Supervisory control of reheating furnace

(Modeling and Optimal Control of The Reheating Furnace System)

Young Il Kim*, Kwang Gi Min, Yung Hee Hahm**, In Sik Nam and Kun Soo Chang

*Research Institute of Industrial Science and Technology
**Instrumentation & Control Dept.,POSCO
Automation Research Center and Dept. of Chemical Eng.,POSTECH
(Tel : (0562)279-6615; e-mail : yikim@RISnet.rist.re.kr)

Abstracts

In steel works, reheating furnace is an essential part of a rod mill plant and it treats various types of billets continuously. Although getting an optimal setting for a single billet is simple, control setting for whole groups of billets is a difficult task.

In this work, we studied a detail mathematical model and optimal control setting of reheating furnace. As the mathematical model of each billet is a partial differential equation, on-line control is almost impossible for the whole billets charged into the furnace. Therefore, we tried to provide a guideline for optimal setting value of the roof(index) temperature for the target billets which account for about 20% of the charged billets.

Keywords Reheating furnace, Mathematical Model, Optimal Control

I. Introduction

The reheating furnace in a steel mill is usually operated based on operator's experience and their knowledge. There is a strong desire to improve the performance of the furnace and to get a best workable procedure for operation.

The purpose of the reheating furnace is to heat the billets uniformly as closely as possible to the target temperature in order to transfer to the next wire rod mill process. The furnace is composed of 3 zones for convenience. They are the preheating, heating, and soaking zones. And each zone is equipped with flat flame burners. In evaluating the cost effectiveness of the wire rod mill, the following three essentials: metallurgical quality generally controlled by the processing time and target(index) temperature, energy consumption which has a close relation to the temperature, rejects caused by decarburization, are important. They are strongly influenced by the billet reheating conditions. Our work covered these points and the overall structure of control process which is made up of the mathematical model and process control logic. One of the main difficulties is the fact that there is no possible means of measurement of center temperature of the billet: indeed the only measurement is made for surface temperature after discharge.

In this article we describe the general structure of the furnace control. the mathematical model and the control logic.

II. Structure of Furnace and Overall Control Logic

The principal dimension data of a reheating furnace and the furnace production data are tabulated as follows.

Table 1 General Information of a wire rod mill

Furnace Data		
Length	Charge Zone	520 cm
	Preheat Zone	282 cm
	Heat Zone	282 cm
	Soaking Zone	282 cm
Width		2000 cm
Height	Charge Zone	78 cm
	Other Zone	147 cm
Burner	Type	Radiant roof burner
	Position	dual center of zone
	Dimension	2x7x3
Thermocouple	Position	Roof
	Preheat	(L/2 x W/2) x 1
	Heat	(L/2 x W/2) x 1
	Soak	(L/2 x W/3) x 1
		(L/3 x 2W/3) x 1
		(L/3 x W) x 1
Billet Data		
Length		1820-1850 cm
Width		12 cm
Height		12 cm
Walking Beam Data		
Walk	Lift	11cm
	Forward	22cm
	Down	11cm

A schematic diagram of the furnace is shown in Fig. 1. The furnace is comprised of four combustion areas which are designated as: charge; preheat; heat; and soak zone each of which is subdivided into three zones along the latitude.

The control logic considers the furnace to be divided into three control zones along its length. Because it is impossible to control the charge zone temperature directly as shown in the figure, we exclude the charge zone from control zones. Each control zone has radiant roof burners depicted as in Fig. 2 which are not controlled individually but in a group manner. This makes each zone independent in the sense that each of them possesses its own burner which is controlled independently of the others. But each billet in a given zone is thermally dependent on the other zones. Burners are primarily fired by COG(coke oven gas).

A billet is a bar of steel whose dimensions are around 10x10x1500 cm and which is intended to be milled in order to produce a wire. A typical category of the billet is shown in Table 2. A processed billet is usually one of the these categories depends on its composition and has the different index temperature and duration (processing) time. Index temperature is the average of each zone's roof temperature because the temperature which actually governs the radiate exchange between the furnace and the billet is mainly related to the roof temperature of the furnace. And this temperature is regarded as the manipulate variable of furnace control problem.

The walking beam is positioned bottom of the furnace and slowly moves the billet through the different zones of the furnace. The gap between the furnace bottom and walking beam is sealed with water and makes possible to move the billet forward. A walking beam cycle time can be varied by the type of the billet or the status of the following milling process but a walk of walking beam is fixed.

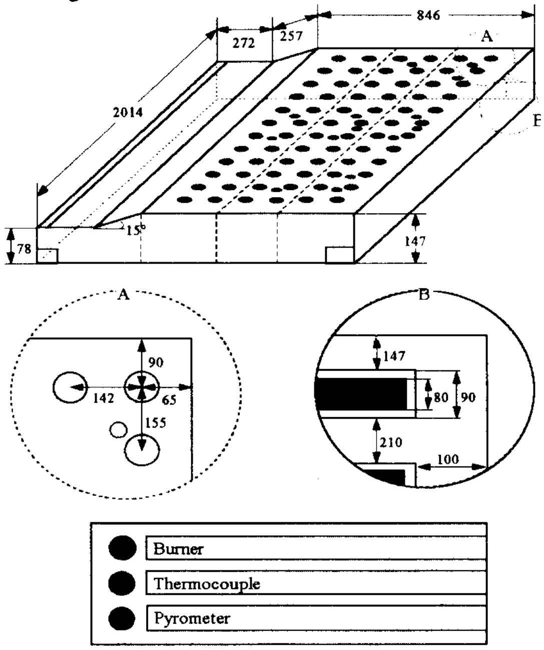

Fig. 1 A schematic diagram of the furnace of wire rod mill (Length [cm]).

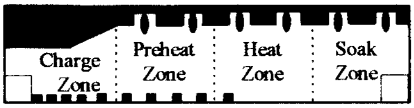

Fig. 2 A schematic diagram of the burner type and position of wire rod mill

The overall control logic schematic diagram is shown in Fig. 3. The main management unit is labeled as FCC which is installed to calculate the temperature profile of the billet, tracking of the billet and to find out the optimal set-point temperatures for the subcontrol unit of the DCS which regulates the fuel and air flow rate. The signal data come from two nodes: one is the DCS(distributed control system) which gathers field information, e.g. zone temperature, pressure, fuel usage; and the other is the SCC which has the billet data, e.g. the billet name, size, type, weight and composition. Tracking program which is infinite looped wakes up the mathematical program when the walking beam moved. Then the mathematical program calculates the inner temperature profile of each billet, and the optimal control program predicts the proper zone roof temperature based on the hypothesis that other conditions except the zone roof temperature are sustained as current sampling time values.

Table 2 A rough category of the wire rod mill products

Type	JIS system	C	Mn
Mild	SWRM6 ~ SWRM22	0.01 ~ 0.21	0.02 ~ 0.25
Hard	SWRH27 ~ SWRH82B	0.25 ~ 0.85	0.15 ~ 0.30
CHQ	SWRCH6A ~ SWRCH50K	0.04 ~ 0.50	0.06 ~ 0.15

III. Mathematical Model

The thermal elements which are involved in the modeling are of three kinds: wall(here we only consider roof), gases, and billets. And the type of the thermal exchanges is radiation and/or convection. The radiation occurred between gases and billets, and between walls and billets. The convection occurred between gases and billets. As the length of the billet is larger than the other dimensions, we only compute the evolution of the temperature in the cross section of the billet. This leads us to make a 2-dimensional model for the diffusion of heat inside the billet.

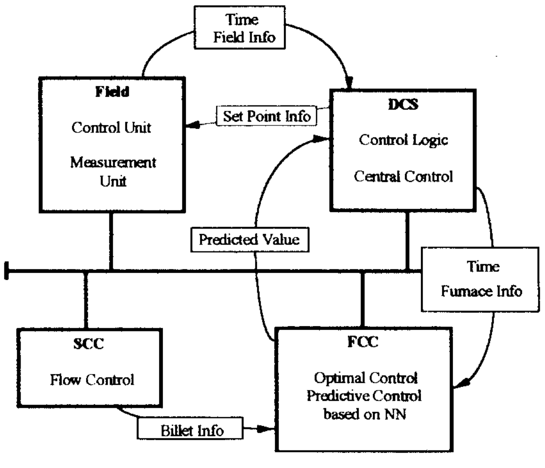

Fig. 3 The overall connectivity of wire rod mill

For a billet the Fourier's equation takes the form:

$$\rho(T)C_p(T)\frac{\partial T}{\partial t} = \mathrm{div}(k(T)\nabla T)$$

$$T(\mathbf{x},0) = T_0(\mathbf{x})$$

where $T(\mathbf{x},t)$ is the temperature of the billet at the point $\mathbf{x} \in D \equiv [0,x_{max}] \times [0,y_{max}]$ at time t. And that $C_p(T)$ is the specific heat capacity, $\rho(T)$ the density and $k(T)$ is the conductivity of the steel at the temperature T.

The boundary conditions have the following form:

$$k(T)\frac{\partial T}{\partial n} = f(T, T_w, T_g) \quad \text{on} \quad B \times]0,\infty[$$

where

$f(\cdot,\cdot,\cdot)$ is real function,

$\frac{\partial}{\partial n}$ is the normal derivative on the boundary B,

$T_w \in R^5$ is the roof temperature of zones

$T_g \in R$ is the gas temperature of zones

Here we make additional assumptions and unfold the detail model of the billet. It is assumed that thermal heat transfer is symmetric with respect to the vertical and the horizontal directions of the billet. This makes only a quadrant of whole billet as domain and change boundary conditions. The refined model is described as the graphical depiction shown in Fig. 4.

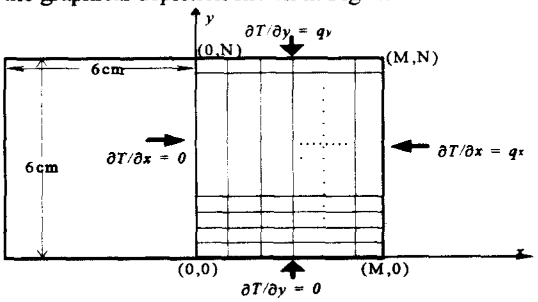

Fig. 4 A scheme of the mathematical model

Governing Equation :

$$\rho(T)C_p(T)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(k(T)\frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(k(T)\frac{\partial T}{\partial y})$$

Initial Condition :

$$T(x,y,0) = T_0(x,y)$$

Boundary Condition :

$$k(T)A_s\frac{\partial T}{\partial x} = \sigma\sum_{i=0}^{4} f_{W,i}^{S}(T_{W,i}^4 - T_s^4) + \sigma A_s(\varepsilon_G T_G^4 - a_G T_s^4) + hA_s(T_g - T_s) \quad \text{on} \begin{cases} x = x_{max} \\ y \in [0, y_{max}] \\ t \in]0,\infty[\end{cases}$$

$$k(T)A_T\frac{\partial T}{\partial y} = \sigma\sum_{i=0}^{4} f_{W,i}^{T}(T_{W,i}^4 - T_s^4) + \sigma A_T(\varepsilon_G T_G^4 - a_G T_s^4) + hA_T(T_g - T_s) \quad \text{on} \begin{cases} x \in [0, x_{max}] \\ y = y_{max} \\ t \in]0,\infty[\end{cases}$$

$$\frac{\partial T}{\partial x} = 0 \quad \text{on} \begin{cases} x = 0 \\ y = [0, y_{max}] \\ t \in]0,\infty[\end{cases}$$

$$\frac{\partial T}{\partial y} = 0 \quad \text{on} \begin{cases} x = [0, x_{max}] \\ y = 0 \\ t \in]0,\infty[\end{cases}$$

where

$f_{W,i}^{S} = \frac{1}{A_{W,i}F_{i\to S}}$ is the reciprocal of the total interchange area between the ith roof wall and the side face of the billet,

$f_{W,i}^{T} = \frac{1}{A_{W,i}F_{i\to T}}$ between the ith roof wall and the top face of the billet,

$\varepsilon_G = R(T_G, P)$ is the emissivity of the gas mixture produced by combustion (N_2,CO_2,H_2O,etc) and is a real function of the gas temperature and the pressure (total pressure & partial pressure of gas components),

$a_G = R(T_G, T_S, P)$ is the absorptivity and is also a real function of the gas temperature, the surface temperature, and the pressure. The previous general work approximately treated these two factors as negligible. But our model shows that the radiative heat transfer between the gas and the surface contributes about 10% of the total.

Our mathematical model evaluates the one sampling time for each billet under the current conditions of sampled surrounding and solves the whole problem in a successive manner. The reason is that the optical pyrometer located at the center of the each zone's roof reads the current surface temperature and when the billet is positioned at this point, the measured value can be used as reference value to our model which accepts it as a true value and modifies tunable parameters(efficiency factors) to satisfy the surface temperature.

Components of the mathematical model are shown in Fig. 5. The profile of figure 6 is the typical center temperature profile with other variables.

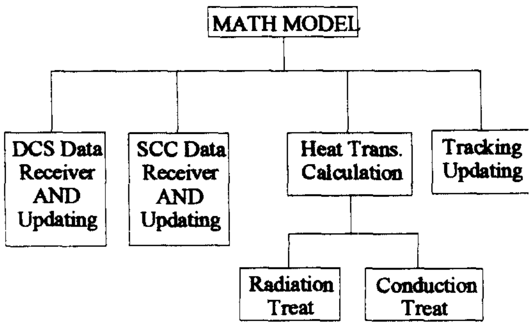

Fig. 5 Mathematical model

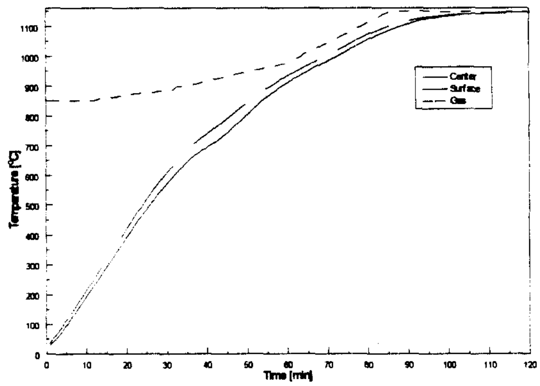

Fig. 6 Temperature profile of 0.23% carbon steel

IV. Optimal Control

The control logic adjusts the roof temperatures to bring the billets to the desired target temperature; minimize energy consumption; and protect the furnace itself(e.g., refracting damage, excessive pressure, steel melting and over heating). The control logic determines the zone set points for the optimal control of the furnace, which gives an optimum billet temperature profile. In this work, we considered DCS has control logic, which relates the roof temperature with the fuel and air flow rate and re-calculated the optimum set point temperature at each sampling time(120 sec) to be accomplished by selecting only some billets as target (about 1/6). At each sampling time, the optimal control program solves the system to minimize the following objective function under the assumptions that the other conditions except the roof temperature will be kept as current sampling value and the mathematical model is close enough to describe the real system.

Objective Function :

$$J = \sum_{i=1}^{M} \left[W_i \left(\left| T_i^* - T_i^f \right| + \left| T_{f,i}^S - T_{f,i}^C \right| \right) \right] + \sum_{j=0}^{N} \left| \lambda_j^B - \lambda_j - \varepsilon \right|$$

where M is the number of target billet, N is number of control zone, W_i is weight factor which is determined by the position and type of the billet, T^* is the target temperature, T_f^S is the surface temperature of the billet at discharged position, T_f^C is the center temperature of the billet, $T^f = (T_f^S + T_f^C)/2$ is the mean temperature of the billet, λ^B is the zone index-temperature of the current sampling time, λ is the predicted optimum zone temperature, ε is the maximum changeable temperature of the zone temperature which depends on the performance of the burner and the sampling time.

The strategy of the optimum set point calculation is summarized as following.

1. select the current zone temperatures as the initial value.
2. solve the mathematical model for each billet from current position to discharged position (Fig. 7). In the figure the billet can be a different type.
3. evaluate the objective function.
4. update the zone temperatures.
5. repeat until there is no change in the zone temperatures or stopping criteria are satisfied.

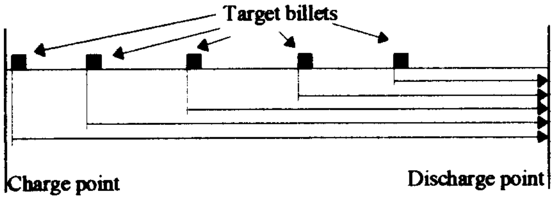

Fig. 7 A schematic drawing of optimization problem

The sample calculation results are summarized in Table 3. Position column shows the distance of a billet from charge point of the furnace, next three columns have result values of the optimized roof temperature of each zone, and T_f column is the predicted final temperature of each billet. The first row of table is the initial roof temperature of the furnace.

As B2 is harder than B1, it has a larger weight factor which makes the obtained set point value skew to B2 as can be seen from Table 3. Status shows that the uniformity of the billet is within the safety region.

Table 3 A sample result (B1:0.23%C B2:0.80%C)

Position	Preheat	Heat	Soak	T_f	Error	Status
	997.000	1156.000	1153.000			
	994.000	1162.117	1147.915			
B1 : 278.57				1145.40	5.4	1
B2 : 71.946				1145.30	4.7	1
	994.941	1163.060	1148.151			
B1 : 348.20				1145.58	5.58	1
B2 : 143.83				1145.50	4.5	1
	995.177	1164.003	1149.094			
B1 : 487.46				1146.33	6.33	1
B2 : 287.58				1146.25	3.75	1
.	.	.	.	.	.	
.	.	.	.	.	.	
.	.	.	.	.	.	

*** Target values : B1=1140°C B2=1150°C**
*** Position is [cm] from the charge point**
*** Error is [°C] from target temperature with absolute value**
*** Status is the check value for uniformity (<5°C).**

V. Discussion

The on-line test at the wire rod mill shows a good performance of heating billets to reach the desired temperature. In this work, we used the detailed mathematical model and also accomplished the desired performance within a short calculation time (2min). The remaining problems are to avoid the duplicated calculation which arises when the same type of billets and same sequence of the billets are charged and also to optimize down stream part of the furnace.

VI. Reference

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