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CALCULATION MODEL OF HEATING CURVES OF A STEEL CHARGE HEATED IN A WALKING BEAM FURNACE BEFORE PLASTIC WORKING

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The paper presents a universal computational model of heating curves for walking beam furnaces, which allows to determine the temperature distribution along the length of the furnace during heating of the steel charge. The model was made based on analytical dependencies regarding transient heat conduction, taking into account the temperature variability of all thermo-physical properties. The methodology of calculations and examples of heating curves for selected cases are presented.

Keywords: steel, walking beam furnace, heating of steel charge, modelling of heating, heating curves

INTRODUCTION

The issues of the analysis of the charge heating process concern the problem of transient heat conduction in a solid [1-3]. The thermal conductivity equation combined with the initial and boundary conditions is a mathematical model of the considered heat transfer phenomenon. The starting point for the consideration of transient heat conduction is the Fourier's differential equation [1, 3-5]:

$$\frac{\partial t}{\partial \tau} = a \cdot \frac{\partial^2 t}{\partial x^2}, \qquad (1)$$

where:

t – temperature/ °C,
τ – time/ s,
a – thermal diffusivity/ m^2/s,
x – distance/ m.

The equation (1) shows that the change in temperature t during τ is proportional to the change in the temperature gradient (in the case of unidirectional heat flow to a change in the temperature gradient along the x axis). The choice of the equation is determined by the fulfillment of the initial and boundary conditions [1, 5-7], the first of which relates to time and characterizes the temperature distribution at the time of process evaluation (t = 0), and the second concerns the surface area and determine the nature of the temperature changes on the surface of the heated body or the interaction of the surface with the surrounding atmosphere.

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CALCULATION MODEL

The computational model for determining the heating curves was developed in the Scilab environment [8]. A schematic diagram of the operational structure of the program is shown in Figure 1.

The developed program works on the basis of a set of procedures based on analytical dependencies. Calculations of the combustion process were carried out using the basic equations for the combustion of gaseous fuels [9-11]. Configuration coefficients were calculated on the basis of analytical dependencies, taking into account the combustion process and the geometry of the charge and individual zones of the furnace [9].

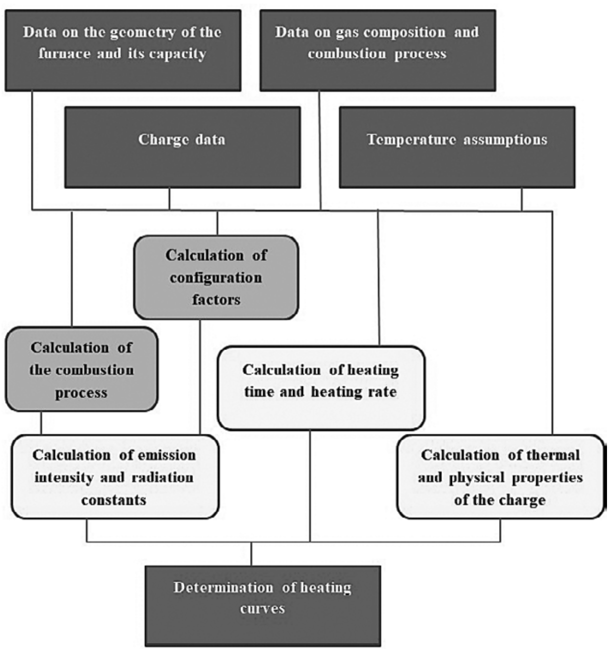

Figure 1 Diagram of the operational structure of the program

Based on the emission diagrams in the literature [5, 9], mathematical relationships describing the effect of exhaust gas temperature on CO_2 and H_2O emissions and the relationship taking into account water vapor emissions were developed. Details of these relationships are described in [12].

One of the procedures was to determine the thermophysical properties of the heated charge. Carrying out the heating calculations required the development of mathematical functions describing the variability of the thermophysical properties of the charge with the average charge temperature in a given heating period. Based on literature data [1, 5], mathematical functions for medium carbon steel charge were established.

The temperature changes of the thermal conductivity λ of steel can be described by appropriate mathematical correlations [13]. In the analyzed case, for the respective ranges of average temperature, the following relationships were used:

- for 0 °C≤t_{sr}<800 °C

$$\lambda = 50,79821 - 0,00992 \cdot t_{sr} - 2,518 \cdot 10^{-5} \cdot t_{sr}^2 , \quad (2)$$

- for 800 °C≤t_{sr}<900 °C

$$\lambda = 26,1 - 0,001 \cdot \left(900 - t_{sr}\right) , \quad (3)$$

- for 900 °C≤t_{sr}<1200 °C

$$\lambda = 34,465 - 0,02505 \cdot t_{sr} - 1,75 \cdot 10^{-5} \cdot t_{sr}^2 , \quad (4)$$

- for t_{sr}≥1200 °C

$$\lambda = 29,6 , \quad (5)$$

where:

λ – thermal conductivity/ W/(m K),

$t_{śr}$ – average temperature/ °C.

The thermal diffusivity a can be described, for the respective ranges of average temperature, with the following relationships:

- for 0 °C≤t_{sr}<700 °C

$$a = 0,052 - 4,82143 \cdot 10^{-5} \cdot t_{sr} , \quad (6)$$

- for 700 °C≤t_{sr}<800 °C

$$a = 0,018 , \quad (7)$$

- for 800 °C≤t_{sr}<900 °C

$$a = 0,018 - 2 \cdot 10^{-5} \cdot \left(t_{sr} - 800\right) , \quad (8)$$

- for t_{sr}≥900 °C

$$a = 0,02 , \quad (9)$$

where:

a – temperature conductivity/ m²/h,

$t_{śr}$ – average temperature/ °C.

It was found that the specific heat *c* can, for the relevant average temperature ranges, be described by relationships:

- for 0 °C≤t_{sr}<800 °C

$$c = 487,45 - 0,00175 \cdot t_{sr} - 30,84 \cdot 10^{-5} \cdot t_{sr}^2 , \quad (10)$$

- for 800 °C≤t_{sr}<900 °C

$$c = 700 , \quad (11)$$

- for 900 °C≤t_{sr}<1000 °C

$$c = 690 - 0,1 \cdot \left(1000 - t_{sr}\right) , \quad (12)$$

- for 1000 °C≤t_{sr}<1100 °C

$$c = 690 , \quad (13)$$

- for 1100 °C≤t_{sr}<1200 °C

$$c = 680 - 0,1 \cdot \left(1200 - t_{sr}\right) , \quad (14)$$

- for t_{sr}≥1200 °C

$$c = 680 , \quad (15)$$

where:

c – the specific heat/ J/(kg K),

$t_{śr}$ – average temperature/ °C.

It was assumed that the charge heating process takes into account the first kind of boundary conditions; in the regeneration and heating zones there is a linear increase in the surface temperature of the charge, while in the equalizing zone there is a constant increase in the surface temperature (temperature equalization across the charge cross-section). The heating calculations required the development of relationships describing the relative temperature for the axis, the Fourier number as a function of temperature equalization, and the functions F(Fo) and F_1(Fo).

It was found that the relative temperature for the axis can, for the respective ranges of the Fourier number, be described by relationships:

- for Fo<0,1

$$\varphi_{1os} = 1,003 - 1,85 \cdot Fo , \quad (16)$$

- for 0,1≤Fo<1,2

$$\varphi_{1os} = 0,92438 - 1,45357 \cdot Fo + 0,59821 \cdot Fo^2 , \quad (17)$$

- for Fo≥1,2

$$\varphi_{1os} = 0 , \quad (18)$$

where:

φ_{1os} – relative temperature for the axis,

Fo – Fourier number.

The Fourier number for the heating period as a function of temperature equalization is described by the following relationship:

$$Fo_w = 0{,}1926 + 1{,}76238 \cdot \exp\left(-\frac{\delta}{0{,}14479}\right), \quad (19)$$

where:

Fo_w – Fourier number for the equalization period,

δ – degree of temperature equalization.

The value of the function $F_1(Fo)$ is described by the following relationships:

- for Fo<0,1

$$F_1(Fo) = 0{,}97643 - 5{,}632 \cdot Fo + 22{,}32 \cdot Fo^2, \quad (20)$$

- for 0,1≤Fo<1,5

$$F_1(Fo) = 0{,}69713 - 1{,}05774 \cdot Fo + 0{,}5406 \cdot Fo^2, \quad (21)$$

- for Fo≥1,5

$$F_1(Fo) = 0, \quad (22)$$

where:

$F_1(Fo)$ – function,

Fo – Fourier number.

The value of the function F(Fo) is described by the relationships:

- for Fo<0,1

$$F(Fo) = 1{,}9289 - 11{,}213 \cdot Fo + 49{,}55357 \cdot Fo^2, \quad (23)$$

- for 0,1≤Fo<1,7

$$F(Fo) = 1{,}4472 - 2{,}23571 \cdot Fo + 0{,}8869 \cdot Fo^2, \quad (24)$$

- for Fo≥1,7

$$F(Fo) = 0, \quad (25)$$

where:

F(Fo) – function.

These relationships were developed on the basis of literature data [1, 5, 9]. The issue of modeling the heating of the steel charge before plastic working is also discussed in works [14-16].

RESULTS OF CALCULATIONS

The following input data should be entered into the developed model:

- gas composition and excess combustion air ratio,
- geometrical parameters of the charge,
- geometrical parameters of the furnace and its individual zones,
- the assumed furnace capacity,
- temperature assumptions for charge and exhaust gas.

After entering the data, the calculation procedure is started, the results of which are the temperature values of the furnace and the charge on the surface and in the axis of individual furnace zones.

Calculations were made for a walking beam furnace with a nominal capacity of 220 t/h. The cold and hot charge and the furnace operating at the optimum capac-

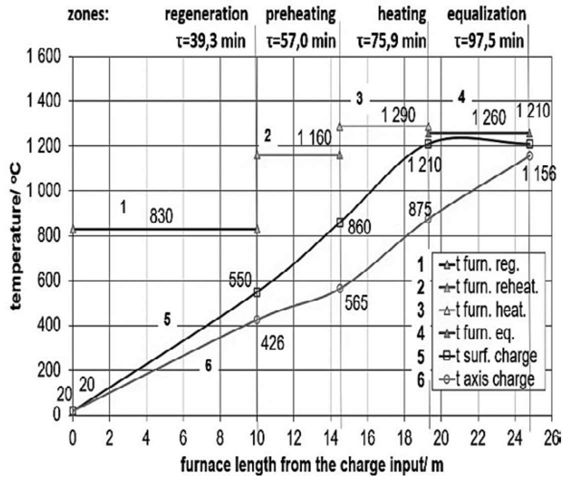

Figure 2 Heating curves for the cold charge for the furnace operating at nominal capacity

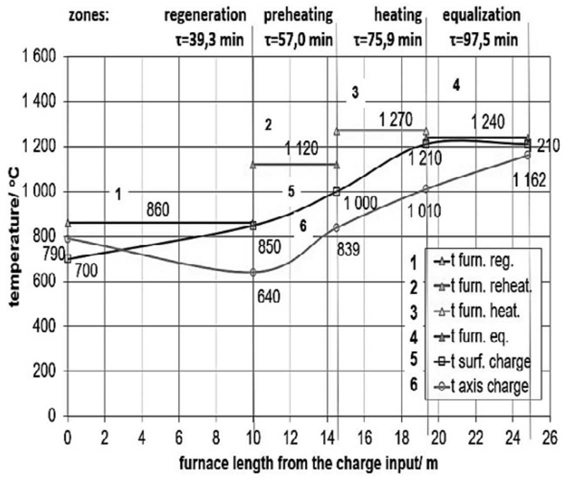

Figure 3 Heating curves for the hot charge for the furnace operating at nominal capacity

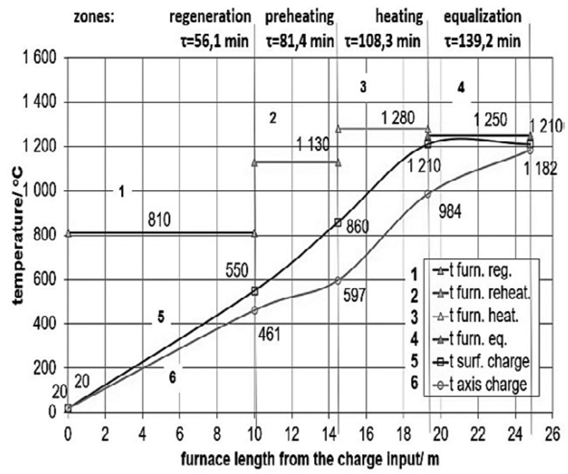

Figure 4 Heating curves for the cold charge for the furnace operating at the optimum capacity (70 % of the nominal capacity).

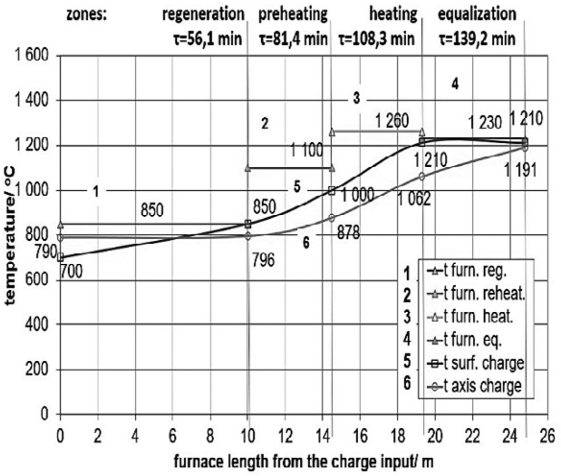

Figure 5 Heating curves for the hot charge for the furnace operating at the optimum capacity (70 % of the nominal capacity).

ity, i.e., reduced to 70 % of the nominal capacity, were taken into account. Examples of averaged heating curves (charge and furnace temperatures in zones) for various furnace operating conditions are shown in Figures 2- 5.

Based on the obtained results, the heating curves presented above were developed. Comparing the curves for the cold and hot charge, it should be stated that with the same heating times, the furnace temperature can be reduced in individual burner zones (where the combustion process takes place). The temperature in the regeneration zone must be kept higher than with the cold load in order to take full advantage of the enthalpy of the hot load. The heating curves for optimal performance show a similar tendency, with the charge being heated over a relatively longer time. The temperature of the regeneration zone is also lower.

SUMMARY

The developed calculation program allows modeling the heating curves for any walking beam furnace and any charge. This is ensured by the possibility of changing the input data in the form of geometric parameters of the furnace and the charge. It is also possible to calculate heating curves for variable, increased, or reduced furnace capacities.

The computational model was developed for the first kind of boundary conditions. It takes into account the charge temperature and the variability of its thermophysical parameters during the heating process. The possibility of changing the gas composition and the value of the excess combustion air ratio allows the freedom to model the necessary calculations for the combustion process.

All these elements make the presented program a universal tool for modeling heating curves in walking beam furnaces.

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