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OPTIMAL CONTROL OF HEATING IN A REHEATING FURNACE

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In this paper a new method is proposed for solving an optimal control problem using the complex model of a reheating furnace that was used to get reference values for the optimal zone temperatures. Validation before using a complex simulation model in optimal control procedure showed that the model worked well for the prediction of thermal behavior. The aim of optimal furnace temperature control is the minimisation of fuel consumption and the minimum deviation between desired and final steel block temperature profiles. The optimisation procedure and some results are described.

Key words: furnace, block heating, saving fuel, model, optimisation

INTRODUCTION

Reheating furnaces are very often used in the steel industry for heating up various types of metal charge, such as slabs or billets, to the required temperature for further treatment in the rolling mill. There, it is necessary to keep the temperature distribution as uniform as possible in order to ensure good product quality. The average fuel consumption of the conventional metal heating process is 1,6 GJ/t [1, 2] or 18 % of the total specific energy costs of rolling steel. If the required final heating temperature is not reached, the specific energy costs for the rolling mill will increase and the quality of rolled steel will decrease. Numerical models can offer a detailed view of the transport phenomena in the furnaces and can be a helpful tool to optimise the heating process, transportation of the furnace loads and other processes [3, 4]. In past many papers [4] addressed the optimization of air for combustion and later oxygen enriched combustion atmospheres [5] in reheating furnaces. Prieler et al. [6] pointed out that the use of oxygen in an oxidizer led to fuel savings of 8 % and simultaneously increased the process efficiency by 3,8 %. In this paper, the aim of optimization will be minimizing energy costs and simultaneously ensuring the good quality of the heating billets at the end of the heating time.

REHEATING FURNACE AND ZONING ARRANGEMENT

The furnace investigated in this work is a rotary hearth-furnace. This industrial furnace serves for heating a steel charge in the form of billets and various semi-products before rolling. The floor plan of the furnace has the shape of an annulus which is bounded by the vertical walls of the lining in which the burners are placed from the inside and outside. The furnace ceiling is also formed by a multi-layer lining. The bottom of the annulus-shaped furnace is a hearth of refractory material that rotates about a vertical axis. The floor plan of the rotary-hearth furnace is shown in Figure 1. The semi-finished steel material is placed on the rotary hearth. The steel blocks are charged into the furnace through a charging door. The dimensions of the steel blocks are 0,2 x 0,2 x 0,7 metres. The charge is heated during one hearth revolution. Then, the heated steel blocks are removed from the furnace hearth through the removal door.

The rotary hearth furnace has to stop during the charging process. The output of furnace is approximately 34 tons per hour. The heat is generated by the combustion of fuel in flame burners spread around the working volume, surfaces of the walls, vault, hearth, and the charge and combustion products transported through the entire furnace by a counter-current system. The furnace is equipped with 25 external and 25 internal burners. Regarding regulation, these burners are divided into five regulation zones (see Table 1). It is ap-

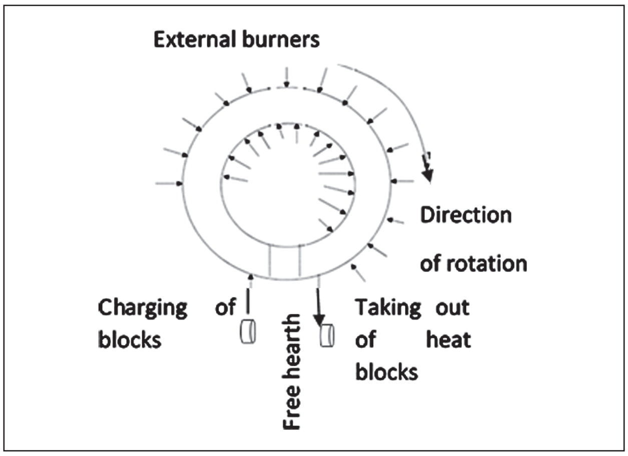

Figure 1 The rotary-hearth furnace

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propriate to use the zone method for the mathematical modelling of complex processes of heating exchange by convection and radiation in the reheating furnace.

In other words, the operating internal area of the furnace is divided into volume and surface zones. The firm free surfaces (areas of steel blocks, masonry) create the surface zones and the free volume of circulating gases creates the volume zones. Equal zoning was chosen so that in every volume zone there was at most one internal and one external burner. There is consider every zone as homogenous, i.e. the zone is characterized by a single temperature, radiation coefficient, etc. The entire furnace is fictitiously divided into 36 volume zones around the perimeter. The last zone is located between the points of charging and removal of the hot steel block. Zone 1 is the place of charging for steel blocks and zone 35 is for removing heated blocks. The flame burners are located from zones 13 to 35. The burners are divided into five regulation zones. Thermocouples measure furnace temperatures in the individual zones which are shown in Table 1. The operator determines the desired furnace temperatures based on experience so that the furnace outlet temperature reaches 1 240 °C. The aim of the control system is to reach the required temperature 1 240 °C of metal blocks with a minimal temperature difference across the section of charge at the end of the furnace, i.e. in zone 35.

Table 1 **Division of burners into control zones**

Regulated zone number	Volume zone number / -	Thermocouple zone location	Desired temp. / °C
1	13,14,15,16,17,18	15	900
2	19,20,21,22,23,24	22	1 020
3	25,26,27,28,29,30	30	1 260
4	31,32,33,34	32	1 265
5	35	35	1 265

The meaning of the data in Table 1 is as follows. The first regulation zone has one controller which regulates the input of fuel for six burners located between zones 13 and 18. The desired furnace temperature for this controller is 900 °C.

OPTIMIZING THE HEATING

The required temperatures stated in Table 1 for regulation zones serve as inputs for regulators, which create a stabilization level for the furnace control system and they are set by the operator of the furnace on the basis of experience. At this point we underline that the required values must be set optimally. If the required values are optimally maintained by the regulators, then the heating of materials in the heating furnace will be optimal. Many papers have addressed the issue of achieving optimum heating curves based on various optimization methods. Tang [7] proposed optimum heating curves using a method of penalty functions for heating slabs in a push furnace. The criterion of optimal control was decreasing energy costs. Wang [8] proposed a dynamic adaptive fuzzy reasoning Petri net for machine state inferences to save energy based on real-time production information. Andreev [2] applied L.S. Pontryagin's maximum method for deriving optimal control of the reheating furnace. Other authors [9–11] considered various approaches to dynamic optimization that can generate heating trajectories.

In this study, the gradient method is used for optimization and mathematical modelling of the rotary hearth furnace. The complex mathematical model of this furnace was created with the aim of designing a reconstruction of the rotary-hearth furnace in the past [12]. A fundamental model was considered, composed of the nonlinear dynamics of metal block temperatures, time-dependent motion of the rotary hearth, and a discrete model for feeding blocks. The entire heating space of the furnace was divided into thirty-five volume zones. Every volume zone is bounded by five surface subzones (the vault, the horizontal walls, the charge, the free surface of the hearth), and each sub-zone was assumed to be homogeneous in temperature distribution with one medium temperature, which was computed on the basis of the overall heat balance for all of the volume and the sub-zones. The mutual heat transfer between zones and subzones determined by radiation and convection is considered through solving non-linear balance equations. The solving of dynamic processes is specifically based on Fourier partial differential equations for all subzones along their thickness. As part of the verification of the simulation model, it was found that the relative deviation for fuel volume flow was less than 2 % in comparison with the real process [12]. Therefore, this complex simulation model was used for the verification of the optimal control system instead of the real process. If we emphasise, that the proposed method of optimization with the model needs multiple repeated simulations, then we would only be able to use the proposed model for designing optimum heating curves offline. If we want to control optimally in real time then it is essential that the simulation run faster. Therefore, the original model [12] was simplified as follows. The heated metal blocks and hearth are solved as a nonlinear dynamic system, but the lines of walls and vault of the furnace are solved according to equations (1) which describe their heating in a steady state.

$$\frac{\partial\left(\lambda_i \frac{\partial t_i}{\partial x}\right)}{\partial x} = 0 \quad for\, i = 1,\ldots,L \tag{1}$$

Where λ – heat conductivity / W×m^{-1} ×K^{-1}, c – heat capacity / J×kg^{-1} ×K^{-1}, ρ – density / kg×m^{-3}, t – temperature / °C, x – coordinate /m, L – total number of line layers, i – an index of line layer in wall or vault of furnace.

The consequence of non-uniform temperature distribution over the steel block thickness is very negative because it increases the energy consumption and decreases the quality of the final product after the rolling process. The aim of heating the steel charge in the furnace is to reach the required temperature of the upper surface with a minimal temperature difference across the cross-section of the batch at its outlet from the furnace. At the same time, we want to achieve minimal fuel consumption during the heating of the batch. This aim can be expressed by the following function

$$J = w_1 \int_0^h \left(t\left(x,\tau_k\right) - t_5^d \right)^2 dx + w_2 \int_0^{\tau_k} \sum_{i=1}^{n} u_i\left(\tau\right) d\tau \qquad (2)$$

which has to be minimised,
where
w_1 – weighting coefficient reflecting the relative importance of $t(x, \tau_k)$, w_2 – weighting coefficient penalizing relatively big changes in fuel, h – the thickness of the steel block /m, t – the controlled temperature in the one dimensional temperature field, τ_k – final time of heating charge, t_5^d – the desired temperature of the charge at the end of heating i.e. in fifth regulation zone /°C, n – the number of regulation zones, u – fuel /m^3s^{-1}, τ – time /s.

Of course, in the complex simulation model, the controllers of the stabilization level and function (2) have been solved in discrete form. The gradient method was used to calculate the new required furnace temperatures for the regulation zones. The elements of optimised vector (3) are defined by the required furnace temperatures of the controllers localized in five zones.

$$\overline{y} = (t_1^r, t_2^r, t_3^r, t_4^r, t_5^r)^{-1} \qquad (3)$$

New required temperatures after the j^{th} iterative step are given by (4), the algorithm of gradient method

$$\overline{y}^{j+1} = \overline{y}^{j} + h \,\mathbf{grad\ J} \qquad (4)$$

where $t_1^r, t_2^r, t_3^r, t_4^r, t_5^r$ are reference values, i.e. desired furnace temperatures of the controllers for five controlled zones and h is the optimisation constant.

After several iterations, the optimal heating curve was found. The steel block temperature history through the reheating furnace after optimization is shown in Figure 2. The optimal set values of regulation zone temperatures, specific fuel consumption and the cross-sectional temperature difference between the upper surface and the bottom of the last block in furnace for the operator and the proposed method are listed in Table 2. The reason why the temperature of the bottom of the block after charging is as much as 1 109 °C (Figure 2) is that they are charged onto the heated rotary hearth.

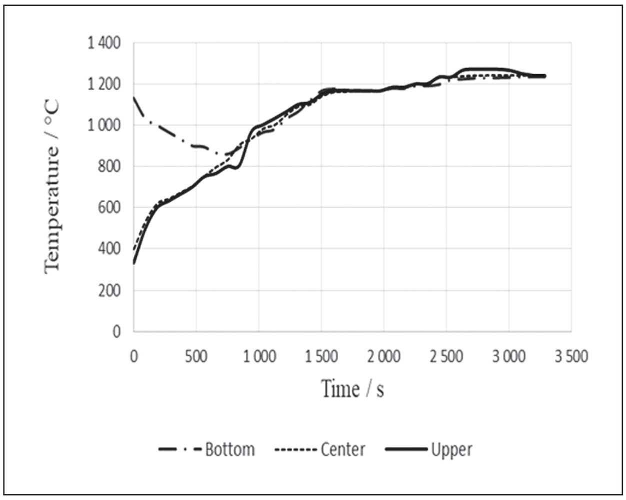

Figure 2 The optimal trajectory of block temperature through the reheating furnace

Table 2 **Comparison of some parameters of optimal control with operator control**

Control	t_1^r	t_2^r	t_3^r	t_4^r	t_5^r	c_s	Δ
Operator	900	1 020	1 260	1 265	1 265	41	9
Optimal	921	1 016	1 252	1 257	1 251	39	5

where c_s – specific fuel consumption / Nm^3t^{-1} , Δ - temperature difference between the top and bottom of the last block at the end of furnace / °C.

Gradually, the temperature is homogenized across the cross-section of the blocks and the temperature of the upper surface reached 1 239.5 °C. Table 2 shows that, in comparison with operator control, the optimal heating of metal blocks has a lower measured fuel consumption and also smaller differences in temperature across the cross-section of the block upon its exit from the furnace in the direction of the hot rolling mill.

CONCLUSIONS

This study presents a new approach for getting the optimal set values of the reheating furnace's zone temperatures at a steady state only for the lines of the walls and the vault. The heating of metal blocks is solved as a dynamic system. Simulations have shown that using the optimal control system reduces the fuel consumption by 5,01 % provided there is enough time to heat the blanks.

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Note: The responsible for English language is Language school START, Košice, Slovakia.