Temperature Control for Reheating Furnace Walking Hearth Type in Heating Curve Up Process

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Abstract: - The slab reheating process for iron rolling to the small diameter wire in Ratchasima Steel Products Co.,Ltd. factory (Nakron Ratchasima, Thailand) use the reheating furnace walking hearth type which control the temperature of the process about 1150-1200 Celsius (up to each zone) and consume time about 2 hours. The air fuel ratio control of this furnace is feedback control which use PID controller. The problems in the present are reducing production cost and increasing performance in energy consumption which most cost of the factory from in the slab reheating process. So the factory has the idea to change the energy source to the cheaper source such as nature gas, bio-gas etc and improve the performance of the temperature control of the reheating furnace in heating curve up process. Consequently the controller isn't suitable for the slab reheating process in the present then can't control the desired temperature and lose the energy. From the mentioned reason, we have to analysis and study to estimate the mathematical model of reheating furnace for design the controller. This paper present the mathematical model of reheating furnace walking beam type using system identification method to estimate the parameter of the mathematical model with the temperature response of slab reheating process and apply adaptive system to design the suitable input with the desire response of slab reheating process by consider to select the optimal process in terms of fuel economy and temperature response.

Key-Words: - **:** Mathematical model of reheating furnace, Thermal system, System identification, Parameters estimation and Adaptive system.

1 Introduction

The slab heating process is one temperature control process which is applied widely in the industry**.** The popular controller which use in temperature control process is PID controller. The manual of the furnace [1] describe the process of the furnace that using the thermal energy to furnace by burner which using double cross limit method adjust the ratio of air and fuel. That the heating burners is the feedback control system.

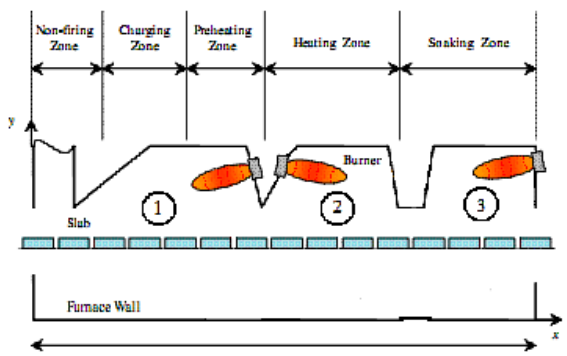

Fig.1 Reheating furnace walking beam type

Structure of iron reheating furnace walking beam type is divided functionally to 3 zones in the figure 1

1. Preheating zone has 8 burners type NXB-300
2. Heating zone has 8 burners type NXB-300
3. Soaking zone has 10 burners type NXB-125

Temperature of each zones are different according to function. Preheating zone serves the humidity away from the slab by heating at approximately 700-800 Celsius. Heating zone provide heat directly to the slab by heating at approximately 1100-1200 Celsius and Soaking zone maintain a constant temperature of slab at approximately 1150-1200 Celsius before the slab leave the reheating furnace. In the begin, heating the furnace can't heat quickly because the reheating furnace wall will be damaged when overheating then must gradually heating properly and keep the constant temperature in a period of time to adjust the inside furnace wall expansion before and then heating temperature up and using the heating up curve is the desired reference temperature of Soaking zone in the opening burner in the figure 2

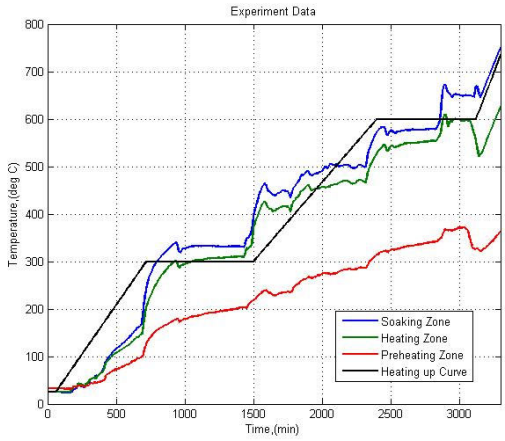

Fig. 2 Temperature response in each zone

Actual temperatures in the range of the reheating furnace apply the two thermocouples to measure the average temperature in each zone. Current ratio of air and fuel is 10:1 and the combustion temperature is approximately 300 Celsius.

From the study of estimated mathematical model of slab reheating furnace [2] studied the thermal energy associated with convection, radiation and the various heat losses from the furnace to occur in the slab heating process. The research [3] has proposed the closed-loop identification of temperature response to iron rod using data from the experiment of one iron rod as a reference and using the quadratic error function to find the parameter coefficient of the mathematical model of the iron heat treatment process. MIMO system identification of the iron reheating furnace using the black box model and ARX model to nonlinear system identification by input is the fuel and the measured output is the temperature value in each interval [4,5]. Study the dynamic model using genetic algorithm in frequency domain [6]. Analysis and design controller of the electromagnetic oven process or the slab reheating furnace by approximation of the mathematical model with adaptive system [7,8]. This paper has proposed open-loop identification and thermal principles to estimate the mathematical model of the slab reheating furnace walking beam type using parameter estimation and design the suitable input (open/close burner) with the desire temperature response in heating up curve process. The mathematical model is the stat-space model equation and the parameter estimation method was applied nonlinear least squares and pattern search to estimate the parameter of the mathematical model. For consideration in the controller design is optimal in term of energy economy and reducing the productive cost in the next time.

2 The Mathematical Model of the Slab Reheating Furnace Process

The system analysis is necessary to estimate the mathematical model of system. We can find from the model that was studied by taking the models are analysis and compared with the experimental results or using the heat transfer principles to find the structure of the mathematical model of system. For this iron reheating furnace walking beam type at Ratchasima Steel Products Co.,Ltd. Factory as shown in Fig. 1. Each zone has two thermocouples to measure the average temperature. In this case we consider all system is the steady state flow process.

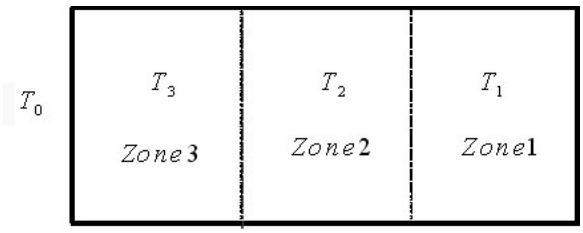

Fig.3 The simple model of reheating furnace walking beam type

The structure of a mathematical model under the data which can be measured in the reheating furnace process, applies with the open-loop identification in parameter estimation of the simple model as shown in Fig. 3. That can be design the control method to control temperature inside the slab reheating furnace in the performance of work under current conditions.

Zone 1 – Soaking zone

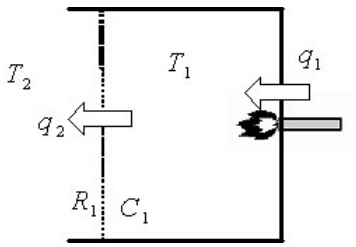

Fig.4 The thermal system at zone 1

From the thermal system consider the heat transfer between the different temperatures as show in Fig. 4 by analysis in term of thermal capacitance as the equation

$$C_1 \frac{dT_1}{dt} = q_1 - q_2 \tag{1}$$

The thermal resistance of heat flow rate from zone 1 to zone 2 can be written

$$q_2 = \frac{T_1 - T_2}{R_1} \tag{2}$$

where C_1 – thermal capacitance at zone 1

R_1 – thermal resistance at zone 1

q_1 – heat flow rate to zone 1

q_2 – heat flow rate from zone 1 to zone 2

T_1 – temperature at zone 1

T_2 – temperature at zone 2

Zone 2 – Heating zone

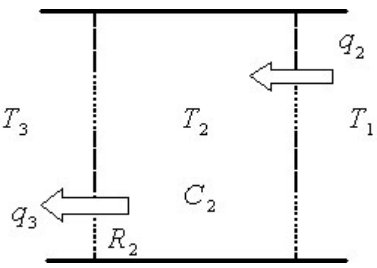

Fig.5 The thermal system at zone 2

The thermal capacitance of zone 2 as shown in fig.5 can be written to

$$C_2 \frac{dT_2}{dt} = q_2 - q_3 \tag{3}$$

The thermal resistance of heat flow rate from zone 2 to zone 3 can be written:

$$q_3 = \frac{T_2 - T_3}{R_2} \tag{4}$$

where C_2 – thermal capacitance at zone 2

R_2 – thermal resistance at zone 2

q_3 – heat flow rate from zone 2 to zone 3

T_3 – temperature at zone 3

Zone 3 – Preheating zone

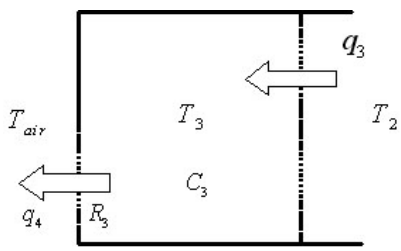

Fig.6 The thermal system at zone 3

The thermal capacitance of zone 3 as shown in Fig. 6, we can write the relative equation to:

$$C_3 \frac{dT_3}{dt} = q_3 - q_4 \tag{5}$$

The thermal resistance of heat flow rate from zone 3 to environment can be written

$$q_4 = \frac{T_3 - T_{air}}{R_3} \tag{6}$$

where C_3 – thermal capacitance at zone 3

R_3 – thermal resistance at zone 3

q_4 – heat flow rate from zone 3 to environment

T_{air} – ambient temperature

We can rearrange the equation 4, 5 and 6 to

$$\dot{T}_1 = -\frac{1}{R_1C_1}T_1 + \frac{1}{R_1C_1}T_2 + \frac{1}{C_1}q_1 \tag{7}$$

$$\dot{T}_2 = \frac{1}{R_1C_2}T_1 - \left(\frac{1}{R_1C_2} + \frac{1}{R_2C_2}\right)T_2 + \frac{1}{R_2C_2}T_3 \tag{8}$$

$$\dot{T}_3 = \frac{1}{R_2C_3}T_2 - \left(\frac{1}{R_2C_3} + \frac{1}{R_3C_3}\right)T_3 + \frac{1}{R_3C_3}T_{air} \tag{9}$$

So we can arrange to state-space equation form

$$\begin{bmatrix} \dot{T}_1 \\ \dot{T}_2 \\ \dot{T}_3 \end{bmatrix} = \begin{bmatrix} -\frac{1}{R_1C_1} & \frac{1}{R_1C_1} & 0 \\ \frac{1}{R_1C_2} & -\left(\frac{1}{R_1C_2} + \frac{1}{R_2C_2}\right) & \frac{1}{R_2C_2} \\ 0 & \frac{1}{R_2C_3} & -\left(\frac{1}{R_2C_3} + \frac{1}{R_3C_3}\right) \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \end{bmatrix} + \begin{bmatrix} \frac{1}{C_1} \\ 0 \\ 0 \end{bmatrix} q_1 + \begin{bmatrix} 0 \\ 0 \\ \frac{1}{R_3C_3} \end{bmatrix} T_{air} \tag{10}$$

From the equation 10 can rearrange the new equation to

$$\begin{bmatrix} \dot{T}_1 \\ \dot{T}_2 \\ \dot{T}_3 \end{bmatrix} = \begin{bmatrix} -a & a & 0 \\ b & -(b+c) & c \\ 0 & d & -(d+e) \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \end{bmatrix} + \begin{bmatrix} f \\ 0 \\ 0 \end{bmatrix} q_1 + \begin{bmatrix} 0 \\ 0 \\ e \end{bmatrix} T_{air} \tag{11}$$

where $a = \frac{1}{R_1C_1}$, $b = \frac{1}{R_1C_2}$, $c = \frac{1}{R_2C_2}$, $d = \frac{1}{R_2C_3}$, $e = \frac{1}{R_3C_3}$ and $f = \frac{1}{C_1}$

3 Problem Solutions

3.1 Open-loop Identification

The slab reheating furnace process is the open-loop control process. The mathematical model of slab reheating furnace process with experiment results can be estimated the parameter via nonlinear least squares and pattern search which increase the temperature of the reheating furnace according to the step open of burner. That is divided to 4 ranges. In the first range the furnace open two burners at zone 1 about 510 minutes, the second range the furnace open four burners until 2670 minutes, the third range the furnace open six burners until 3170 minutes and the forth range the furnace open ten burners until 3310 minutes. The system which control air to fuel ratio of 10:1 is the closed-loop system using PID controller. In the condition at flow rate is 40,000 m^3/h, pressure is 5 bars, the air temperature is 350 Celsius and the fuel is 110 Celsius.

The method of open-loop identification via parameter estimation technique can be estimated the mathematical model of slab reheating furnace with measuring temperature in heating curve up process. The investigation of the coefficients in the mathematical model (11) is a complex problem because of restricted information input temperature can be measured. The logical criterion might be to minimize the sum of residual errors (e) for all the available data, as in

$$e = \sum_{i=1}^{N} \left[T_1(i) - \tilde{T}_1(i) \right]^2 \tag{13}$$

where N -total number of data, $\tilde{T}_1(t)$ is the temperature measurement from the mathematical model of slab reheating furnace in heating curve up process

3.2 Experimental and Simulation Results

In the experiment to estimate the parameter with Non-linear least squares and Pattern search of the slab reheating furnace process at Ratchasima Steel Products Co.,Ltd. Factory use the increased furnace's temperature process according to the heating curve up.

The response of temperature from experimentation and simulation as shown in figure 7, 8 and 9 take to estimate the parameter with nonlinear least squares and Pattern search method as shown in Table 1. The average error for all 3 zones using the parameter estimation compare with measured temperature with non-linear least squares method is 7.3953 and Pattern search method is 15.1496.

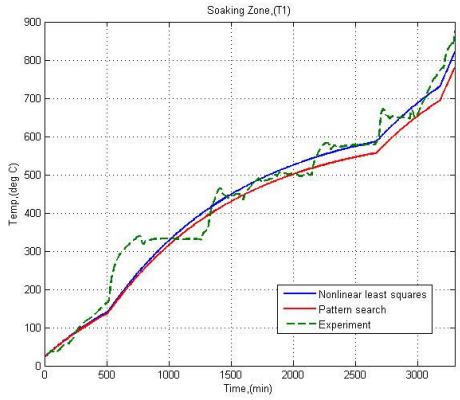

Fig. 7 Temperature responses of the experiment and the estimate model at zone 1

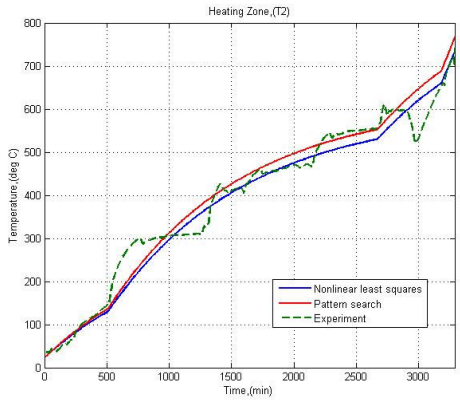

Fig. 8 Temperature responses of the experiment and the estimate model at zone 2

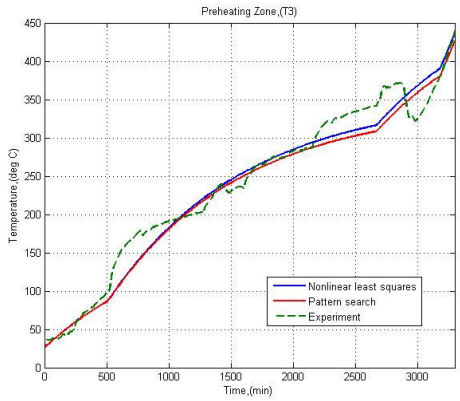

Fig. 9 Temperature responses of the experiment and the estimate model at zone 3

Table1. Parameter estimation of the mathematical model

Parameters	Parameter estimation	
	Pattern search	Nonlinear least squares
a	0.12028	0.00888
b	0.92183	2.9412
c	0.017474	0.78088
d	3.1801	0.96634
e	2.7854	0.72051
f	0.15592	0.14266
*Error**	15.1496	7.39533

3.3 Design Procedure of the Open Burner via Adaptive System and Constraint Function

The design procedure of the open 10 burners in heated furnace process must consider the response of temperature in soaking zone (T_1) according to heating curve up and saving energy. When we have the estimated mathematical model of slab reheating furnace process and variable via parameter identification method, we can apply the adaptive system and constraint function to find out the number of burners that are opened (k) and the corresponding time (t). The gradient method is to adjust parameter in such a way that the loss function is minimized

$$J(k) = \frac{1}{2}e^2 \tag{14}$$

where $e = T_{ref} - T_1$, T_{ref} – temperature of heating curve up at soaking zone.

The objective of an adaptive system is adjust the number of burners until the error between the temperature of heating curve up (T_{ref}) and the temperature (T_1) of the estimated mathematical model of slab reheating furnace process is close to zero. Thus we assign the parameter of the number of burners in the negative gradient of J

$$\frac{\partial k}{\partial t} = -\frac{\gamma e \partial J}{\partial k} = -\frac{\gamma e \partial e}{\partial k} \tag{15}$$

and

$$\frac{\partial e}{\partial k} = -\frac{\partial T_1}{\partial k} \tag{16}$$

where γ is adaptation gain. The sensitivity function is

$$\frac{\partial u}{\partial t} = -au + av + k\frac{\partial q_1}{\partial t} + q_1 \tag{17}$$

where $u = \frac{\partial T_1}{\partial k}$, $v = \frac{\partial T_2}{\partial k}$ and $w = \frac{\partial T_3}{\partial k}$

$$\frac{\partial v}{\partial t} = bu - bv - cv + cw \tag{18}$$

$$\frac{\partial w}{\partial t} = dv - dw - ew \tag{19}$$

The constraint functions are

k is integer number and $2 \le k \le 10$

t is real number and $t > 0$

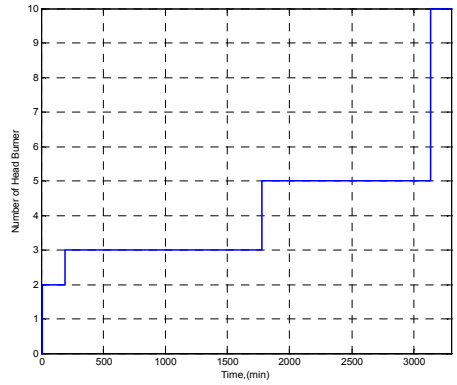

Fig. 10 Step of burners opening from the program

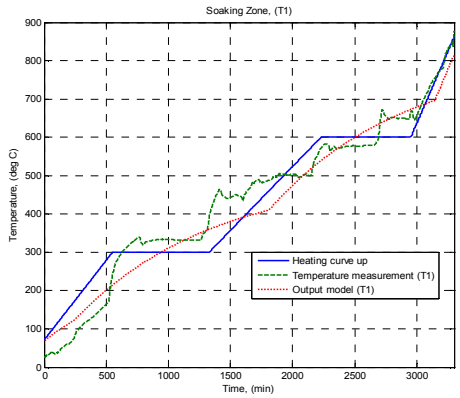

Fig. 11 The response of temperature to the opening of the new burners in soaking zone.

The result of the program to find the number of burners (k) and corresponding time (t) as shown in the fig.10 and the response of temperature to the opening of burners as shown in the fig.11. We can reduce the error (e_{rms}) of temperature down to 26.21 % and saving energy to 2.26%.

4 Conclusion

This paper has proposed the estimated method to estimate the mathematical model using the open-loop identification for the slab reheating furnace walking beam type with non-linear least squares and pattern search method in heating curve up process. The results from simulate and measured temperature response have relative response so the mathematical model can take to design open-close burner to control the suitable temperature with heating curve up and save the energy of the slab reheating furnace.

Acknowledgement

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References:

[1] Bangkok Steel Industry Rolling Mill, (1998). *Reheating Furnace-Function Specification*.

[3] A Kuster and G.A.J.M van Ditzhuijzen, (1994). MIMO System Identification of a Slab Reheating Furnace, paper presented in *the 3rd IEEE Conference on Control Applications*, Glasgow, Scotland, UK.

[4] Lars Malcolm Pederson and Bjorn Wittenmark, (1998).On the Reheat Furnace Control Problem, paper presented in *the 1998 American Control Conference*, Philadelphia, USA.

[5] Gustaaf Van Dit zhuijen.,Dirk Staaman.,Arnol Koorn, (2002). Identification and Model Predictive Control of a Slab Reheating Furnace, paper presented in *the 2002 IEEE International Conference on Control Applications*, Glasgow, Scotland, UK.

[6] C.H. Lo, K.M. Chow, Y.K. Wong and A.B. Rad., (2001). Qualitative system identification with the use of on-line genetic algorithm, *Simulation Practice and Theory*, Vol.8(6-7), March 2001, pp.415-431.

[7] L.Balbis, J. Balderud and M. J. Grimble, (2008). Nonlinear Predictive Control of Steel Slab Reheating Furnace, paper presented in *the 2008 American Control Conference*, Washington, USA.

[8] Jiraphon Srisertpol and Supot Phungpimai, (2010).Model Reference Adaptive Temperature Control of the Electromagnetic Oven Process in Manufacturing Process, paper presented in *the 9th WSEAS International Conference on Signal Processing, Robotics and Automation*, Cambridge, UK.