Advances in Thermal Processes and Energy Transformation
Volume 7, 2024, BORY02, pp. 01-04, ISSN 2585-9102
https://doi.org/10.54570/atpet2024/07/01/0001

Computer Calculation Program for Heating the Cylinder at a Constant Surface Temperature of the Charge

Jarosław Boryca[1]

[1]*Department of Production Management, Faculty of Production Engineering and Materials Technology, Czestochowa University of Technology, 42-201 Częstochowa, Al. Armii Krajowej 19, Poland, e-mail: jaroslaw.boryca@pcz.pl*

Category : Original Scientific Paper
Received : 21 February 2024 / Revised: 15 March 2024 / Accepted: 20 March 2024

Keywords : cylinder charge, chamber furnace, equalization of temperatures, heating of steel charge

Abstract : As part of the work, on the basis of analytical relationships, a computer program was developed, which was used to calculate the heating process of a cylindrical charge. Calculations were made for heating at a constant temperature of the charge surface. Changes in the temperature of the charge axis, furnace temperature and unit heat flow during heating were also determined.

Citation: Boryca Jarosław: Computer Calculation Program for Heating the Cylinder at a Constant Surface Temperature of the Charge, Advance in Thermal Processes and Energy Transformation, Volume 7, No.1 (2024), pp. 01-04, ISSN 2585-9102. https://doi.org/10.54570/atpet2024/07/01/0001.

1 Introduction

Heating furnaces currently used in industry are complex thermal devices based on complex heat and mass transfer phenomena. One of the most important factors affecting the efficiency of their work is the heating technology, because it determines their efficiency and, therefore, heat consumption. Thanks to the appropriate selection of technology, it is possible to reduce energy consumption in a rational process. This process requires appropriate distribution of thermal power along the length of the furnace and sometimes a change in its structure [1].

In order to minimize heat consumption, technologies should be used to achieve the highest possible efficiency. For this purpose, it is necessary to ensure the proper adoption of the heating curve, which is an important element of the technology enabling the minimization of production costs [1-4].

The process of heating the charge can be simplified to a two-stage heating process, where the second stage is equalizing the temperatures across the cross-section of the charge. Temperature equalization occurs at a constant temperature of the charge surface [2].

Heat flow is a complex phenomenon. In high-temperature furnaces, the share of radiation in heat transfer is 90÷95%, hence the heat flow phenomena can be limited to radiation. The specificity of heat transfer in the working space of the furnace is described in the works [3, 5-8].

2 Heating of cylnder charge

The amount The heating of the charge is related to the unsteady heat flow. The starting point for considerations of unsteady heat conduction is the Fourier differential equation [5-10].

The selection of the appropriate equation in the heating process is determined by the fulfilment of the initial and boundary conditions, the first of which concern time and characterize the temperature distribution at the moment from which the process is considered ($\tau = 0$), and the second concern the surface and determine the nature of temperature changes. on the surface of a heated body or the interaction of the body surface with the surrounding atmosphere [1, 2].

Boundary conditions are divided into three types depending on whether they are known:
1) temperature distribution on the surface of the heated element (these conditions include the cases of constant surface temperature and linearly variable surface temperature) - boundary conditions of the first type;
2) heat flux flowing to the surface - boundary conditions of the second type;
3) temperature distribution of the surrounding medium (in particular, a constant temperature of the medium and a linearly variable temperature of the medium may occur) - boundary conditions of the third type.

For a cylinder of infinite length, the basic Fourier equation (in cylindrical coordinates) is expressed in the following form [3, 8]:

$$\frac{\partial t}{\partial \tau} = a \cdot \left(\frac{\partial^2 t}{\partial r^2} + \frac{1}{r}\frac{\partial t}{\partial r}\right), \text{ m} \quad (1)$$

where:
t – temperature, °C,
τ – time, s,
a – thermal diffusivity, $m^2.s^{-1}$,
r – radius of the cylinder at any point in the cross-section, m.

The article considers the case when there is a parabolic temperature distribution on the cross-section at the initial moment.
For this type of boundary conditions, the solution was obtained [1, 3]:

$$\frac{t_p - t^{"}}{t_p - t'_{oś}} = \varphi_1\left(Fo, \ \frac{r}{R}\right), \quad (2)$$

where:
t_p – surface temperature of the charge, °C,
$t'_{oś}$ – initial temperature in the axis of the charge, °C,
$t^{"}$ – final temperature of the charge, °C,
φ_1 – the value of the function depends on the Fourier number and on the ratio r to R,
R – radius of the cylinder, m.
Fo – Fourier number,
where:

$$Fo = \frac{\bar{a}\cdot\tau}{R^2} \text{ or } Fo = \frac{\bar{a}\cdot\tau}{l^2} \quad (3)$$

where:
l – linear dimension, m,
$\bar{a}$ – average thermal diffusivity, $m^2.h^{-1}$.

For all variants, the δ function was the ratio of temperature differences:

$$\delta = \frac{t_p - t^{"}_{oś}}{t_p - t'_{oś}}, \quad (4)$$

where:
δ – degree of temperature equalization,
$t^{"}_{oś}$ – final temperature in the axis of the charge, °C.
Equation (4) is used to determine the temperature in the axis of the batch.

If Fo≥0.08, the temperature in the axis for the short cylinder can be calculated from the following relationship [1, 3]:

$$\delta = 1.14 \cdot exp\left(-2.47 \cdot \frac{\bar{a}\cdot\tau}{l^2} - 5.76 \cdot \frac{\bar{a}\cdot\tau}{R^2}\right), \quad (5)$$

The unit heat flux is determined by the relationship:

$$\frac{\dot{q}\cdot R}{\lambda \cdot \Delta t'} = F(Fo), \quad (6)$$

where:
$\dot{q}$ – unit heat flux, $W.m^{-2}$,
λ – thermal conductivity coefficient, $W.(m\cdot K)^{-1}$,
$\Delta t'$ – initial temperature difference across the cross-section of the charge, K,
F(Fo) – the value of the function depends on the Fourier number.

The furnace temperature can be calculated from the equation [3, 12]:

$$t_{piec} = 100 \cdot \sqrt[4]{\frac{\dot{q}}{C_{p-m}} + \left(\frac{T_p}{100}\right)^4} - 273, \text{ °C} \quad (7)$$

where:
C_{p-m} – radiation constant of the furnace-metal system, $W.(m^{-2} . K^{-4})$,
T_p – surface temperature of the charge, K.

The radiation constant of the furnace-metal system is determined by the relationship [3, 12]:

$$C_{p-m} = C_0 \cdot \varepsilon_{p-m} \cdot \varphi_{m-ś}, \ W.(m^{-2} \cdot K^{-4}) \quad (8)$$

where:
C_0 - the black body radiation constant, $C_0 = 5{,}67$ $W.(m^{-2}.K^{-4})$,
ε_{p-m} – equivalent emissivity of the furnace-metal system,
$\varphi_{m-ś}$ – angular radiation coefficient of the metal-furnace surface system.

The emissivity of the furnace-metal system is determined from the relationship [3, 11]:

$$\varepsilon_{p-m} = \frac{\varepsilon_m}{1-\varphi_{m-m}\cdot(1-\varepsilon_m)}, \quad (9)$$

where:
ε_m – equivalent emissivity of the metal,
φ_{m-m} – angular radiation coefficient of the metal-metal system.

This relationship shows that the emissivity of the furnace-metal system depends on the configuration factor and the emissivity of the charge, which is a property characteristic of the heated material and does not depend on the furnace atmosphere. The configuration coefficients of the metal-metal system and the metal-furnace surface system are a function of geometric parameters: dimensions and arrangement of the charge and dimensions of the furnace working chamber.

The configuration factors are determined from the following relationships [3, 11]:

$$\varphi_{m-m} = \varphi_{ś-m} = \frac{A_m}{A}, \quad (10)$$

where:
A_m – the surface of the metal (steel charge) participating in heat transfer, m^2,

A – total heat transfer surface (metal and furnace surface), m^2.

$$\varphi_{m-ś} = \varphi_{ś-ś} = 1 - \varphi_{m-m}, \quad (11)$$

More extensive theoretical considerations for the process of heating the cylinder at a constant surface temperature are included in the works [1, 3].

3 Computer calculation program

In order to develop a computational computer program, theoretical relationships regarding the heating of a cylindrical charge were used [1, 3, 8].

Conducting heating calculations required the development of mathematical functions describing the variability of the thermal and physical properties of the charge with the average temperature of the charge in a given heating period. These properties include:
- thermal conductivity coefficient λ, W/(m ·K),
- temperature compensation coefficient a, m^2/h.

Mathematical functions have been developed and are described in more detail in [12].

The function δ was determined from the relationship:

$$\delta = 0.96208 - 3.98358 \cdot Fo + 5.59887 \cdot Fo^2 - 2.59316 \cdot Fo^3, \quad (12)$$

The total heating time for a round load was determined according to the following formula:

$$\tau = \frac{ln\left(\frac{\delta}{1.14}\right)}{\left[\left(-2.47 \cdot \frac{\bar{a}}{l^2}\right) + \left(-5.76 \cdot \frac{\bar{a}}{R^2}\right)\right]}, \text{ h} \quad (13)$$

For the case under consideration, the heat transfer surfaces were determined from the following relationships:

$$A = 2 \cdot (B \cdot L + B \cdot H + L \cdot H) + n \cdot \pi d \cdot l, \text{ m}^2 \quad (14)$$

$$A_m = n \cdot \left(\pi d \cdot l + \frac{\pi d^2}{4}\right), \text{ m}^2 \quad (15)$$

This allowed for the calculation of heat transfer parameters related to radiation.

The function F(Fo) was determined from the relationship:
for Fo≤ 1.0:

$$F(Fo) = 1.67554 - 14.19018 \cdot Fo + 52.90179 \cdot Fo^2, \quad (16)$$

for Fo> 1.0:

$$F(Fo) = 1.43539 \cdot exp\left(-\frac{Fo}{0.15285}\right) + 0.03324, \quad (17)$$

The program window is shown in Fig. 1.

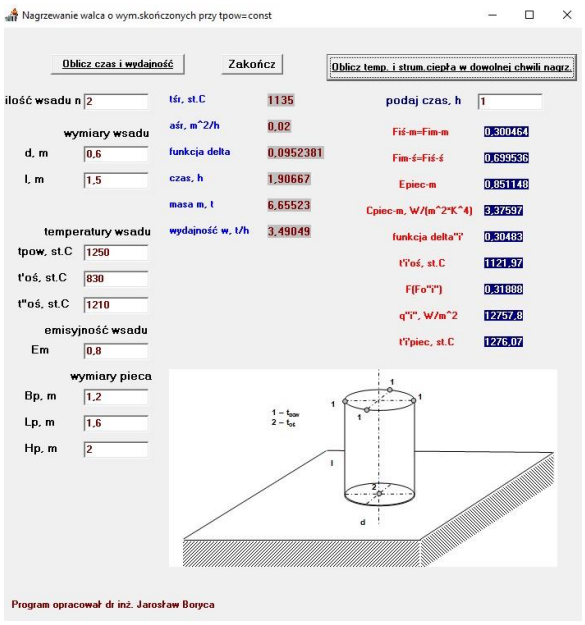

Figure 1 The program window

4 Calculation results

It was assumed that in the chamber furnace a finite-sized charge made of medium carbon steel is heated on one side, with a constant surface temperature.

The following technological assumptions were adopted for the calculations:
- surface temperature of the charge t_p = 1250°C,
- initial temperature in the axis of the charge $t'_{oś}$ =830°C,
- final temperature in the axis of the charge $t''_{oś}$ = 1210°C.

Other calculation assumptions:
- dimensions of the round insert d=0.6 m, l=1.5 m,
- furnace dimensions L = 1.6 m, B = 1.2 m, H = 2 m,
- charge density ρ=7850 kg.m^{-3},
- number of pieces of charge in the furnace n=2,
- emissivity of the charge ε_m=0.8.

The values of material parameters (λ, a) of the batch were calculated for the average temperature.

Based on the described functions and dependencies, a computer program was developed. Calculations of the heating process were carried out. The overall results are shown in Table 1, and for individual time intervals are presented in Table 2. The temperature course during heating is shown in Fig. 2.

Table 1 The overall results of calculations

Name	Symbol	Value
average temperature	$\bar{t}$, ºC	1135
average thermal diffusivity	$\bar{a}$, $m^2.h^{-1}$	0.02
degree of temperature equalization	δ	0.09524
time	τ, h	1.90667
efficiency	w, $t.h^{-1}$	3.49049
angular radiation coefficient of the furnace surface-metal system	$\varphi_{ś\text{-}m} = \varphi_{m\text{-}m}$	0.30046
angular radiation coefficient of the metal-furnace surface system	$\varphi_{m\text{-}ś} = \varphi_{ś\text{-}ś}$	0.69954
equivalent emissivity of the furnace-metal system	$\varepsilon_{p\text{-}m}$	0.85115
radiation constant of the furnace-metal system	$C_{p\text{-}m}$, $W.(m^{-2}.K^{-4})$	3.37597

Table 2 The results of calculations for individual time intervals

τ_i, h	δ_i	$t_{i\ oś}$, ºC	$F(Fo_i)$	$\dot{q}_i$,W/m²	$t_{i\ piec}$, ºC
0	1.05814	830.0	1.63134	65267	1371.5
0.2	0.82498	903.5	1.17696	47087	1340.3
0.4	0.64320	979.9	0.84914	33972	1316.7
0.6	0.50148	1039.4	0.61262	24510	1299.0
0.8	0.39098	1085.8	0.44199	17683	1285.8
1.0	0.30483	1122.0	0.31888	12758	1276.1
1.2	0.23766	1150.2	0.23006	9204	1268.9
1.4	0.18530	1172.2	0.16598	6641	1263.7
1.6	0.14447	1189.3	0.11975	4791	1260.0
1.8	0.11263	1202.7	0.08640	3457	1257.2
1.907	0.09863	1210.0	0.07259	2904	1256.1

where:
i – index denoting the value for individual time intervals.

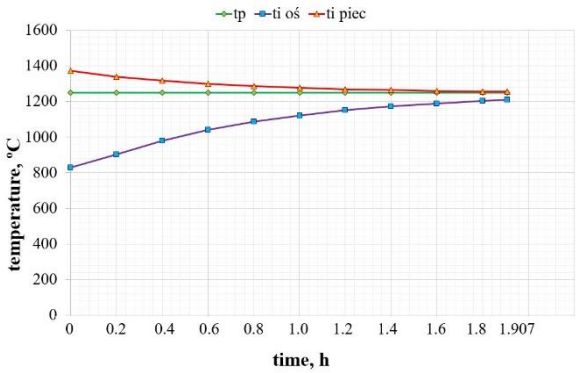

Figure 2 The temperature course during heating

5 Conclusions

The computer computational program presented in the article is an interesting and at the same time simple engineering tool. It allows you to determine the parameters of heat transfer by radiation and calculate the heating of a cylindrical charge.

The program is designed for heating at a constant temperature of the charge surface and a parabolic temperature distribution across the cross-section. It is therefore the second stage for the calculation of two-stage heating of the charge. Combining it with a calculation program with a linear increase in the temperature of the defect surface will allow for quick calculations for the entire process.

The presented calculations confirm the usefulness of the program for quick calculations of the heating process in the described range. The program can also be used for teaching purposes.

The reference list

[1] KIELOCH, M.: *Energooszczędne i małozgorzelinowe nagrzewanie wsadu stalowego,* Prace naukowe Wydziału Inżynierii Procesowej, Materiałowej i Fizyki Stosowanej, Seria Metalurgia nr 29, Częstochowa 2002.

[2] KIELOCH M., BORYCA J., PIECHOWICZ Ł.: Modelowanie pracy cieplnej pieców grzewczych w dwuetapowym procesie nagrzewania, *Hutnik-Wiadomości Hutnicze*, No. 7, pp. 351 – 357, 2006.

[3] KIELOCH, M.: *Technologia i zasady nagrzewania wsadu*, Skrypt Politechniki Częstochowskiej, Częstochowa 1995.

[4] BORYCA, J.: Ph.D. Thesis *Przyczepność warstwy zgorzeliny powstałej w procesie nagrzewania wsadu stalowego*, Politechnika Częstochowska, Częstochowa 2005.

[5] RABAH, A.: *Heat transfer: Detailed Approach*, Khartoum University Press, Khartoum 2023.

[6] GOŁDASZ, A., MALINOWSKI, Z.: Identification of the heat transfer coefficient at the charge surface heated on the chamber furnace, *Archives of Metallurgy and Materials*, Vol. 62, No. 2, pp. 509-513, 2017.

[7] HAHN, D.W., NECATI ÖZIŞIK, M.: *Heat Conduction*, John Wiley&Sons, Inc., Hobolen, New Jersey 2012.

[8] SENKARA, T.: *Obliczenia cieplne pieców grzewczych w hutnictwie*, „Śląsk", Katowice 1981.

[9] KIELOCH, M.: *Racjonalizacja nagrzewania wsadu*, Wyd. WIPMiFS Politechniki Częstochowskiej, Seria Monografie nr. 8, Częstochowa 2010.

[10] HAN, J.-C.: *Analytical Heat Transfer*, CRC Press, 2012, [Online], Available: http://www.crcpress.com, [24 Jan 2024].

[11] KIELOCH, M., KRUSZYŃSKI, S., BORYCA, J., PIECHOWICZ Ł.: *Termodynamika i technika cieplna - ćwiczenia rachunkowe*, Skrypt Politechniki Częstochowskiej, Częstochowa 2006.

[12] BORYCA, J., KOLMASIAK, C., WYCZÓŁKOWSKI, R., BAGDASARYAN, V., AGHBALYAN, S.: Calculation model of heating curves of a steel charge heated in a walking beam furnace before plastic working, *Metalurgija*, Vol. 63, No. 3-4, pp. 457-460, 2024.