Conference Paper

Mathematical Model of Metal Heating in the Continuous Walking Beam Reheating Furnace

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Abstract

The article describes a two-dimensional mathematical model of metal heating in the continuous walking beam reheating furnace. The mathematical description of metal heating includes a differential thermal conductivity quotation with initial and boundary conditions. The model incorporates dependencies between the thermophysical properties of heated metal and temperature. The process of pre-set plate heating with a time variable load was modeled in Ansys software. Distribution of temperatures over the slab section at the furnace exit was determined. The obtained results of the virtual experiment were compared with the data of the industrial experiment carried out at the existing plant of a steel production factory. The comparison between the calculations of the adapted mathematical model and data of the industrial experiment showed a coincidence of 97%. The prospects for further use of the mathematical model in the automated control system of furnace thermal operation were defined.

Keywords: continuous reheating furnace, thermal conductivity quotation, finite difference method, mathematical model

1. Introduction

Slab heating in the continuous reheating furnace is one of the major stages in the rolling production process. The primary focus is on achievement and distribution of the design temperatures over the surface and section of the heated metal. Non-optimized fuel consumption during achievement of these temperatures leads to higher production costs of the output products [1]. The energy-saving problem is solved by establishing a fast-acting mathematical model for calculation of metal heating in the continuous reheating furnace. This model enables to implement an automatic control of the heating process with determination of the temperature field in the slab section during transportation of the slabs in the furnace. The model facilitates calculations of metal heating in the furnace related to changes in productivity, metal grades and slab discharge rate [2]. The finite difference method was used for solution of the problems of this type [3].

2. Furnace Heating Diagram

Figure 1 shows the general design of the furnace. The furnace is equipped with 133 BLOOM burners (USA). Heating is performed with a mixture of natural and blast-furnace gas. The burner layout is given in Figure 2. The burners in the upper zones are equipped with radiant flat-flame burners. They are located on the roof in staggered rows up to the soaking zone consisting of seven and eight burners. The lower sub-zones 4 and 6 are equipped with three-line burners with a variable flame length. They are located opposite each other on the side furnace walls at the height where the flame goes under the lower surfaces of the slabs. The upper soaking zone is different from other zones as it is divided into the central zone 7 and peripheral sub-zone 8 and the heating power of these zones can be controlled independently. The zones consist of three rows of burners and each row of burners includes four central burners and four external burners, the latter being installed by two on the right and on the left. The ‘Curtain’ zone has only one row of eight roof burners. It has an independent heating control. The curtain performs two tasks: it creates a thermal barrier limiting air suction during opening of the discharge door and it compensates significant heat losses next to the doors and thus enables to avoid excessive cooling of the slabs waiting for discharge when delay in discharge exceeds the normal period. The side burners are also equipped with a manual cut-off butterfly valve. In the pre-heating sub-zone 2 the first three lower side burners on different sides of the furnace are equipped with automatic cut-off valves. The first three rows of the burners on the roof of the upper pre-heating sub-zone 1 are also equipped with automatic cut-off valves. To control the flame length, the side burners in zones I and II are equipped with two-circuit valves in the air supply line controlling air supply into the flame center or periphery. Flame distribution over different zones is performed using pipelines of different diameters.

3. Mathematical Model of Metal Heating

The mathematical description of metal heating includes a two-dimensional differential thermal conductivity quotation (1) for the plate subject to dependencies between the thermophysical properties of heated metal and temperature (5, 6, 7). The quotation is

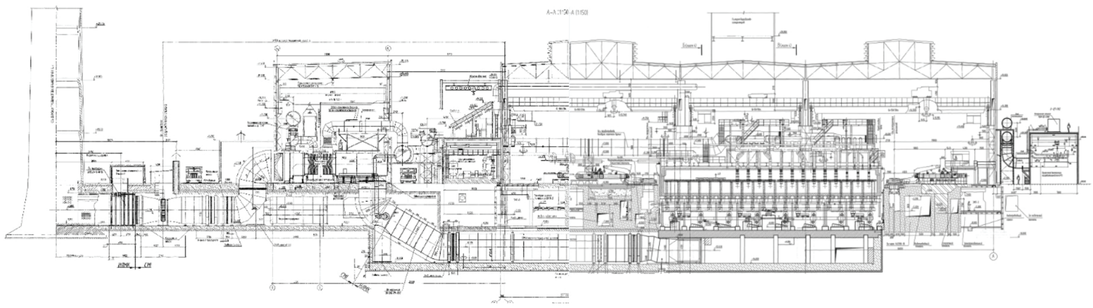

Figure 1: Walking beam reheating furnace design.

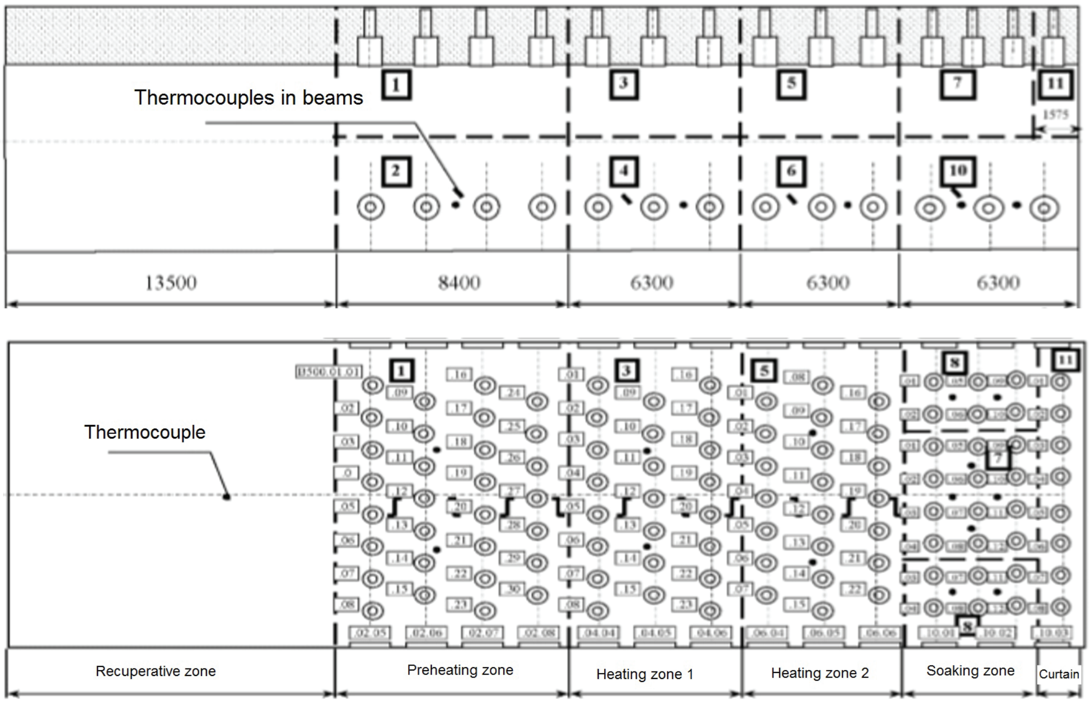

Figure 2: Burner layout.

also added with initial (2) and boundary conditions (3, 4). In order to check the model adequacy, we used experimental research results of slab heating in walking beam furnaces of the rolling mill 2000 operated in the hot rolling department of Novolipetsk Iron and Steel Works (NLMK). Ten thermocouples were installed in the experimental slab made of low carbon steel of ‘08ю’ grade. The thermocouple layout is shown in Figure 2. The heating temperatures are given in Table 1. Using the autonomous temperature recorder and measuring software, we received functions of bulk temperature variation [5].

Fourier thermal conductivity equation:

$$\rho(T)\,c(T)\,\frac{dT}{d\tau}=\frac{\partial}{\partial x}\left(\lambda(T)\,\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda(T)\,\frac{\partial T}{\partial y}\right) \tag{1}$$

Initial condition:

$$T\left(x, y, T_0\right) = \phi(x, y) \tag{2}$$

Boundary conditions for the upper surface of the slab:

$$\lambda \frac{\partial T}{\partial y} = \sigma \left[\left(\frac{T_s}{100} \right)^4 - \left(\frac{T_m}{100} \right)^4 \right] \tag{3}$$

Boundary conditions for the lower surface of the slab:

$$\lambda \frac{\partial T}{\partial y} = \frac{\alpha_1 (T_s - T_T)}{1 + (\frac{x}{R})^2} - \alpha_2 (T_s - T_m) \tag{4}$$

Dependence between the thermal conductivity and temperature:

$$\lambda(T) = \begin{cases} 1.35 \cdot 10^{-5} t^2 - 5.24 \cdot 10^{-2} t + 63.48, \ 0 \le t \le 850 \\ 9.38 \cdot 10^{-6} t^2 - 1.07 \cdot 10^{-2} t + 29.04, \ 850 \le t \le 1200 \end{cases} \tag{5}$$

Dependence between the density and temperature:

$$\rho(T) = \begin{cases} -0.355t + 7875, \ at \ 0 \le t \le 850 \\ 0.098t + 7508, \ at \ 800 \le t \le 900 \\ -0.542t + 8086, \ at \ 900 \le t \le 1200 \end{cases} \tag{6}$$

Dependence between the heating capacity and temperature:

$$c(T) = \begin{cases} 4.45 \cdot 10^{-9} t^3 - 3.80 \cdot 10^{-6} t^2 + 1.3 \cdot 10^{-3} t + 0.412, \ at \ 0 \le t \le 750 \\ -1.81 \cdot 10^{-8} t^3 + 5.84 \cdot 10^{-5} t^2 - 6.23 \cdot 10^{-2} t + 22.64, \ at \ 750 \le t \le 1200 \end{cases} \tag{7}$$

where: λ – thermal conductivity coefficient, W/(m·K);

x – furnace length coordinate, m;

y – slab thickness coordinate, m;

C – heating capacity, J/K;

τ – time, s;

ρ – density, kg/m^3;

σ, σ_2 – reduced radiation heat transfer coefficient, W/(m^2 · K^4);

T_m – heated slab temperature, K;

T_s – heating medium temperature, K;

α_1 – heat transfer coefficient from the medium to the pipe, W/m^{2}K;

α_2 – heat transfer coefficient from the medium to the slab, W/m^{2}K;

T_T – temperature of the extremal surface of the heat-insulated beam, K;

R – radius of the supporting heat-insulated beam, m.

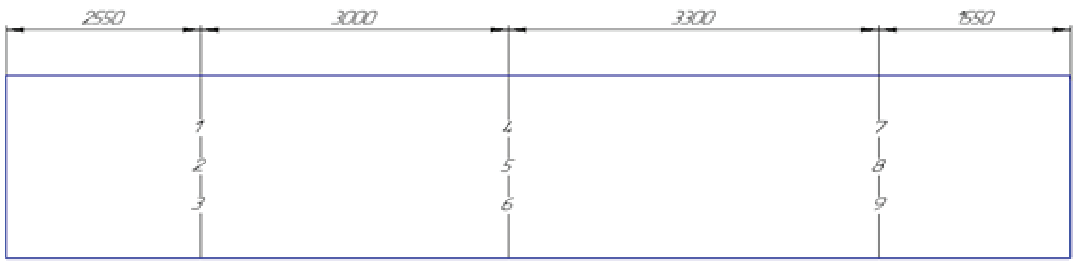

Figure 3: Thermocouple layout and installation diagram in the slab (thermocouple installation depth:1, 4, 7 – 30 mm; 2, 5, 8 – 125 mm; 3, 6, 9 – 240 mm).

In parallel with the industrial experiment, we modelled the process of pre-set slab heating (Table 1) with a time variable load [6] in Ansys 14.5 software. We entered in the software the thermophysical (heating capacity, density, thermal conductivity coefficient) and geometrical parameters of the material. The results of the experiment are given in Figure 4 as distribution of temperatures over the slab thickness.

Table 1: Pre-set slab heating.

Zone	Preheating	Heating 1	Heating 2	Soaking
Time from the start of heating, s	4245	7430	10615	13800
Temperature, °C	1220	1263	1328	1261

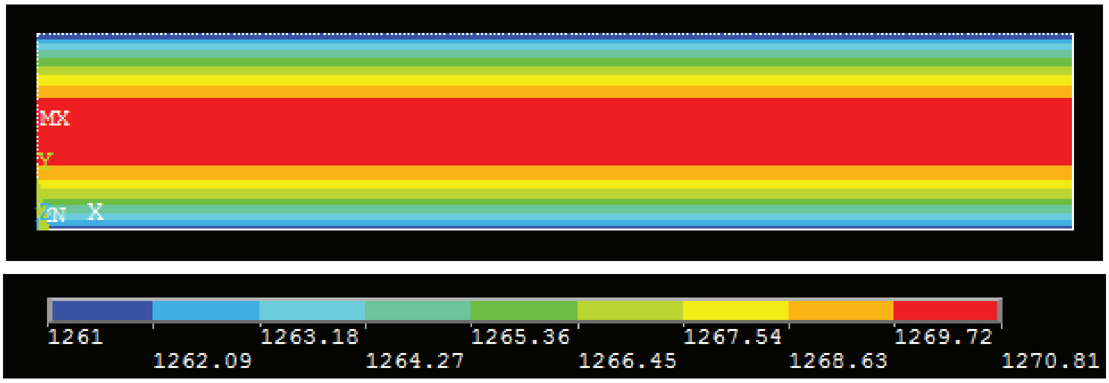

Figure 4: Distribution of temperatures over the slab thickness.

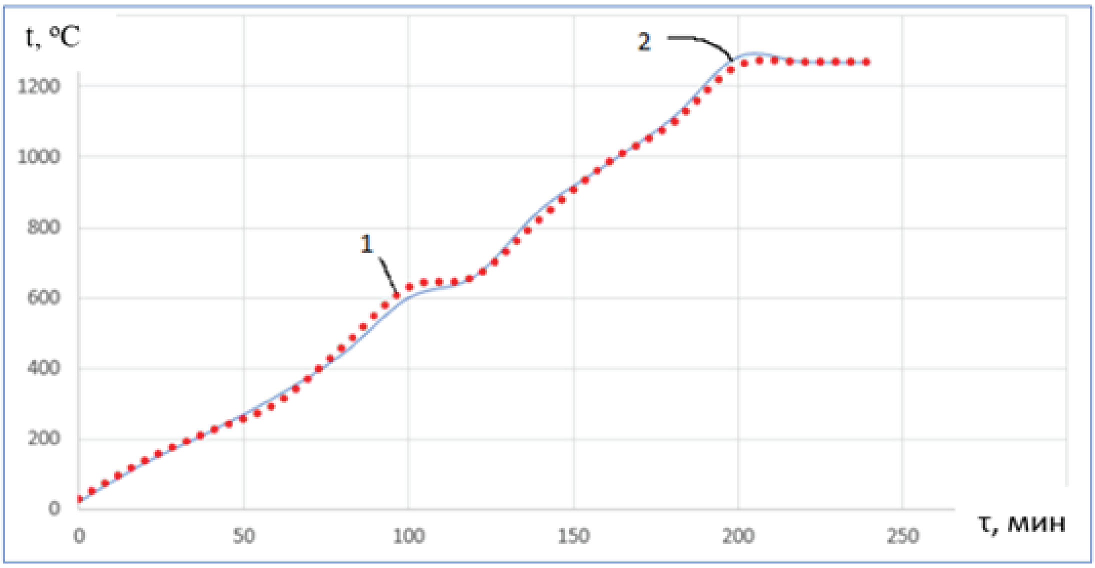

Figure 5: Comparison of experimental (2) and design (1) bulk temperatures during slab heating.

4. Summary

In the course of the industrial experiment at the existing plant and virtual experiment in Ansys software, we received the diagrams of bulk temperature variation in time (Figure 5). The comparison between the calculations of the adapted mathematical model and data of the industrial experiment showed a coincidence of 97%. These results make it further possible to adapt the mathematical model in respect of the emissivity factor of effective radiation for each zone and adjust fuel-firing devices. Using software applications, the obtained adapted mathematical model enables to analyze almost any number of options and select the optimum conditions for thermal operation of the continuous reheating furnace for heating different products. Therefore, it is recommended to use the obtained mathematical model for solving the problem of fuel consumption optimization and temperature calibration in the continuous walking beam reheating furnace of the rolling mill 2000 operated in the hot rolling department of Novolipetsk Iron and Steel Works (NLMK).

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