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NUMERICAL ANALYSIS OF THE PROCESS OF HEATING OF A BED OF STEEL BARS

NUMERYCZNA ANALIZA PROCESU NAGRZEWANIA ZŁOŻA PRĘTÓW STALOWYCH

The article describes the computation of the time of heating of a bed of bars in the heat treatment process. The charge was subjected to under-annealing, which is used in industry, e.g., to facilitate sawing of bars or billets into a sections intended for hot forging. The beds under examination were regarded as solid elements, which was possible thanks to the knowledge of the effective thermal conductivity, λ. The value of this quantity for the temperature range under consideration was determined based on the author's original investigation.

During heating of a bundle of bars at a constant heating medium temperature, a temperature difference occurs on the charge cross-section, which is significantly greater than that provided for by the technology. It is therefore essential to carry out a second soaking stage in order to achieve the cross-sectional temperature difference at a level of 20°C.

The computation of soaking was conducted for the assumed conditions of a constant temperature on the charge surface and the parabolic distribution of temperature on the cross-section.

Keywords: heating of porous charge, bed of bars

W artykule przedstawiono obliczenia czasu nagrzewania złoża prętów w procesie obróbki cieplnej. Wsad poddano wyżarzaniu niezupełnemu, które stosuje się w przemyśle np. w celu ułatwienia cięcia prętów lub kęsów na piłach, na odcinki przeznaczone do kucia na gorąco. Analizowane złoża rozpatrywano jako element lity, co było możliwe dzięki znajomości efektywnego współczynnika przewodzenia ciepła. Wartość tego współczynnika dla rozpatrywanego zakresu temperatury określono na podstawie badań własnych autora.

Podczas nagrzewania wiązki prętów w stałej temperaturze ośrodka nagrzewającego na przekroju wsadu pojawia się znaczna różnica temperatur niż zakłada to technologia. W związku z tym niezbędne jest przeprowadzenie drugiego etapu wygrzewania celem uzyskania na przekroju wsadu różnicy temperatur na poziomie 20°C. Obliczenia wygrzewania przeprowadzono dla założonych warunków stałej temperatury na powierzchni wsadu i parabolicznego rozkładu temperatury na przekroju.

1. Introduction

In industrial practice, several or even a dozen or so items are subjected to heat treatment at a time, whose arrangement within the furnace has a key influence on the heating intensity. Due to handling reasons, steel bars are commonly bound into bundles, which are then laid on the furnace hearth. This procedure prevents the charge from being scattered within the furnace, and provides also a great convenience either when moving the charge on the production plant's site or when transporting it to the customer.

Designing a technology for heating porous charge in industrial heating furnaces involves the need for considering numerous complex heat and mass exchange phenomena. It therefore becomes necessary to use the computer simulations of those processes using mathematical and numerical modelling. A particularly difficult process is to develop a technology for heating of porous charge, which is a bed of steel bars, while ensuring the conditions of low energy-intensity of the heating process, as well as meeting the requirements for the emission of harmful components to the atmosphere.

Although there are a lot of numerical data concerning the heating of solid charge, which are published in literature [1-5], this does not, however, provide a direct correlation with the phenomenon under examination. This is so primarily due to the complex geometry of porous materials, and thus complex heat exchange, which is determined chiefly by parameters, such as [6-11]:

- the conductivity of the solid phase and the fluid filling the spaces between bars,
- the dimensions of bars and spaces forming the bed,
- porosity,
- heating temperature,
- emissivity of the bar surface.

To gain a detailed knowledge of the above-mentioned parameters and their influence on the charge heating process, a thorough theoretical analysis of the phenomenon and laboratory and industrial tests will be required.

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2. Preliminary assumptions

The starting point for the analytical determination of the time of heating of porous charge is the knowledge of the thermal properties of the charge. This problem was examined on the example of a flat bed of bars. A complex flow of heat occurs in such a bed during heating. Conduction occurs in the cross-sections of individual bars, in the medium filling the pores, and at the contact between bars. In pores, there occurs also radiation between the surfaces of adjacent bars and possibly natural convection. Heat transfer in that case is most convenient to be expressed with the effective thermal conductivity, λ [12-17]. The value of the coefficient λ is selected so that the amount of heat transferred as a result of complex conduction, radiation and convection be equal to the amount of heat conducted in the solid material with the identical temperature field.

A 100×1000×3500 (height × width × length, in mm) bed or bars, as limited by the external structure, was assumed for computation. It was assumed that the charge heated up at a constant ambient temperature of and with an equalized initial temperature distribution on the charge cross-section. The charge was heated until a surface temperature of 1073K was reached. Data necessary for carrying out the simulation were taken from the author's studies [19-20]:

$$\rho C_p \frac{\partial T}{\partial \tau} - \lambda \Delta T = 0 \tag{1}$$

where:

ρ– density; $\left(\frac{kg}{m^3}\right)$,

λ– heat conduction coefficient; $\left(\frac{W}{m\cdot K}\right)$,

C_p – heat capacity; $\left(\frac{J}{kg\cdot K}\right)$,

T– temperature; K,

τ– time; s.

Due to the fact that the bed porosity is approx. 10%, the density and heat capacity were calculated from the following formula [20]:

$$\rho = 0,9 \cdot \rho_s = 0,9 \cdot 7850 \frac{kg}{m^3} = 7065 \frac{kg}{m^3} \tag{2}$$

$$c = 0,1 \cdot c_g + 0,9 \cdot c_s = 0,1 \cdot 1,024 \frac{kJ}{kg\cdot K} + 0,9 \cdot 0,59 \frac{kJ}{kg\cdot K} = 0,633 \frac{kJ}{kg\cdot K} \tag{3}$$

where indexes s and $g$concern solid and gas phases respectively.

As the value of the λ coefficient depends on the bar diameter, among others, a fixed diameter of d_p = 20 mm was assumed for each of the charges examined. For bars with this diameter, an averaged fixed value of the λ coefficient, being equal to $12\frac{W}{m\cdot K}$, was taken for the temperature range under examination.

To simplify of computational procedure and avoid the repeatability of results, the condition of axial symmetry in the mid-width of the charge was assumed.

The same problem, in aim to verify the numerical procedure used, in the analytic road was considered [14,20]. So, the charges under consideration should be heated at a constant temperature of the medium and the equalized initial distribution of temperature. For this type of heating, the temperature of bundles at any arbitrary point and after an arbitrary time is calculated from the following formula:

$$T'' = T_f + (T' - T_f) \cdot \Theta_S(Bi, Fo, \frac{x}{S}) \cdot \Theta_B(Bi, Fo, \frac{y}{B}) \tag{4}$$

where:

T'' – end temperature; K,

T' – initial temperature;K,

T_f– ambient temperature;K,

S– characteristic dimension (width); m,

B– characteristic dimension (height)); m.

$$\Theta_S(Bi, Fo, \frac{x}{S}) = \sum_{l=1}^{\infty} \frac{2\sin\eta_l}{\eta_l + \sin\eta_l \cos\eta_l} \cos(\eta_l \frac{x}{S}) \exp(-\eta_l^2 \frac{a\tau}{S^2}) \tag{5}$$

$$\Theta_B(Bi, Fo, \frac{y}{B}) = \sum_{m=1}^{\infty} \frac{2\sin\eta_m}{\eta_m + \sin\eta_m \cos\eta_m} \cos(\eta_m \frac{y}{B}) \exp(-\eta_m^2 \frac{a\tau}{B^2}) \tag{6}$$

Temperatures for particular computation points of the charge heated in the furnace at a constant temperature, as determined from equation (4), are represented in Figures 2.

During the heating of the examined bundles at the constant heating medium temperature, larger temperature differences occur on the bundle cross-sections than permitted by the technology. Therefore, soaking should be applied in order to achieve the final temperature difference on the charge cross-section at a level of $\Delta t''$ =20°C. The computation of the soaking process was carried out for a constant charge surface temperature and the parabolic distribution of temperature on the cross-section at the initial moment. For this type of heating, the bed temperature at any arbitrary point and after an arbitrary time was calculated from the following formula:

$$T'' = T_{sf} + (T'_a - T_{sf}) \cdot \Theta_S(Fo, \frac{x}{S}) \cdot \Theta_B(Fo, \frac{y}{B}) \tag{7}$$

where:

$$\Theta_S(Fo, \frac{x}{S}) = \sum_{l=1}^{\infty} \frac{4(-l)^{l+1}}{\delta_l^3} \cos(\delta_l \frac{x}{S}) \exp(-\delta_l^2 \frac{a\tau}{S^2}) \tag{8}$$

$$\Theta_B(Fo, \frac{y}{B}) = \sum_{m=1}^{\infty} \frac{4(-l)^{m+1}}{\delta_m^3} \cos(\delta_m \frac{y}{B}) \exp(-\delta_m^2 \frac{a\tau}{B^2}) \tag{9}$$

where:

T_{sf}– surface temperature; K,

T_a– temperature in the axis; K.

The values of δ_l are the zero loci of the cos function and can be expressed by the equation:

$$\delta_l = \frac{2l-1}{2}\pi, \qquad dla \quad l = 1, 2, 3... \tag{10}$$

The distribution of temperature in the axis of the charge being heated, as obtained from equation (7), for considered charges, is shown in Figure 5.

3. Simulation results

The computation was carried out using the Heat Transfer Module provided by the COMSOL Multiphysics software [21].

The obtained examination results are shown in Figures 1, 2 and 3. As indicated by the simulation carried out, the charge attains the assumed surface temperature after one hour of heating.

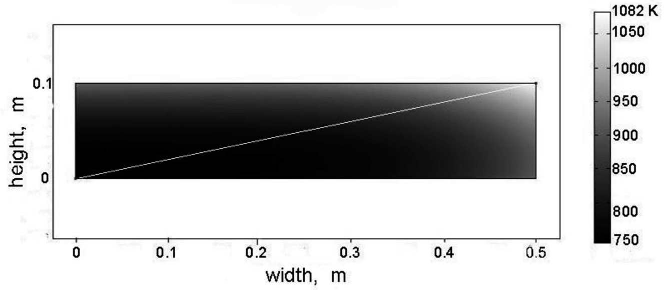

Fig. 1. Distribution of temperature in the cross-section of the charge (heating time, τ = 3600s)

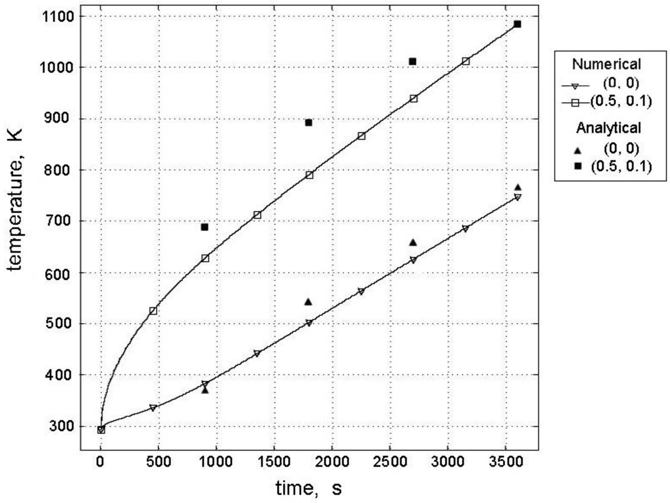

Fig. 2. Distribution of temperature during heating at selected points of the charge

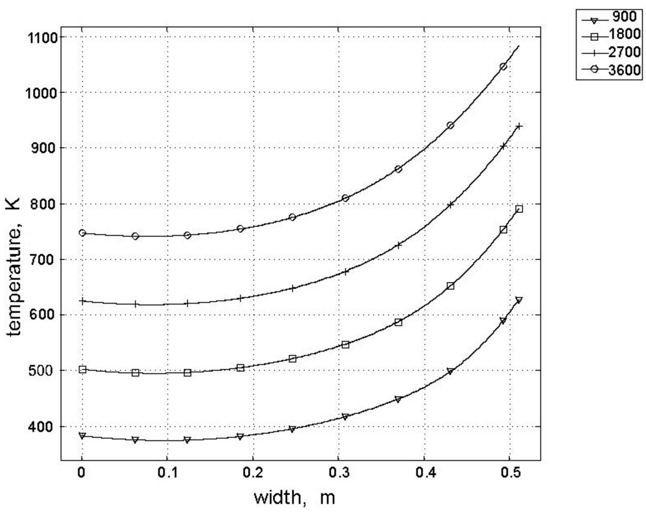

Fig. 3. Distribution of temperature during heating along the dividing line generated in Fig. 1

Figure 2 shows the distribution of temperature in the heated charge at two selected points of the charge:

1) in the charge axis (0,0); and
2) on the charge surface (0.5,0.1).

It was observed that within one hour's heating time, a great temperature difference formed in the charge cross-section, whose consequence might be the occurrence of stresses having the effect of impairing the properties of the charge.

A transverse dividing line was generated in the program, which is shown in Fig. 1 in white colour. The distribution of temperature within the heated charge was determined along this line at intervals of 15 minutes, as shown in Fig. 3.

Because of the occurrence of a difference temperature in the charge cross-section, a second process stage, namely soaking, was carried out to achieve the final temperature difference on the charge cross-section at a level of $\Delta t''$ =20K. The computation of the soaking process was performed for a constant charge surface temperature of (T = 1073K) and the parabolic temperature distribution on the cross-section at the initial moment, while preserving the same heating chamber operation conditions and charge dimensions. The remaining data necessary for carrying out the simulation were taken from the author's work [20].

The figures below illustrate the obtained examination results. As can be seen from Fig. 4, after one hour of soaking, a temperature difference not greater than 10K is observed in the charge cross-section.

So, elongating the soaking duration by another 15 minutes does not bring about the intended effects (Fig. 5), and quite the opposite, it results in increase in the energy intensity of the process, and also has the effect of impairing the properties of the heated charge through the formation of unnecessary scale.

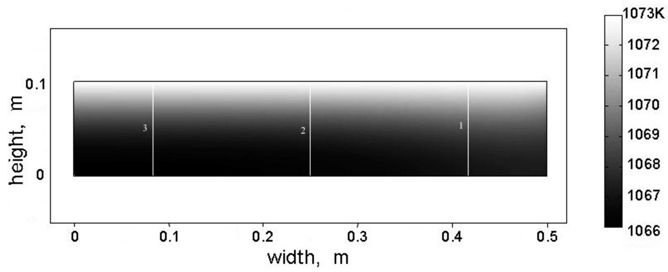

Fig. 4. Distribution of temperature in the cross-section of the charge (soaking time, τ = 3600s)

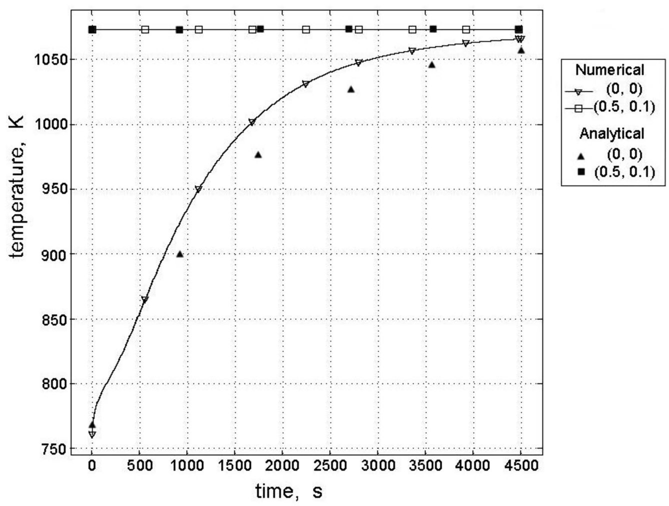

Fig. 5. Distribution of temperature during soaking at selected points of the charge

Figure 5 shows the distribution of temperature during charge soaking for two chosen points of the charge: at point (0,0), and on the charge surface (0.5,0.1). The assumed temperature difference of $\Delta t''$ =20K on the charge cross-section was achieved after a soaking time of τ =50 min. Therefore, further simulation was conducted for $\tau = 3000s$.

Transverse dividing lines were generated within the COMSOL Multiphysics, which are shown in Fig. 4 in light shade. The distribution of temperature in the heated charge was determined along the line after a soaking time of $\tau = 3000s$, Fig. 6.

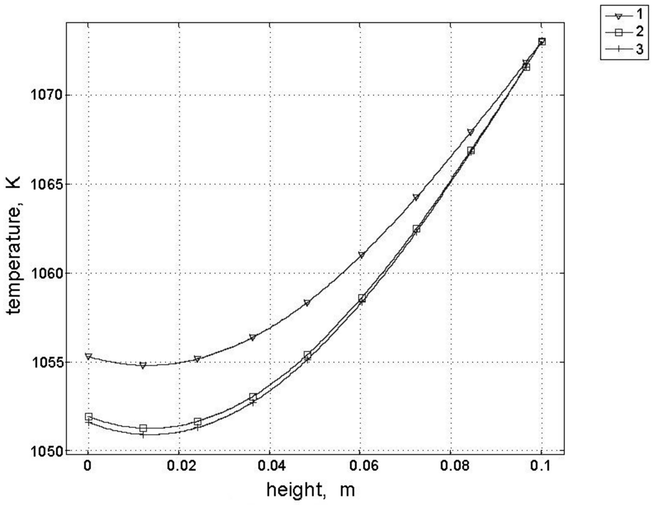

Fig. 6. Distribution of temperature along the dividing lines generated in Fig. 2 (soaking time, $\tau = 3000s$)

4. Summary

Due to the lack of suitable ready-made relationships in relevant literature, the time of heating of porous charge should be determined numerically or analytically from the basic heat conduction equations. In view of the above, the present study has been devoted to the problem of heating porous charge in the form of a flat steel bar bed composed of bars of a diameter of d=20 mm.

Mainly computer simulation of the process of heating of a bed of steel bars has been presented in this article. The purpose of the performed analysis was to assess the possibility of using software for simulation of thermal phenomena occurring during the heating of porous materials.

The temperature distribution in the charge cross-section, as generated from the computation, provided an incentive to carry out a second computation stage, i.e. soaking, to achieve the charge cross-sectional temperature difference at a level of 20°C.

The observed soaking period is determined by the parameters of the charge, and primarily by its porosity, whose direct effect is a low value of the effective heat conductivity, and thus elongated charge heating periods.

As well, in aim to verify the numerical procedure used, the same problem in the analytic road was considered. In both cases the large convergence of results was received. The employed solutions should be under either laboratory or industrial conditions in order to verify the procedure used. The developed tool will constitute a functional system for the computer-aided design of technologies of heating porous steel charge in industrial heating furnaces.

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REFERENCES

[1] M. K i e l o c h, Energooszczędne i małozgorzelinowe nagrzewanie wsadu stalowego. Częstochowa 2002.
[2] M. K i e l o c h, Technologia i zasady obliczeń nagrzewania wsadu. Częstochowa 1995.
[3] L. S z e c ó w k a, Wymiana ciepła w piecach przemysłowych. Częstochowa 2006.
[4] A. B o k o t a, A. K u l a w i k, Model and numerical analysis of hardening process phenomena for medium-carbon steel. Archives of Metallurgy and Materials **52**, 2, 337-346 (2007).
[5] A. B o k o t a, T. D o m a n s k i, Modelling and numerical analysis of hardening phenomena of tools steel elements. Archives of Metallurgy and Materials **54**, 3, 575-587 (2009).
[6] M. K a v i a n y, Principles of heat transfer in porous media. Springer 2002.
[7] J. B e a r, Modelling transport phenomena in porous media. In: Quintard M., Todorovic M.; Heat and Mass Transfer in Porous Media, Elsevier Publishing Corp. 1992, s. 15-59.
[8] Argo W. B., Smith J. M.: Heat transfer in packed beds. Chemical Engeginering Progress, 1953, s. 443-451.
[9] Quintard M., Withaker S.: Transport in ordered and disordered porous media. Transport porous media, 9-110 (1992).
[10] N.A. B o z k o v, V.K. Z a i t s e v, S.N. O b r u c h, Analitical and experimental investigation of combined heat transfer in porous composite materials. Inzhenerno – fizicheskii zhurnal, 554-561 (1990).
[11] P. R u b i o l o, J.M. G a t t, Modeling of the radiative contribution to heat transfer in porous media composed of spheres of cylinders. International Journal of Thermal Sciences **41**, 401-411 (2002).
[12] E. G o n z o, Estimating correlations for the effective thermal conductivity of granular materials. Chemical Engineering Journal **90**, 299-302 (2002).
[13] G. B u o n a n n o, A. C a r o t e n u t o, The effective thermal conductivity of a porous medium with interconnected particles. International Journal of Heat and Mass Transfer **40**, 393-405 (1997).
[14] R. K r u p i c z k a, Analysis of thermal conductivity in granular materials. International Chemical Engineering **7**, 122-143 (1967).
[15] T.H. B a u e r, A general analytical approach toward the thermal conductivity of porous media, International Journal of Heat Mass Transfer **36**, 4181-4191 (1993).
[16] A. J a g o t a, C.Y. H u i, The effective thermal conductivity of a parking of spheres. Journal of Applied Mechanics, 789-791 (1990).
[17] I.H. T a v m a n, Effective thermal conductivity of granular porous materials. International Communications in Heat and Mass Transfer, 169-176 (1996).
[18] D. M u s i a ł, Analiza procesu nagrzewania wsadu porowatego na przykładzie złoża prętów stalowych. Hutnik -Wiadomości Hutnicze, 546-550 (2008).
[19] D. M u s i a ł, L. S z e c ó w k a, R. W y c z ó ł k o w s k i, Określanie efektywnej przewodności cieplnej wiązek prętów stalowych metodą płaskiej nieograniczonej płyty. Hutnik-Wiadomości Hutnicze 9, 468-472 (2007).
[20] D. M u s i a ł, Wymiana ciepła w wiązce prętów stalowych podczas nagrzewania. Rozprawa doktorska, 2007.
[21] Femlab, Heat Transfer Module User's Guide, 2004.