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HEAT FLUX IDENTIFICATION AT THE CHARGE SURFACE DURING HEATING IN CHAMBER FURNACE

In this study, a method of determining the heat flux, which reaches the surface of a charge, has been presented with the use of an inverse analysis. The research on the heating process of a square 15HM steel charge was conducted in a natural gas-fired laboratory furnace. The inverse solution was based on the search of the minimum standard error between the measured and the calculated temperatures. The temperature of the charge has been calculated by the finite element method, solving the heat conduction equation for a square charge heated on all the surfaces. As a result, the mean value of the heat flux on each of the heated surfaces of the charge was estimated.

Keywords: heat flux, inverse method, finite element method, chamber furnace.

1. Introduction

Chamber furnaces which serve for heating the charges, tend to consume a lot of energy, and in the case of gas-firing, an emission of combustion process-based impurities occurs. In the overall economic balance of a steelmaking process, these features constitute a relatively large load. The focal point of the researchers [1] is to design a procedure which would make it possible to conduct a full analysis of the work of such appliances. The numerical modeling of the heat transfer in a chamber furnace and in the charge during heating is very problematic. The value of a heat flux which reaches the surface of a heated charge depends among others on: the type of the furnace and its geometry, the type and the lay-out of the burners, the type of the fuel and also on the thermophysical properties of the material being heated. Almost 90% of the heat flux is delivered through the radiation heat transfer [2-4], the exhaust gases convection and the thermal conduction from the furnace bottom constitutes the remaining part. Estimating each of the heat flux components is not easy and generally bears low accuracy. Thus, the goal is to design a method of determining the boundary conditions, which would make it possible to define the total heat flux which reaches the surface of the charge. It is possible, by using the inverse methods, referred to in the literature as IHCPs (inverse heat conduction problems) [5, 6].

The research in this field has been presented in [7]. The heating of the charge was conducted for a 20 mm thick, 80 mm wide and 100 mm long slab ingot. The temperature measurement was performed in 3 points, which were located 5, 11 and 17 mm deep. In this solution, from the temperature distributions at the first 2 points the boundary condition has been determined. The goal of the solution was to determine the heat flux on the surface of the charge with the use of a Matlab suite. In turn, in the study [8], the heat fluxes were determined on 6 surfaces of a chamber furnace with the use of the CGM (Conjugate Gradient Method) method. The research was conducted up to the temperature of 250 °C with the use of thermographic cameras. Aluminum and the convective heat transfer coefficient on the inner side at about 100 W/(m^{2}K) were taken as the material. In the study [9], the heat flux which reaches the heated charge in a walking beam furnace was determined for the lateral surface areas, as well as for the upper and the bottom surface area. Dynamic matrix control (DMC) was used therein, for stabilizing and controlling the desired heat flux values, which is an objective function dependent on the measured temperature values. The model has been verified on the basis of the data emerging from the literature. Heat fluxes on the upper and bottom surface of the heated charge [10] were also determined for the walking beam furnace, based on the inverse method, which is commonly used in reference to the inverse radiation problems. The solution was obtained on the basis of the temperature measurements at 3 points, localized at ¼, ½, and ¾ of the depth of the charge, with the frequency of 900s.

2. The model of heating a charge in a chamber furnace

The model of heating a charge in chamber furnaces has been based on the finite element method used for solving the heat conduction equation, which, in the Cartesian coordinates, takes the following form:

$$\frac{\partial T}{\partial \tau} = \frac{1}{\rho c}\left[\frac{\partial}{\partial x_1}\lambda\left(\frac{\partial T}{\partial x_1}\right) + \frac{\partial}{\partial x_2}\lambda\left(\frac{\partial T}{\partial x_2}\right) + \frac{\partial}{\partial x_3}\lambda\left(\frac{\partial T}{\partial x_3}\right)\right] + \frac{q_v}{\rho c} \quad (1)$$

where:
λ – thermal conductivity, W/(m·K);
x_1, x_2, x_3 – Cartesian coordinates, m;
ρ– density, kg/m^3;

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c – specific heat, J/(kgK);
q_v – capacity of the external heat source, W/m^3;
τ – time, s.

Determining the temperature field of a charge heated in a chamber furnace, requires defining the boundary conditions on the surface of the heated material. For the description of the heat transfer, a simplified model was used, in which the furnace chamber is regarded as a closed system, consisting of 2 isothermal surface (F_1 - of the charge, F_2 - of the furnace walls) and of an isothermal lump of gas.

The average density of the heat flux absorbed by the charge is the sum of the waste gas convection and radiation fluxes, and of the radiation of the furnace walls.:

$$\dot{q}_w = \propto_{gw} \left(T_g - T_2\right) + \varepsilon_g \varepsilon_2\, 5.67 \cdot 10^{-8}\left(T_g^4 - T_2^4\right) + \varepsilon_{sw} P_g\, 5.67 \cdot 10^{-8}\left(T_1^4 - T_2^4\right) \quad (2)$$

where:
ε_g – emissivity of a lump of gas,
ε_2 – emissivity of the surface of a charge,
ε_{sw} – substitute emissivity of the walls - charge system,
P_g – transparency of a lump of gas for a radiation on the surface of a charge,
α_{gw} – the coefficient of the convective heat transfer on the surface of a charge,
T_g – absolute temperature of a lump of gas,
T_1 – absolute temperature of the surface areas of the furnace walls,
T_2 – absolute temperature of the surface of a charge.

Emissivity ε_1 of the surface of the furnace walls is to be taken from the range of 0.75 to 0.85, depending on the type of the insulating material used in the furnace chamber. Emissivity ε_2 of the charge is to be determined from the equation [11]:

$$\varepsilon_2 = 1.1 + \frac{(T_2 - 273)}{1000}\left(\frac{0.125(T_2 - 273)}{1000} - 0.38\right) \quad (3)$$

Transparency of a lump of gas of the T_g temperature was determined from the Hottel charts [12]. The average temperature T_2 of the surface of the charge was being calculated as the average integral value on a particular area, the temperature of the walls was in turn calculated on the basis of the temperature of the waste gases.

$$T_1 = T_g - 5.67\frac{1 - \varphi_{12}}{\alpha_{g1}}\frac{\varepsilon_1 \varepsilon_2}{\varepsilon_1 + \varphi_{12}\varepsilon_2(1 - \varepsilon_1)}\left[\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4\right] \quad (4)$$

The average coefficient of the φ_{12} configuration is defined by the equation:

$$\varphi_{12} = \frac{F_2}{F_1} \quad (5)$$

The effective heat transfer coefficient of the gas - furnace wall heat exchange was calculated from the equation:

$$\alpha_{g1} = \frac{5.67\varepsilon_1 \varepsilon_g}{T_g - T_1}\left[\left(\frac{T_g}{100}\right)^4 - \left(\frac{T_1}{100}\right)^4\right] \quad (6)$$

The α_{gw} convective heat transfer coefficient, which emerges from the waste gasses flow round charge surface, was determined on the basis of the average Nusselt number for the flow over a flat surface.

$$Nu = 0.037\, Re\, Pr_g^{0.43}\left(\frac{Pr_g}{Pr_s}\right)^{0.25} \quad (7)$$

where:
Re – Reynolds number, calculated for the average speed and temperature of the waste gases,
Pr_g – Prandtl number, calculated for the T_g, temperature of the waste gases,
Pr_s – Prandtl number, calculated for the temperature of the T_2 surface of the charge.

The effective α_w heat transfer coefficient on the surface of a charge, which allows for the radiation of walls, the radiation of a lump of gas and the movement of waste gases around the charge, was calculated from the equation:

$$\alpha_w = \frac{\dot{q}_w}{T_g - T_2} \quad (8)$$

The decrease of heat penetration into the surface of the charge by the growth of the scale was also taken into account. The thickness of the oxide layer was determined with the use of the function.

$$g_z = 84.4\left[e^{-\frac{9983}{T}}\right]\tau^{0.5} \quad (9)$$

On the basis of the determined thickness of the oxide layer, a correction of the α_{we} effective heat transfer coefficient is performed on each stage of the calculations, according to the equation:

$$\alpha_{we} = \frac{1}{\frac{1}{\alpha_w} + \frac{g_z}{1000\,\lambda_z}} \quad (10)$$

where:
λ_z – thermal conductivity of the scale.

To solve the equation (1), the finite element method (FEM) was used, which is based on the solution of a system of partial differential equations:

$$K_{ij}(\tau) \cdot T_j(\tau) + C_{ij}(\tau)\frac{\partial T}{\partial \tau} = G_i(\tau) \quad (11)$$

where:
$K_{ij}(\tau)$ – thermal conductivity matrix;
$C_{ij}(\tau)$ – thermal capacity matrix;
$G_i(\tau)$ – thermal load vector.

The Galerkin scheme and the nonlinear shape functions, described with Hermite's polynomials were assumed.[13]

3. The inverse problem

In the study, the average value of heat flux on each wall of the heated charge was being determined. An inverse solution based on the approximation function method was created for the analyzed system. In this method, the solution of the inverse problem comes down to determining the minimum of the objective function, which is the sum of the squared deviations of the measured and the calculated temperatures.

$$E(p_k) = \frac{1}{NT \cdot NP} \sum_{i=1}^{NT} \sum_{j=1}^{NP} \left(\frac{Te_i^j - T(p_k)_i^j}{Te_i^j} \right)^2 \qquad (12)$$

where:

p_k – vector of the unknown parameters,

NT – number of the temperature sensors,

NP – number of the temperature measurements performed by one sensor,

Te_i^j – the sample temperature measured by the sensor i at the time τ_j,

T_i^j – the sample temperature at the location of the sensor i at the time τ_j calculated from the finite element solution to the heat conduction equation.

The minimum of the objective function was being determined by the variable metric method with the use of the BFGS algorithm. The sensitivity test of the inverse model has been presented in [6].

4. Numerical calculations

The tests of the solution were performed for the heating of a cube shaped steel charge with a 0.15 m side. The 15HM steel was assumed for the charge. The physical properties of the charge were being established as temperature dependent functions - fig.1.

For the purposes of the analysis of the accuracy of the designed model of charge heating in a chamber furnace, the simulated temperature readings were generated at 30 temperature measurement points, five of which were localized on each wall, 3 mm below the surface. The heating time was 3600 s, and the maximum temperature of the furnace – 900 °C. The assumed division into finite elements was of 3x3x3 elements. As part of the initial simulations, the time step was evaluated. In figure 2, the temperature distribution of a selected point, localized on the upper surface of the charge was presented and compared with the expected value. Correct results of the temperature distribution were obtained, which are close to the reference model. The determined δt error, calculated as the root of the sum of the squared deviations between the temperatures, calculated by the FEM model and the reference model, was 1.03 K. The maximum positive temperature deviation (Δt_{max}) between the reference values and the values calculated from the FEM model, was 5.29 K. In turn, the maximal negative temperature deviation (Δt_{min}) was -3.91 K. Taking the high value of time step and the rare finite element mesh into consideration, the results are to be declared as correct. Moreover, the results ensure a significant reduction of the time of calculation for the real processes, which are distinguished by a much longer heating time.

Heating of the charge in a laboratory gas-fired chamber furnace (fig. 3a) was performed in order to determine the distributions of the heat flux at charge walls. Internal dimensions of the furnace chamber were: 450×550×1340 mm. The furnace has a fibrous lining and, is equipped with one 50 kW kinetic burner. On each of the charge walls , a temperature measurement in 5 points was conducted with the use of 1 mm thick Type K thermocouples, fixed 3 mm below the charge surface (fig. 3b). In order to provide

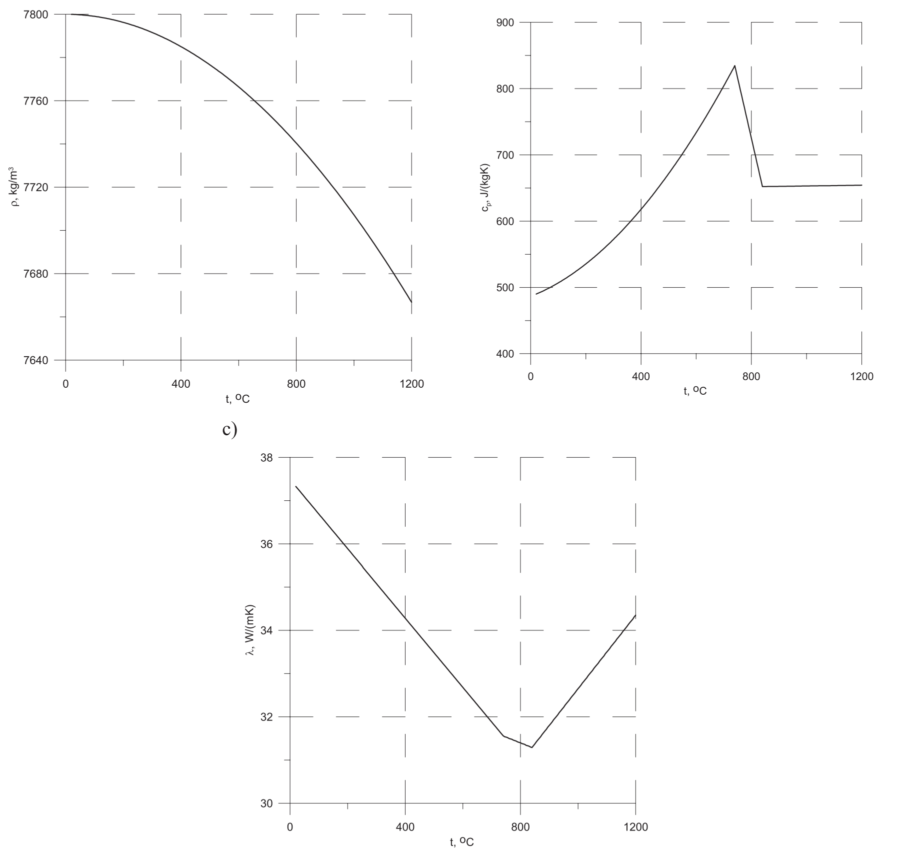

Fig. 1. The physical properties of 15 HM steel: a) density; b) specific heat; c) thermal conductivity

a reliable reflection of the real conditions, the charge was placed on a metal support. As a result, the measurement from the side of the furnace bottom was also possible. The registration of the 30 temperature measurement points was performed with the help of an MGCplus measuring system with an accuracy of ±0,2%. The maximum error in the measuring system did not exceeded 2.26 K of the the measured temperature.

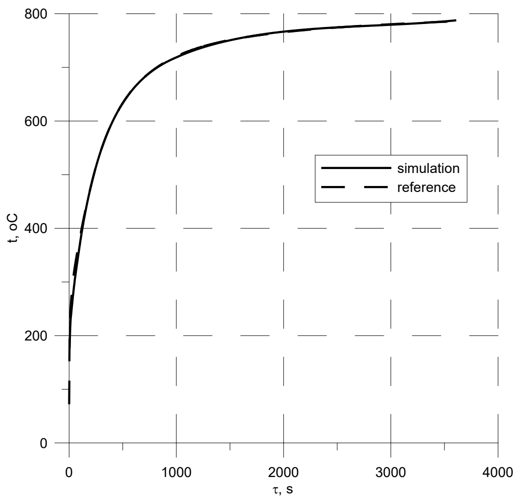

Fig. 2. The comparison of the temperature distribution on the surface of the charge with the reference distribution

a) b)

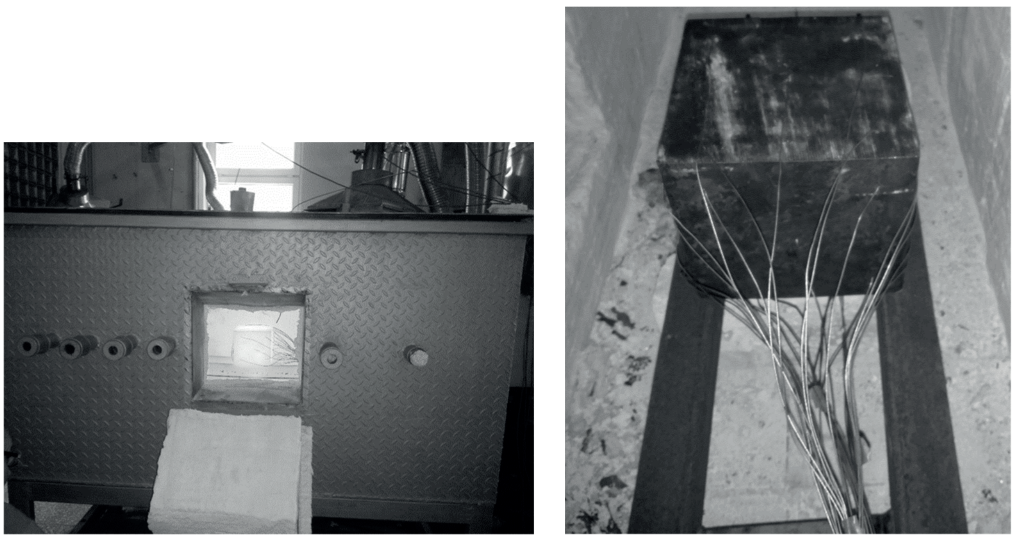

Fig. 3. The test stand: a) the furnace chamber; b) charge

a) b)

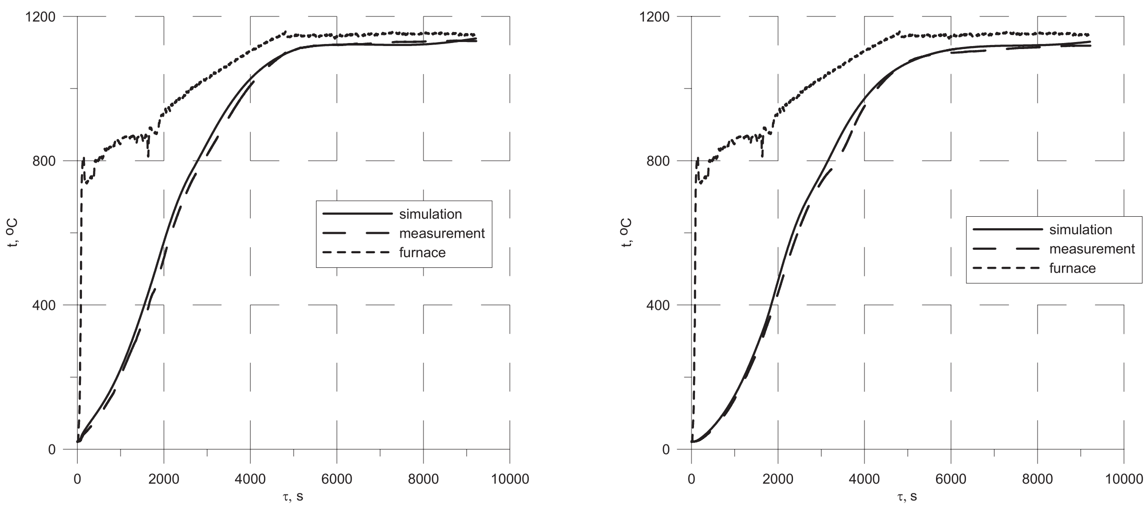

Fig. 4. The comparison of temperature distributions in the characteristic points: a) the top surface; b) the bottom surface

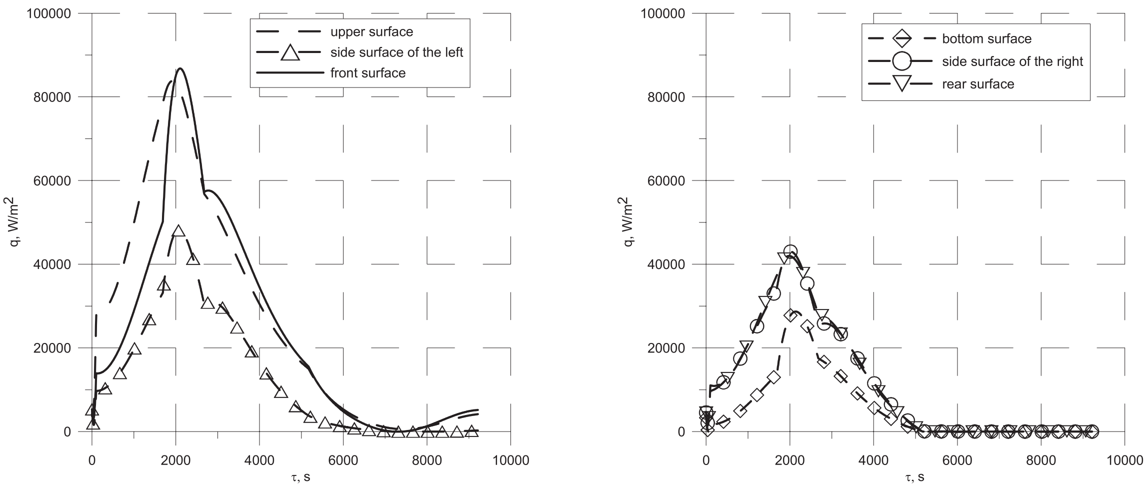

Fig. 5. The heat flux distribution during the charge heating, 15 HM steel5. Summary

After about 7000 s, when the temperature of the surface stabilizes at the level around 1120 °C, the heat flux assumes a null value, followed by a rise to the value of around 5 kW/m^2 but only on the front and the upper surfaces. The heating was performed until the maximum temperature of the furnace of about 1160 oC has been reached. The process was stopped after the temperatures in the measuring thermocouples were equalized. The heating time was 9224 seconds. The calculations by the inverse method were being conducted for the previously selected time step and the division into elements. The temperature distributions at points located in the middle of the charge walls, obtained from the measurements, was compared with the calculations, fig. 4. A reliable compatibility of the temperature distributions were obtained, the average square error δt, obtained from the calculations, was 6.75 K. The maximum positive and negative temperature deviation was between 31.73 and -22.91 K. The results should be recognized as satisfactory, taking the relatively substantial temperature deviations of the atmosphere in the manually controlled furnace into consideration.

As a result of the conducted calculations, the distributions of average heat fluxs were obtained on all the 6 surfaces of the heated charge, fig. 5. The maximum value of the heat flux does not exceed 85 kW/m^2 in the case of the front surface of the charge, located at the burner side. A similar result can be observed in the case of the upper surface. The lowest values of the heat flux were reported for the bottom surface (maximally 27 kW/m^2), whereas similar values were obtained for the lateral surfaces and for the rear surface from the flue side (maximally 47 kW/m^2).

In the study, the method of identification of a boundary condition defined by the heat flux on each surface of the heated charge was presented. The solution of the problem of heat transfer in the heated charge, involved the finite element method. The inverse method made it possible to determine the demanded value of the boundary condition. The designed solution was being tested for the reference data and, a reliable conformity was obtained.

The maximum value of heat flux was observed after about 2000 s, when the charge begins to receive progressively smaller amounts of heat on all the surfaces. The obtained results might be favorable used as entry data for a detailed analysis of the heating process of any given charge in chamber furnaces. On that account, it is vital to conduct a temperature measurement analysis for the trial version. The boundary conditions obtained from the solution can be favorably implemented into any given simulation program . It will make it possible to significantly simplify the heating process analysis. Conducting the measurements with traditional methods involves giving consideration to the equations of radiation heat transfer and the numerical fluid mechanics, which virtually makes it impossible to obtain the final result in a relatively short period of time.

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