zagadnienie ma istotne znaczenie z praktycznego punktu widzenia, ponieważ ma związek z optymalizacją procesów obróbki cieplnej prętów stalowych.

Słowa kluczowe: stalowy wsad porowaty, efektywna przewodność cieplna, obróbka cieplna, czas nagrzewania