Estimation of the Mathematical Model of the Reheating Furnace Walking Hearth Type in Heating Curve Up Process

Jiraphon Srisertpol, Suradet Tantrairatn, Prarinya Tragrunwong and Vorapot Khomphis

***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 walking hearth type 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 hearth type using system identification method to estimate the parameter of the mathematical model with the temperature response of slab reheating process.

***Keywords*—** Mathematical model of reheating furnace, Thermal system, System identification and Genetic algorithm.

I. 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. The heating burners are the feedback control system. Structure of iron reheating furnace walking hearth type is divided functionally to 3 zones in the figure 1.

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

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.

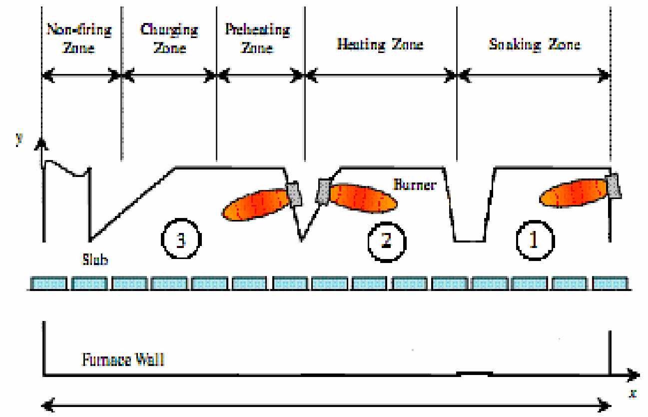

Fig.1 Reheating furnace walking beam type

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.

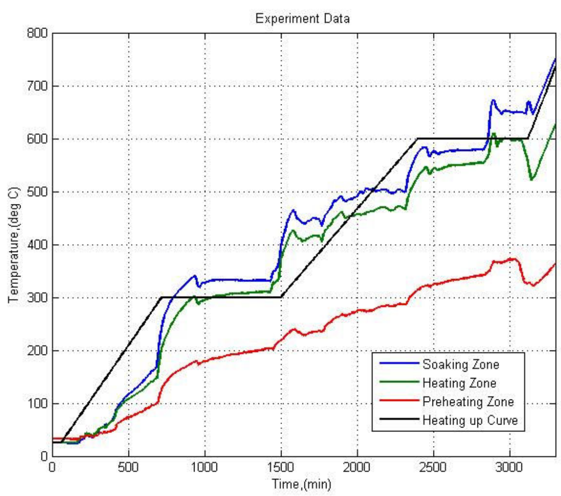

Fig. 2 Temperature response in each zone

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. An estimation temperature has been developed and presented for prediction of thermal behavior in a reheating furnace via heat transfer model [3]. The research 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 are demonstrated [7-8]. The optimization and control of the CO_2 emissions released in atmosphere for the burning process using off-line and on-line component are presented [9]. The genetic algorithm (GA) performances are optimized based on the proposed tuning procedure for parameter identification of a cultivation process model [10]. A parameter estimation algorithm is developed by GA to estimate the unknown parameters [11-13].

The estimation of the mathematical model of the slab reheating furnace walking beam type is needed in the design of control process. This paper has proposed open-loop identification and principle of thermal system to estimate the mathematical model of the slab reheating furnace walking beam type using genetic algorithm with the temperature response in heating up curve process. The mathematical model is the state-space model equation under the terms of data of the slab reheating furnace and the system identification method was applied genetic algorithm to estimate the parameter of the mathematical model.

II. 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 slab 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.

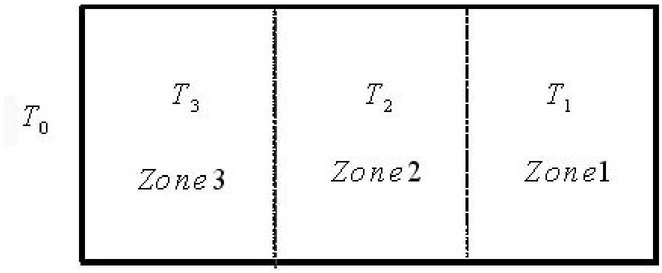

Fig.3 The simple model of reheating furnace walking beam type

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

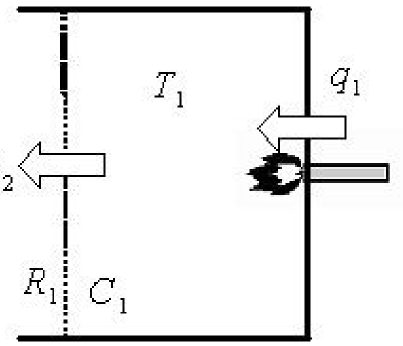

Fig.4 The thermal system at zone 1

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

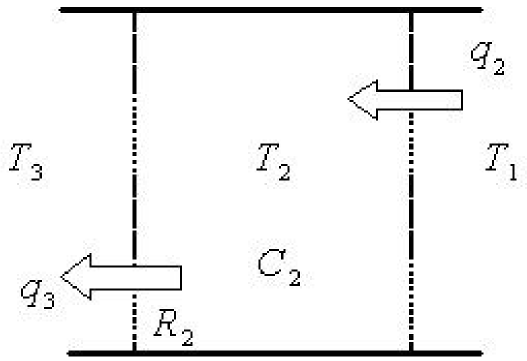

Fig.5 The thermal system at zone 2

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

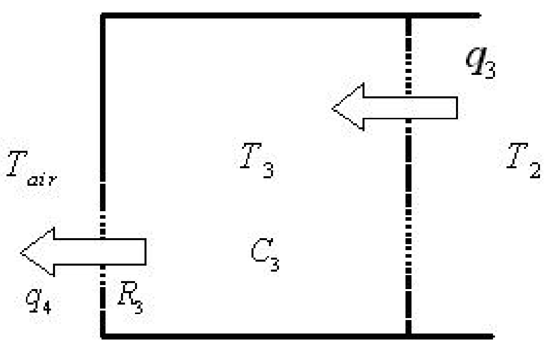

Fig.6 The thermal system at zone 3

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 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 $f = \frac{1}{C_1}$

III. 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 genetic algorithm which increases the temperature of the reheating furnace according to the step open of burner. 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_w) for all the available data, as in

$$e_w = \sum_{i=1}^{N} \left[T_w(i) - \tilde{T}_w(i) \right]^2 \qquad (12)$$

where N -total number of data, w=1,2,3, $T_w(i)$ is the temperature measurement from thermocouples, $\tilde{T}_w(i)$ is the temperature measurement from the mathematical model of slab reheating furnace in heating curve up process

IV. EXPERIMENTAL AND SIMULATION RESULTS

In the experiment to estimate the parameter with genetic algorithm 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 1st experiment of step of burner opening. The experiment 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 2,670 minutes, the third range the furnace open six burners until 3,170 minutes and the forth range the furnace open ten burners until 3,310 minutes as shown in Fig. 7.

The response of temperature from the 1st experiment and simulation each zone is shown in figure 8, 9 and 10. The parameter estimation of the slab reheating furnace process with genetic algorithm is demonstrated in Table I. The mean error, number of population and GA cycle for all 3 zones using the parameter estimation compare with measured temperature are presented in Table II. The results of estimation parameters for each zone, we find that the soaking zone has maximum mean error, heating zone and preheating zone, respectively.

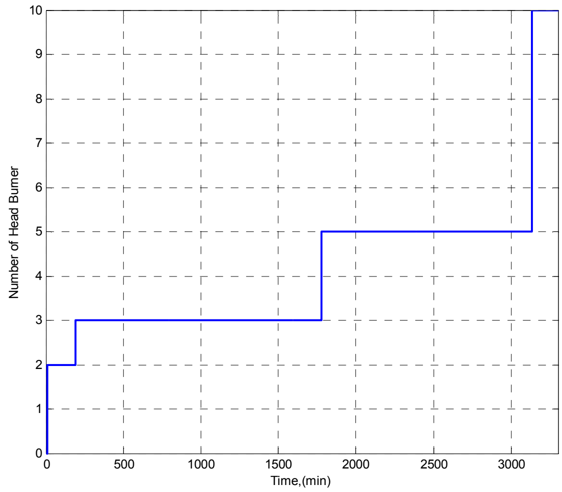

Fig. 7 The 1st experiment of step of burner opening

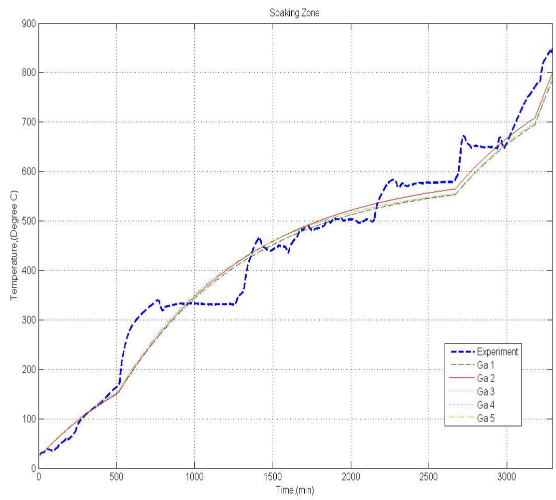

Fig. 8 Temperature responses of the experiment and the estimate model at zone 1

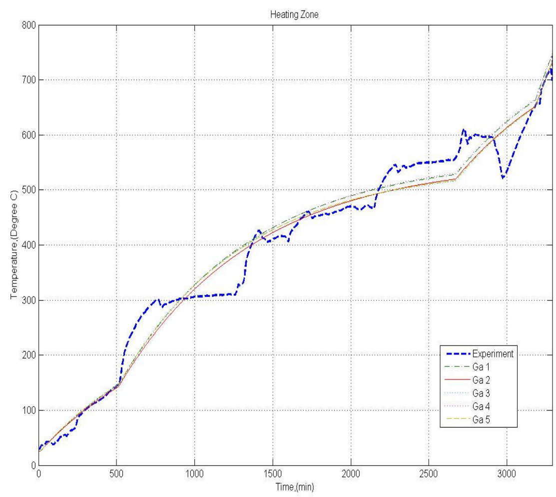

Fig. 9 Temperature responses of the experiment and the estimate model at zone 2

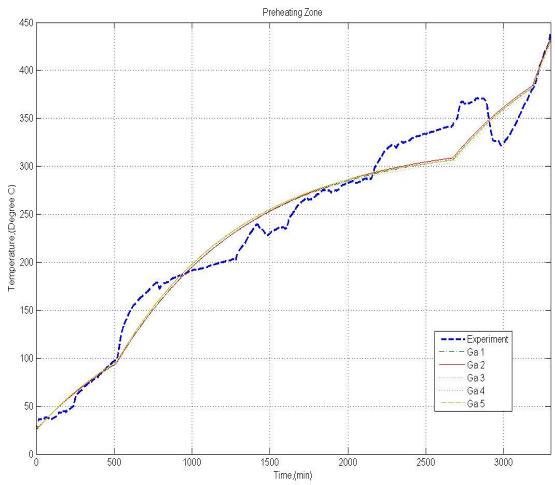

Fig. 10 Temperature responses of the experiment and the estimate model at zone 3

Table I
Parameter estimation of the mathematical model

	Parameter Estimation				
	Ga1	Ga2	Ga3	Ga4	Ga5
a	0.014091	0.026634	0.018050	0.018050	0.026634
b	0.505932	0.371374	0.397970	0.398863	0.362392
c	0.107607	0.041534	0.071383	0.070972	0.039671
d	0.820709	1.029495	0.232927	0.235736	1.033556
e	0.621138	0.824891	0.180905	0.179877	0.827300
f	0.169089	0.175663	0.181113	0.178897	0.173331

Table II
The mean error, population and GA cycle

	Parameter Estimation				
	Ga1	Ga2	Ga3	Ga4	Ga5
Population	20	100	20	20	100
GA cycles	100000	30000	50000	25000	12000
Soaking zone (e_1)	7.77797	14.8143	9.8551	10.3565	15.0111
Heating zone (e_2)	1.86829	5.78559	0.52143	0.53254	5.96567
Preheating zone (e_3)	1.97467	2.81093	3.14606	1.54982	2.61733

The 2nd experiment of step of burner opening. The experiment is divided to 6 ranges. In the first range the furnace open two burners at zone 1 about 1,900 minutes, the second range the furnace open five burners until 3,100 minutes, the third range the furnace open six burners until 3,300 minutes, the forth range the furnace open eight burners until 3,400 minutes, the fifth range the furnace open ten burners until 3,500 minutes and the sixth range open eighteen burners until 3,800 minutes as shown in Fig. 11.

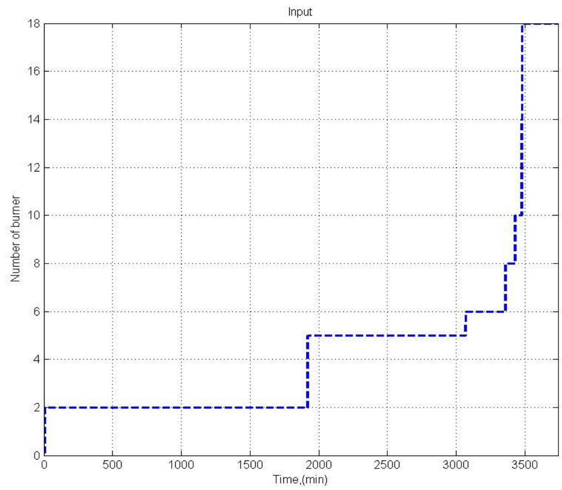

Fig. 11 The 2nd experiment of step of burner opening

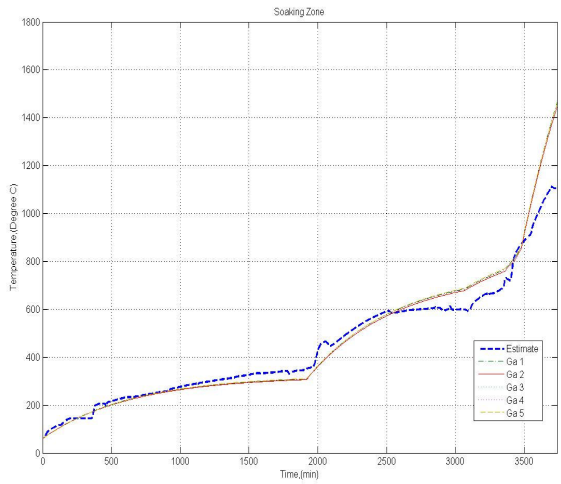

Fig. 12 Temperature responses of the experiment and the estimate model at zone 1

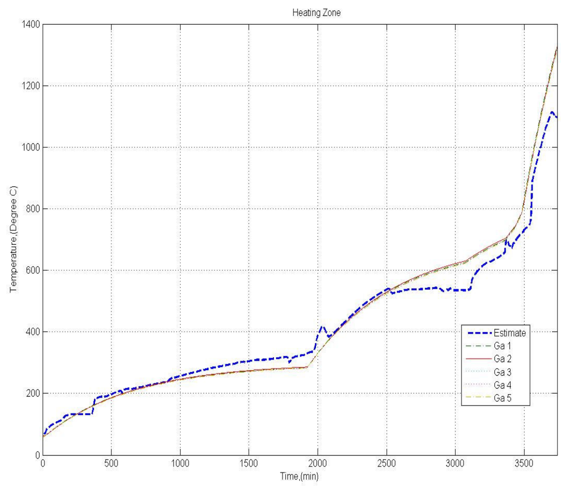

Fig. 13 Temperature responses of the experiment and the estimate model at zone 2

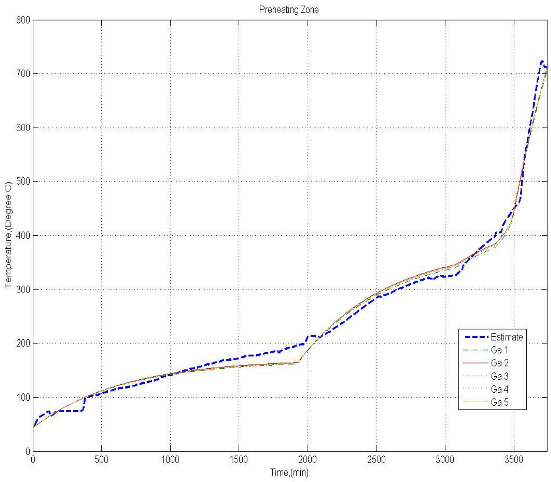

Fig. 14 Temperature responses of the experiment and the estimate model at zone 3

Table III
Parameter estimation of the mathematical model

	Parameter Estimation				
	Ga1	Ga2	Ga3	Ga4	Ga5
a	0.017757	0.026152	0.017215	0.016929	0.015274
b	0.777766	0.092164	0.452683	1.019546	1.148326
c	0.162612	0.015482	0.098812	0.222680	0.273625
d	0.223048	0.926437	0.291674	0.435669	0.784380
e	0.205235	0.833869	0.260814	0.390541	0.697966
f	0.235191	0.279172	0.234959	0.231264	0.227348

Table IV
The mean error, population and GA cycle

	Parameter Identification				
	Ga1	Ga2	Ga3	Ga4	Ga5
Population	20	100	20	20	100
GA cycles	100000	30000	50000	25000	12000
Soaking zone (e_1)	12.9584	8.87045	12.6680	12.7047	14.0345
Heating zone (e_2)	10.9252	11.6114	9.39441	9.75466	7.89346
Preheating zone (e_3)	3.39671	0.59536	1.35214	1.2942	1.47378

The response of temperature from the 2nd experiment and simulation each zone is shown in figure 12, 13 and 14. The parameter estimation of the slab reheating furnace process with genetic algorithm is demonstrated in Table III. The mean error, number of population and GA cycle for all 3 zones using the parameter estimation compare with measured temperature are presented in Table IV. The mean errors are likely the same trend from the first estimation parameters.

We used the mean of parameter estimation for considered temperature response of reheating furnace in each zone as shown in Table V. Fig.15-17 shows temperature response of the mathematical model with the genetic mean parameter for the 1st experiment of step of burner opening.

Table V
The mean of the parameter estimation

	Parameter Estimation		
	Mean of 1st experiment	Mean of 2nd experiment	Genetic mean parameter
a	0.017757	0.026152	0.020121
b	0.777766	0.092164	0.299049
c	0.162612	0.015482	0.061544
d	0.223048	0.926437	0.873573
e	0.205235	0.833869	0.727504
f	0.235191	0.279172	0.224131

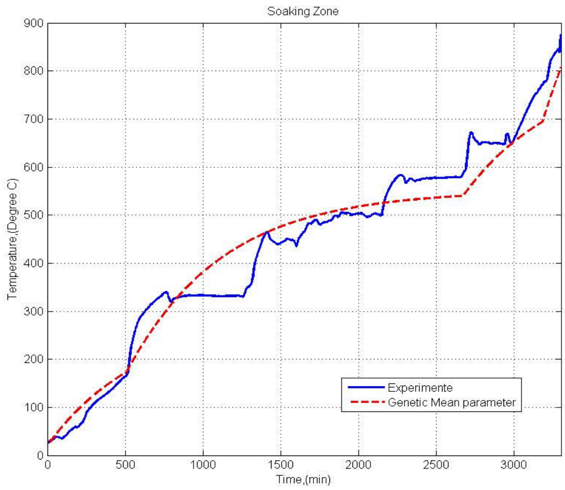

Fig. 15 Temperature responses of the 1st experiment and the estimate model with genetic mean parameter at zone 1

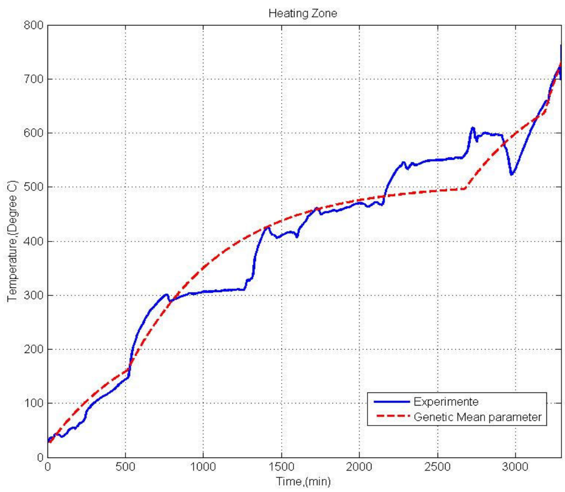

Fig. 16 Temperature responses of the 1st experiment and the estimate model with genetic mean parameter at zone 2

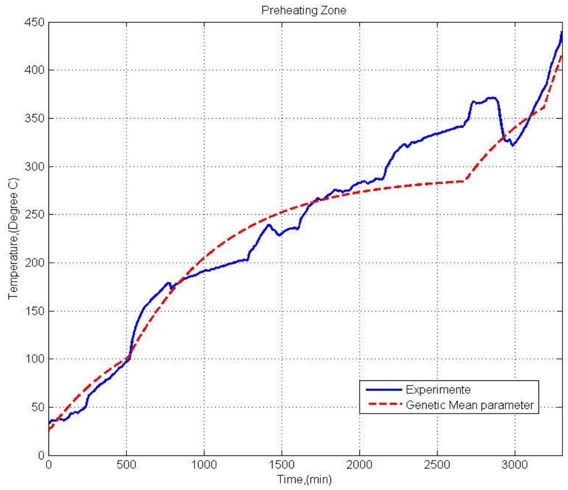

Fig. 17 Temperature responses of the 1st experiment and the estimate model with genetic mean parameter at zone 3

The temperature responses of the 2nd experiment and the estimate model with genetic mean parameter for all zones are shown in Fig.18-20. The application of the genetic mean parameter has reduced mean error in the each zone for 1st experiment but 2nd experiment has increased mean error as shown in Table VI.

Table VI
The mean error

	1st experiment	2nd experiment
Soaking zone (e_1)	1.9298	27.6431
Heating zone (e_2)	2.5859	23.3231
Preheating zone (e_3)	8.1102	12.7087

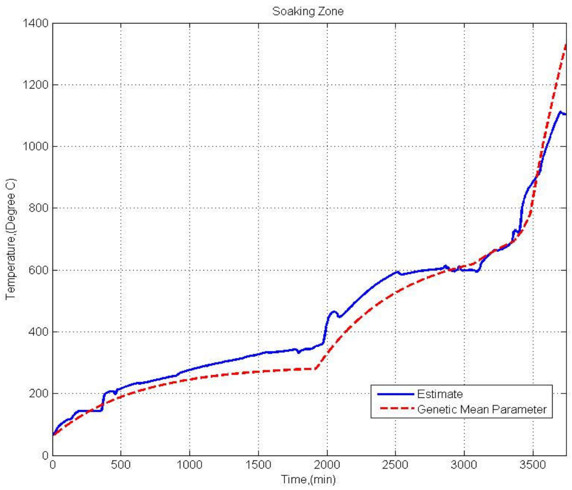

Fig. 18 Temperature responses of the 2nd experiment and the estimate model with genetic mean parameter at zone 1

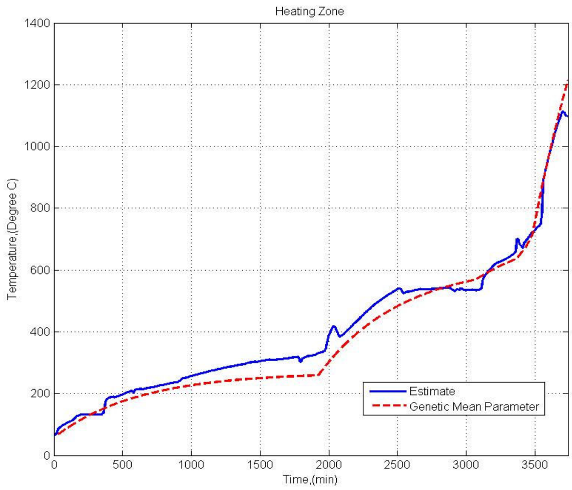

Fig. 19 Temperature responses of the 2nd experiment and the estimate model with genetic mean parameter at zone 2

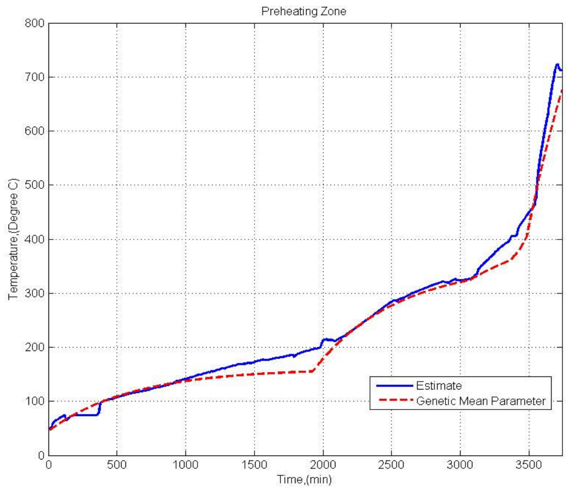

Fig. 20 Temperature responses of the 2nd experiment and the estimate model with genetic mean parameter at zone 3

V. Conclusions and Suggestion

The mathematical model of the reheating furnace walking hearth type may be less accurate because the reheating furnace has been working for long time and the position of temperature measurement has less. The system identification method can be investigated the suitable mathematical model only system with explicit input and output. The reheating furnace has many mode of input in heating curve up process. Therefore, it is necessary to approximately mathematical model. The adequate mathematical model must have many experiment and accuracy of the measurement data.

This paper has proposed the estimated method to estimate the mathematical model using the open-loop identification for the slab reheating furnace walking hearth type with genetic algorithm in heating curve up process. The responses of experimental and simulation are consistent. The approximately mathematical model can be design open-close burner to control the suitable temperature with heating curve up and save the energy of the slab reheating furnace.

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