Temperature Distribution and Analysis of Steel Heating Process in Walking Beam Furnace

Milisav Lalović[1], Žarko Radović[1], Nada Jauković[1]

[1]University of Montenegro, Faculty of Metallurgy and Technology Podgorica, Cetinjski put bb, Podgorica, Serbia and Montenegro
lmilisav@cg.ac.yu

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Abstract. The study of temperature distribution during metal heating was motivated by investigations into heat transfer in metallurgical furnaces, which is concerned with a number of problems in the procedure of hot metal rolling.

Introduction

The problems of heat transfer mechanisms during heating and cooling of steel billets are essential studies of many areas of metalworking process [1-3]. Metal temperature is one of the most important variables governing the behaviour of metals under hot-working conditions [3-7]. In many practical cases of heating, when the boundaries of system are irregular or when the temperature along the boundary is non uniform, analytical solution cannot be used for the solving of heat transfer problems. Such problems can be solved by one of the numerical methods [8].

The aim of the paper was to develop a model a model that may predict the temperature distribution within the steel billet during heating.

Formulation of the model

For heating process, when the billet length is many times bigger than its wide, the problem can be simplified by ignoring heat flow in direction of billet length. In that case, a selected section of the billet can be taken into consideration. The boundary conditions for horizontal and vertical surfaces are:

for y = b; $-\frac{\partial t}{\partial y} = \alpha_t (t_f - t_s)$ (1)

for x = b/2; $-\frac{\partial t}{\partial x} = \alpha_l (t_f - t_s)$ (2)

for y = 0; $-\frac{\partial t}{\partial y} = \alpha_b (t_b - t_s)$ (3)

The boundary conditions for the center line can be written as:

for x = 0; $\frac{\partial t}{\partial \tau} = 0$ (4)

The two-dimensional nonsteady conduction can be expressed by equation:

$$\frac{\partial t}{\partial \tau} = a\left(\frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2}\right) \tag{5}$$

The equations 1–5 form a mathematical model which will predict temperature field and the heat transfer rate during steel billet heating in a walking beam furnace.

Explicite case of the finite difference formulation

In order to obtain numerical solutions of the model equations, a computer program was constructed expressing these in a finite difference form. According to that, for the two-dimensional heat transfer, chosen segment of billet was divided into finite number of equal elements in both x and y direction. An element of unit depth and dimensions Δx and Δy, when $\Delta x = \Delta y$, is chosen as a system to which the principle of conservation energy is applied. That surface is divided into I anuli in the direction of x, but J anuli in the y direction. The center of each element is called *a node*. Nodal points are designated as shown: subscript *i* and *j* denotes x and y position.

Heat transfer consists of the heat flow to the surface, conduction into the body of billet and accumulation of heat in the metal. Heat flow to the surface of the billet can be expressed by equation:

$$Q_s = \alpha_k(t_f - t_s)A\Delta\tau + C_R\left[\left(\frac{T_f}{100}\right)^4 - \left(\frac{T_s}{100}\right)^4\right]A\Delta\tau \tag{6}$$

The differential equation which governs the heat flow within the solid body is Fourier's law (Eq. 5), whose analytical expression defines the direction of the heat flow. For the two-dimensional process of transient heat flow, the time derivate in Eq. 5 is approximated by:

$$\frac{\partial \tau}{\partial \tau} = \frac{t_{i,j,k} - t_{i,j}}{\partial \tau} \tag{7}$$

In these equations the subscript *i* denotes the x position , *j* the y position and *k* designates the time increment. The temperature $t_{i,j}$ is a known temperature at the beginning of a time increment ($\Delta\tau$), but $t_{i,j,k}$ is the "future" value of the temperature after $\Delta\tau$.

Results and discussion

Developed mathematical model, described in the previous paragraph, gives a temperature field for the whole surface of the billet section. In the equation system used for temperature calculation, some parameters are not physical constants of the heated steel or furnace atmosphere. Those parameters, so called initial or given data, are: temperature of furnace atmosphere, specific heat flow, heat transfer coefficient and thermal properties of steel. The results of modelling of billet heating process in a walking beam furnace are available in graphical form and given in Figs. 1-6.

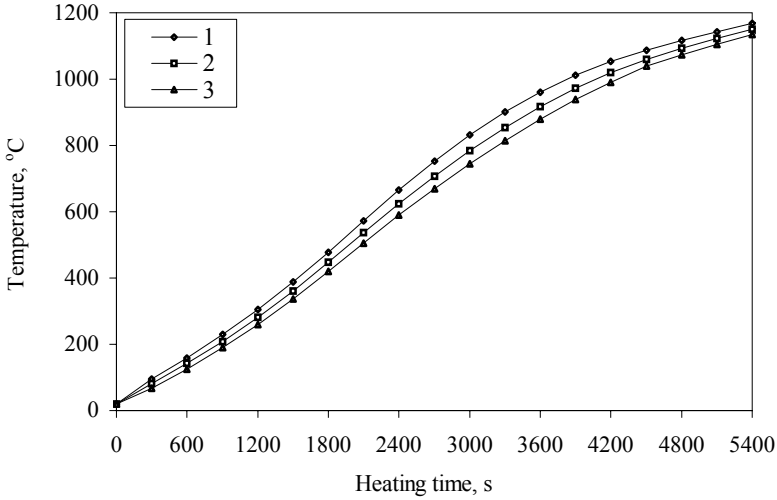

Fig. 1. *Changes of boundary surface temperature (mean values)*
1 – top surface (i=1-8, j=1)
2 – bottom surface (i=1-8, j=16)
3 – lateral surface (i=8; j=1-16).

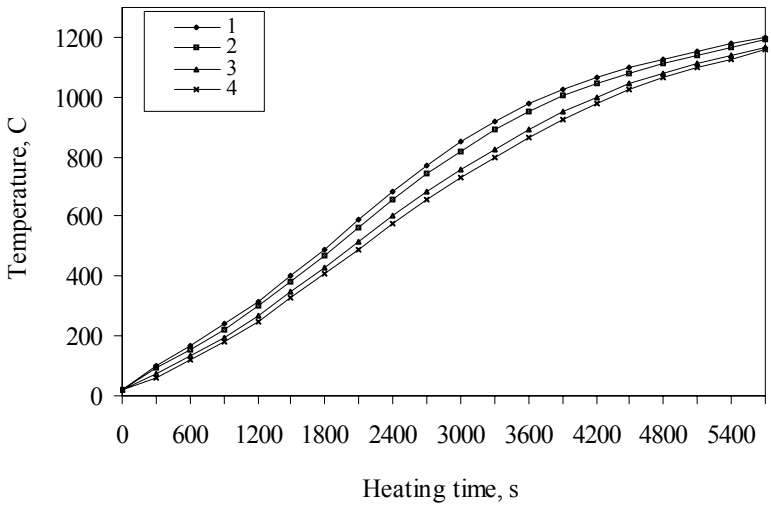

Fig. 2. *Temperature changes of elements with extreme temperature values*
1 – (i=1, j=1); 2 – (i=8, j=1); 3 – (i=1; j=13); 4 – (i-8, j=13).

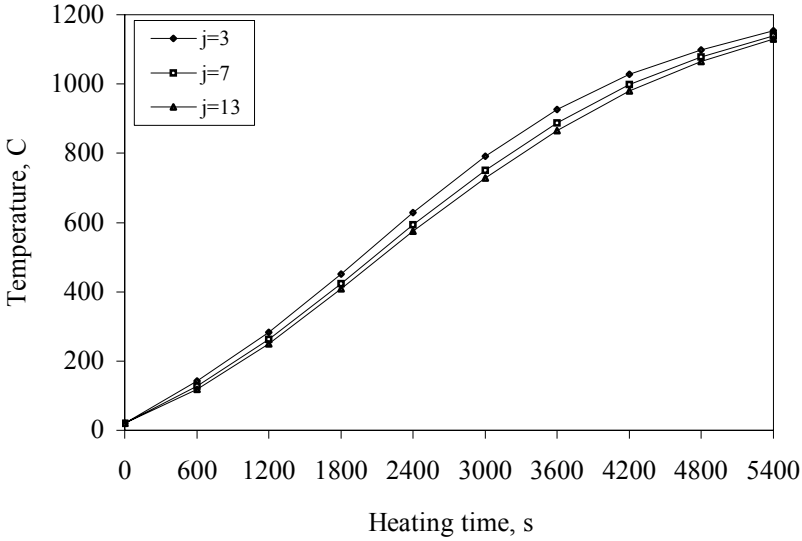

Fig. 3. *Temperature changes of nonradiation (internal) elements*
1 – (i=1, j=1-16}; 2 – (i=4, j=1-16); 3 – (i=7, j=1-16).

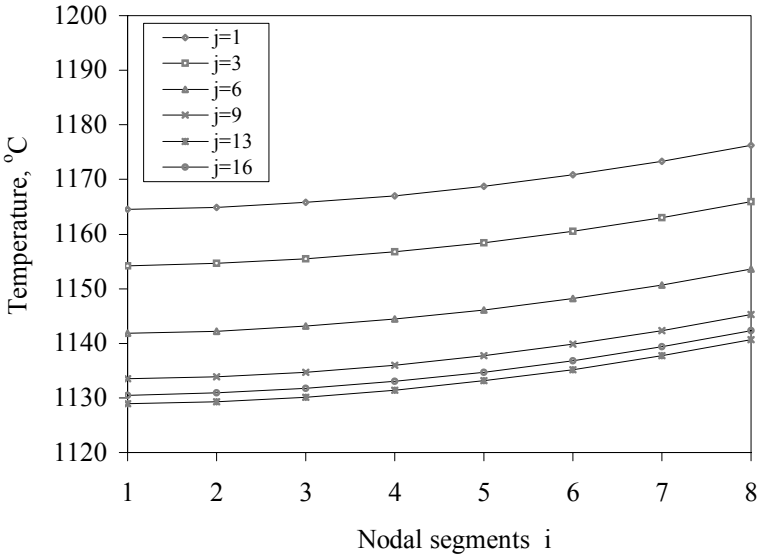

Fig. 4. *Temperature changes in direction of billet section width*
(x axis position; τ = 5400 s).

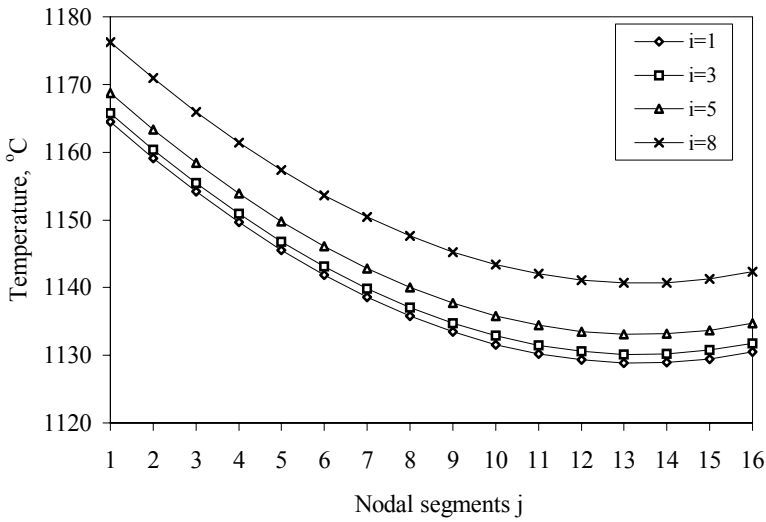

Fig. 5. *Temperature changes in direction of billet section height* (y axis position; τ = 5400 s).

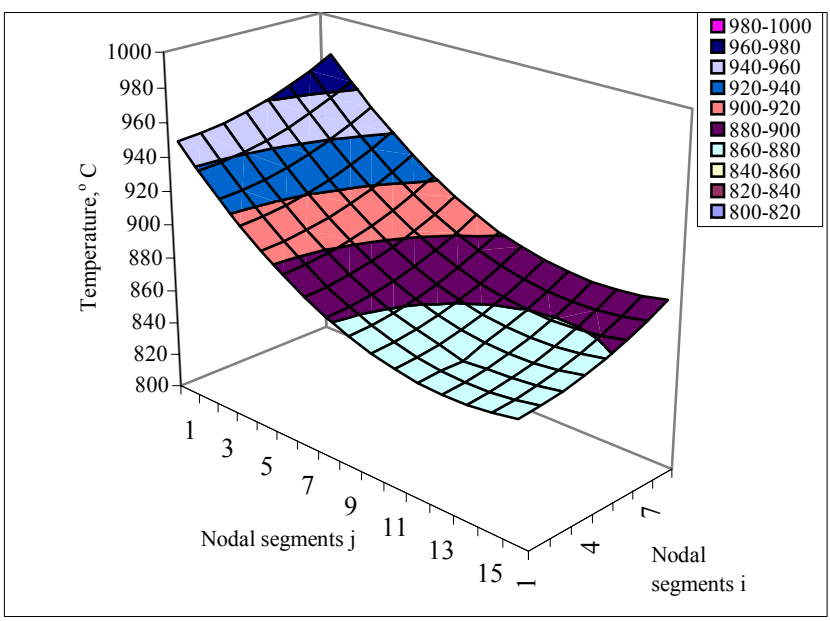

Fig. 6. *Temperature field of the billet section* (τ = 3600 s).

A finite difference two-dimensional model has been developed to describe a nonsteady process of heat transfer during steel billets heating in walking beam furnaces. Using obtained model equations in conjunction with some experimental data, explicit values of

steel temperature at any position in the billet, at the end of any time increment, were calculated. Temperature distribution analysis shows that the differences in the heat flow rate, depends on the boundary surfaces, or to the different intensity of heating. The temperature is decreases from the top of the surface to the section part with j=13 designation in the direction of y axis. After a noticeable slow increase occurs in the direction of the temperature values to the bottom of the billet surface.

Temperature is increasing from the center to the lateral billet surfaces (vertical side of billet section). Temperature difference varies with the two space coordinates. The bigest temperature changes are found in the direction of y axis (height of section), and the smallest in the x direction (width of section). The warmest surface is the top side of billet, whereas the coldest one is the bottom billet surface. Element with the maximum temperature value is i=8, j=1 node at the top surface, and the coldest element is i=1, j=13 node.

Derived equations of this model, with additional changes of initial parameters values can be used as a step in the investigation of the nonsteady heating process and as the basis of a control system of steel heating.

Conclusions

Mathematical model of heat transfer during steel billets heating in walking beam furnace has been developed. The model considers the two-dimensional transient process of heat flow and it was used to predict the temperature distribution within the steel billet during heating.

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List of symbols

α - surface heat transfer coefficient
t_f , t_s – furnace atmosphere temperature and billet surface temperature
a – thermal diffusivity of steel
C_R – radiation coefficient
q – heat flow rate per unit area at billet surface