Effect of Error in Predictive Model of Model Prediction Control to Minimize Temperature Change of Plate with Varying Heat Generation

Shigeki Hirasawa*, Kazuya Koike, Tsuyoshi Kawanami, Katsuaki Shirai

Department of Mechanical Engineering, Kobe University, 1-1 Rokkodai, Nada, Kobe, Hyogo, 657-8501 Japan

*hirasawa@kobe-u.ac.jp

***Abstract*- Precise temperature control to decrease temperature change of works within 0.001 ℃ is required in semiconductor manufacturing process. We analytically and experimentally study the model predictive control to minimize temperature change at an object position in a 2-dimensional vertical plate with a varying noise-heat-generation. The noise-heat-generation is that the heating is OFF and ON every 300 s, and it causes temperature change about 3 ℃ without control. A control-heater in the plate is controlled with the model predictive control method using the step response pattern as a dynamic predictive model. In this work, we study the effect of error in the dynamic predictive model. We found that artificial error in the dynamic predictive model causes various patterns of temperature change at the object position such as periodical error and oscillation error. Experimental result of temperature change at the object position is 0.08 ℃ and has periodical error of 300 s period using the averaged step response pattern obtained by experiment. It is because the step response pattern obtained by experiment has random noise error. The temperature change at the object position is 0.07 ℃ and has periodical error of 600 s period using the step response pattern obtained by the network model calculation. It is because the step response pattern obtained by the network model calculation has some modelling errors entirely.**

Keywords- Precise Temperature Control; Heat Transfer; Process Control; Model Predictive Control; Dynamic Predictive Model

I. INTRODUCTION

Recent advances in VLSI technology incorporate high-density devices, which require very accurate temperature control during the semiconductor manufacturing process. Also, in nano-engineering very accurate process temperature control is required. For example, temperature change of 0.001 ℃ causes 1 nm-movement of position by thermal expansion of a steel plate of 100 mm width. So precise temperature control to decrease temperature change of works within 0.001 ℃ is required during the manufacturing process to achieve nm-order accuracy. On the other hand, local temperature of the manufacturing apparatus changes more than 0.1 ℃ even in a constant-temperature room with air-conditioning facilities, because of noise-heat-generation from the working apparatus. Therefore it is necessary to develop precise temperature control method to decrease temperature change of works within 1/100 times smaller than that without control under circumstances of noise-heat-generation.

Some works on precise temperature control have been reported. Experiments on temperature control within 0.0001 ℃ in a thermally insulated room without noise-heat-generation were reported [1-3]. Kudo et al. [4] developed an inverse problem method to control object temperature by changing boundary conditions. Diaz et al. [5] reported an adaptive neurocontrol method to keep constant air temperature coming out from heat exchangers. Lawton et al. [6] analyzed and designed a precise temperature control system for fluid flow by using frequency-dependent attenuation technique. Sweetland et al. [7] analyzed active thermal control for IC devices. Hoshino et al. [8] developed a precise temperature control method by improving a PID control method for the adiabatic demagnetization refrigerators. Model predictive control method was reported to be preferable for process control method under circumstances of random noise [9, 10]. In the model predictive control method future response of the object is predicted using a dynamic predictive model and the controlling rate is determined so that the response comes to be an ideal response pattern.

Authors [11-13] reported analytical and experimental study to minimize temperature change at an object position in one-dimensional or two-dimensional vertical plates with varying noise-heat-generation with the model predictive control method. The temperature change at the object position can be decreased to 0.002 ℃, which is 1/1000 times smaller than that without control, using the model predictive control method in analysis [12]. Experimental results show that the minimum temperature change at the object position is 0.04 ℃, which is 1/80 times smaller than that without control, in a vacuum surrounding [13]. This is the minimum accuracy of the thermometer to measure temperature change in the experiment. We found that accuracy of the dynamic predictive model used in the model predictive control method is very important.

In this work we study the effect of error in the dynamic predictive model on temperature change at the object position by numerical simulation and experiment.

II. ANALYTICAL METHOD

A calculation model of a vertical plate with varying noise-heat-generation is shown in Fig. 1. In this work we studied precise temperature control methods for a simple model. A vertical plate is placed in an atmosphere. The vertical plate is steel (thermal conductivity is 43 W/mK, density is 7850 kg/m^3, and specific heat is 465 J/kgK) with 100 mm in height, 100 mm in width, and 5 mm in thickness. There is a noise-heat-generation at the position C. A control-heater is placed at the position B. Purpose of the control in this work is to minimize temperature change at the object position-a using the control-heater at the position B. Initial temperature condition of the vertical plate is the steady state with 1.3 W constant heating of the heater C. The noise-heat-generation at the position C is that the heating-OFF for 300 s and 1.3 W-heating-ON for 300 s are repeated twice after the initial steady temperature condition.

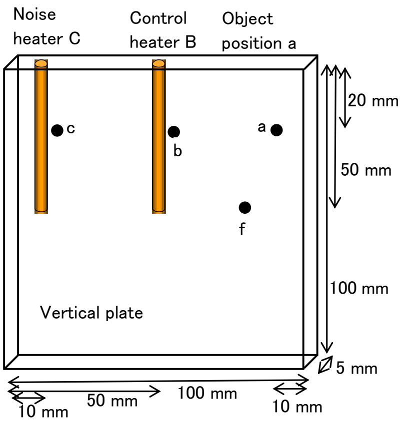

Fig. 1 Calculation model

Two-dimensional temperature distribution in the vertical plate is calculated by Eq. (1).

$$\rho C_p \frac{\partial T}{\partial t} = \lambda \left\{ \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2} \right\} + q \tag{1}$$

where, T is the temperature, t is time, x and z are coordinates, ρ is density, C_p is specific heat, λ is thermal conductivity, q is summation of the the natural convection heat transfer rate, the radiation heat transfer rate of both sides of the vertical plate and the heat generation rate per unit volume. The summation of the natural convection and the radiation heat transfer coefficient is assumed to be 10 W/m^{2}K. Equation (1) is calculated by the implicit finite-difference method. Mesh spacing of the numerical calculation is 10 mm and calculation time step is 1.25 s. Initial steady temperate rise of the vertical plate is 5.8℃ at the position-a from the atmosphere temperature. In this work we will show the temperature change from the initial steady temperature.

At first, unsteady temperature change was calculated without control-heat-generation for the model of one object position. Figure 2 shows the calculation result of the temperature changes at the positions a − f when noise-heat-generation of the heating-OFF and ON for 300 s at the position C is repeated. The temperature changes in Fig. 2 are different from the initial steady temperate rise (5.8℃ at the position-a). Maximum change of the object temperature without control-heat-generation is 2.3℃ at the position-a.

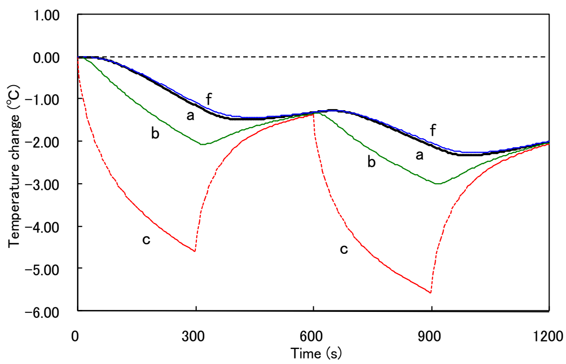

Fig. 2 Temperature change without heat control in vertical plate

III. MODEL PREDICTIVE CONTROL METHOD

Basic idea of the model predictive control is as following. Future response of the object is predicted using a dynamic predictive model. And the controlling rate is determined so that the response comes to be an ideal response pattern. At the same time, difference between the predicted response and the actual response is modified. In our calculation model shown in Fig. 1, change of the noise-heat-generation at the position C is predicted using the monitoring temperature at the position-c. The control-heating rate at the position B is determined using the dynamic predictive model so that the temperature change at position-a comes to be zero after 15 s under the predicted noise-heat-generation, and the control-heating rate is modified to decrease the difference between the predicted temperature and the monitoring temperature at position-a. In advance, dynamic step responses of the temperature change at positions-a and c are obtained for step change of - 1.0 W of the noise-heat-generation at the position C, or + 1.0 W of the control-heat-generation at the position B (Fig. 3). The obtained step response pattern is used as the dynamic predictive model. Our control time interval is 5 s.

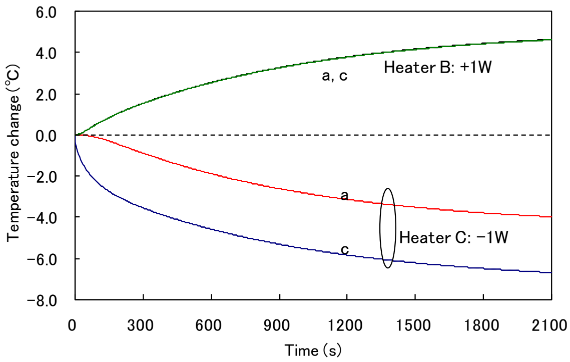

Fig. 3 Temperature response for step heat generation

Figures 4 and 5 show the calculation result of the temperature changes at the positions a – f and heat generations for the calculation with the model predictive control using an ideal step response pattern. Temperature change at the object position-a is 0.002 ℃, which is 1/1000 times smaller than that without control.

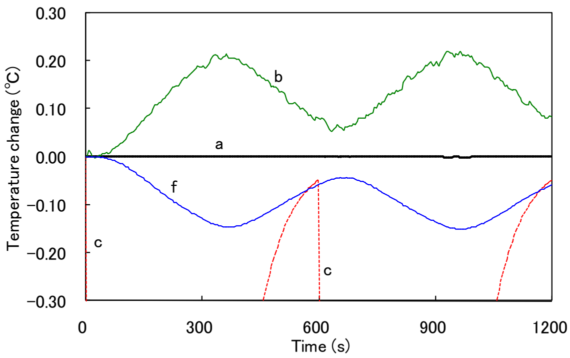

Fig. 4 Temperature change for model predictive control

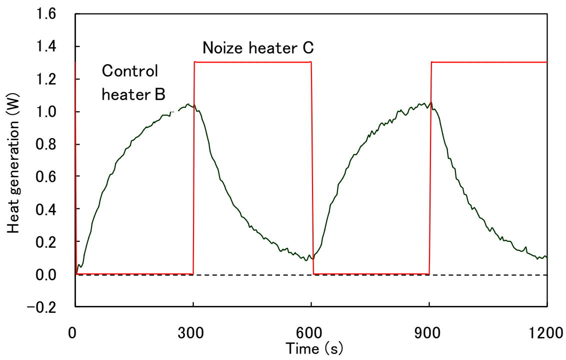

Fig. 5 Change of heat generation for model predictive control

IV. EFFECT OF ERROR IN DYNAMIC PREDICTIVE MODE

In order to know relation between the error in the dynamic predictive model and temperature change at the object position, we examined the effect of artificial error added in the step response pattern on temperature change at the object position-a. The base step response patterns of the temperature change without artificial error are shown in Fig. 3. The data of the base step response patterns are changed artificially by adding some errors. Temperature change of the vertical plate is calculated with the model predictive control using the dynamic predictive model which has some artificial errors. As the dynamic predictive model has some artificial errors, the calculated temperature change at the object position-a is different from that without artificial error (Fig. 4). In this work we examined the effects of four types artificial errors on the temperature change at the object position-a.

Figure 6 shows calculation result of the temperature change at the object position-a when the step response pattern at position-a for step heat generation +1 W of heater-B has error of +0.03 ℃ from 0 s to 75 s. The temperature change at the object position-a has periodical error of 600 s.

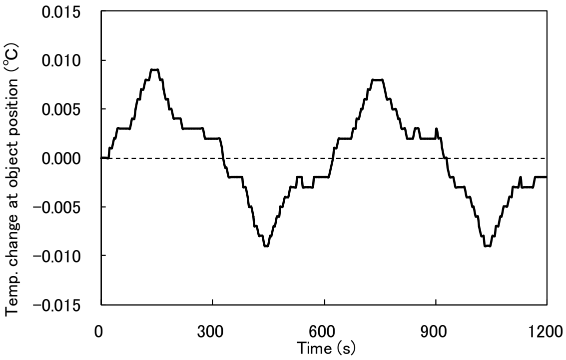

Fig. 6 Temperature change at position-a for control with error of +0.03 ℃ from 0 s to 75 s in step response pattern for position-a and heater-B

Figure 7 shows calculation result of the temperature change at the object position-a when the step response pattern at position-a for step heat generation +1 W of heater-B has error of +0.03 ℃ from 75 s to 150 s. The temperature change at the object position-a has periodical error of 300 s.

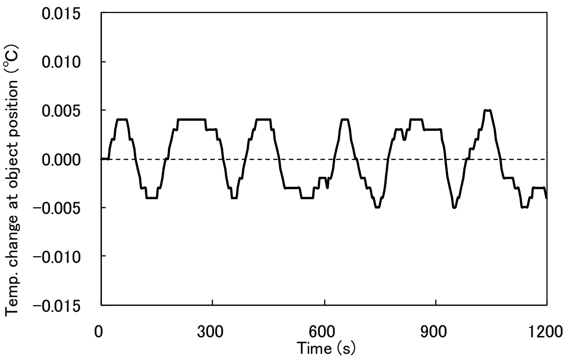

Fig. 7 Temperature change at position-a for control with error of +0.03 ℃ from 75 s to 150 s in step response pattern for position-a and heater-B

Figures 8 and 9 show calculation results of the temperature change at the object position-a and heat generation when the step response pattern at position-a for step heat generation +1 W of heater-B has error of +0.02 ℃ only at 35 s. The temperature change at the object position-a is small until 1200 s. But oscillation of the control-heat-generation increases gradually and temperature change at the object position-a increases to be large after 1200 s.

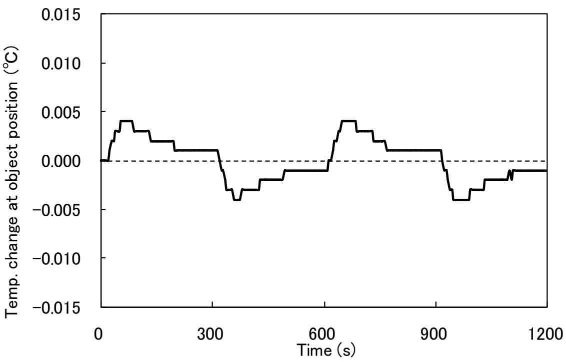

Fig. 8 Temperature change at position-a for control with error of +0.02 ℃ at 35 s in step response pattern for position-a and heater-B

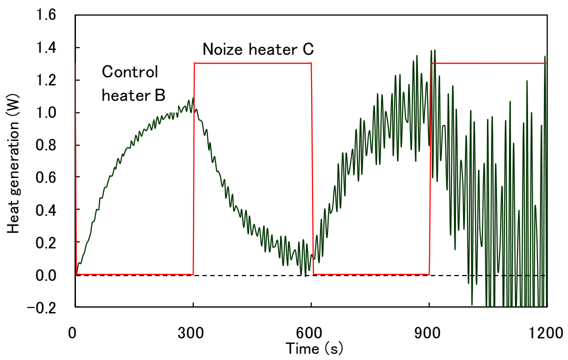

Fig. 9 Heat generation for control with error of +0.02 ℃ at 35 s in step response pattern for position-a and heater-B

We found that artificial error in the step response pattern causes various patterns of temperature change at the object position-a: periodical error of 600 s or 300 s, and oscillation error.

V. EXPERIMENTAL APPARATUS

In order to check the calculation results, we measured temperature change of a vertical plate in an experimental apparatus. The experimental apparatus is the same as Fig. 1 and the details is written in our previous paper [13]. The vertical steel plate of 100 mm in height, 100 mm in width, and 5 mm in thickness is placed in an atmosphere. Heater is a coil of constantan wire, and DC current is supplied to the heater. Temperature distributions are measured by T-type thermocouples of 0.2 mm in diameter. Accuracy of the thermometer is 1.0 ℃ and resolution is 0.01 ℃, which are written in the specification of the thermometer. However, temperature fluctuation during constant 1.3 W heating of the heater C is 0.05 ℃ at our calibration test and this is the actual accuracy of our thermometer to measure temperature change in our experiment. So we discuss temperature change of order of 0.05 ℃ in this work. Initial steady temperature rise of the vertical plate is 5.0 ℃ at the position-a from the atmosphere temperature. In this work we will show the temperature change from the initial steady temperature. The noise-heat-generation at the position C is that the heating-OFF for 300 s and 1.3 W-heating-ON for 300 s are repeated after the steady state. Control-heating rate is calculated in a personal computer with the model predictive control method. Change of the noise-heat-generation at the position C is predicted using the monitoring temperature at the position-c. The control-heating rate at the position B is determined using the dynamic predictive model so that the temperature change at position-a comes to be zero after 30 s under the predicted noise-heat-generation. At the same time, difference between the predicted temperature and the monitoring temperature at position-a is obtained, and the control-heating rate is modified to decrease the difference. Signal of the calculated control-heating rate is sent to the DC power supply for the control-heater. Control time interval is 5 s. Maximum change of the object temperature without control-heat-generation is 3 ℃ at the position-a. Experimental results of the temperature change and calculation results using the dynamic predictive model without artificial error are similar as shown in our previous paper [12]. In this work experimental results and calculation results using the dynamic predictive model with artificial error are compared.

VI. EXPERIMENTAL RESULTS

A. Control with Step Response Pattern by Experiments

Step responses of the temperature change are measured four times and the averaged step response patterns at positions-a and c are used as the dynamic predictive model. Figure 10 shows the experimental result of the temperature change at the

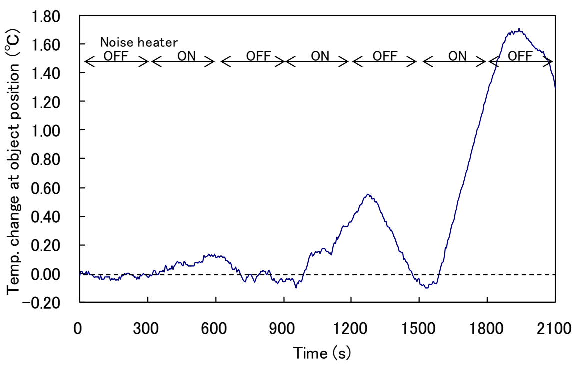

Fig. 10 Temperature change at position-a for control with step response pattern obtained by experiments

object position-a. The temperature change at the object position-a is 1.8 ℃. The temperature change is large because the step response patterns obtained by experiments have random noise of 0.05 ℃, which is the accuracy of our thermometer, as shown as broken line in Fig. 11. The random noise in the dynamic predictive model caused prediction error repeatedly at every control time step and the error accumulated after many steps of the control. It is similar to Fig. 9. So we think that the random error at near 35 s in the step response pattern of heater-B caused the large error of the temperature change at the object position-a.

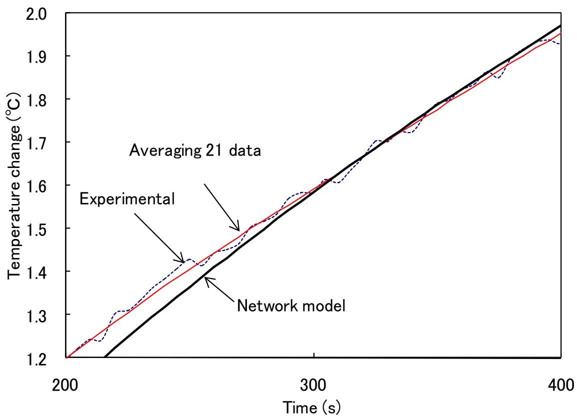

Fig. 11 Temperature response at position-a for step heat generation +1 W of heater-B

B. *Control with Step Response Pattern by Average 21 Data Along Time Steps*

The step response patterns obtained by experiments are modified by average 21 data along the time steps, which are from 50 s-before to 50 s-after, at each time step. Broken line in Fig. 11 shows experimental data of temperature response at position-a for step heat generation +1 W of heater-B, and thin solid line shows averaging 21 data along the time steps. The noise error in the temperature response is reduced by averaging data along the time steps. Figure 12 shows the experimental result of the temperature change at the object position-a controlled with the averaged step response pattern. The temperature change at the object position-a is 0.08 ℃. The temperature change at the object position-a is defined as 95% width of the change of the experimental data. The temperature change at the object position-a in Fig. 12 has periodical error of 300 s period and it is similar to Fig. 7.

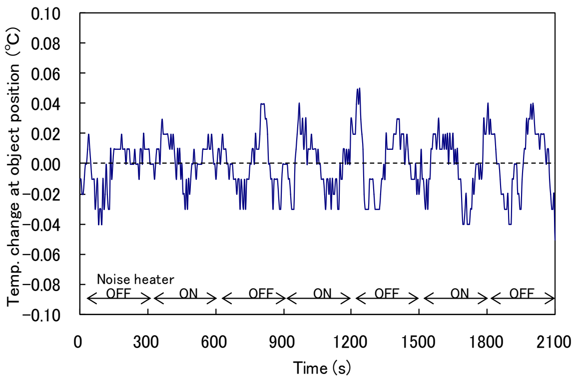

Fig. 12 Temperature change at position-a for control with averaged pattern

C. *Control with Step Response Pattern by Network Model Calculation*

A simple network model of the object is built as shown in Fig. 13. The calculation result of the step response pattern of the network model is used as the dynamic predictive model. Thermal properties and heat transfer coefficient are modified so that calculation result comes close to the experimental results. Thick solid line in Fig. 11 shows temperature response at position-a for step heat generation +1 W of heater-B. The step response pattern shifts entirely from the experimental result before 300 s. Figure 14 shows the experimental result of the temperature change at the object position-a controlled with the dynamic predictive model obtained by the network model calculation. The temperature change at the object position-a is 0.07 ℃. The step response pattern obtained by the calculation is very smooth without random noise but it has some modelling errors entirely. The temperature change at the object position-a has periodical error of 600 s period in Fig. 14. The temperature change at the object position-a in Fig. 14 is similar to Fig. 6. So we think that the error at time from 0 s to 75 s in the step response pattern of heater-B caused the periodical error of the temperature change at the object position-a.

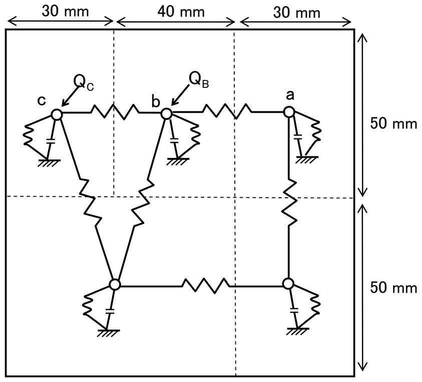

Fig. 13 Network model

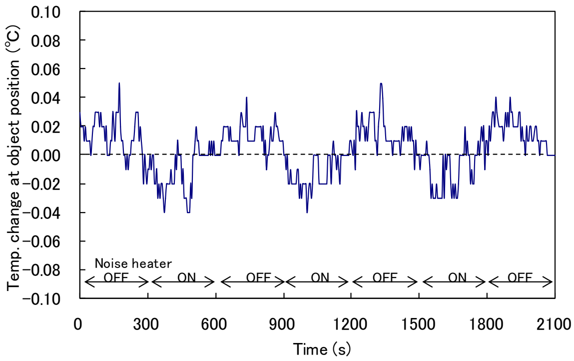

Fig. 14 Temperature change with pattern by network model calculation

D. Control with Combined Step Response Pattern by Experiments and Network Model Calculation

The step response pattern obtained by the network model calculation is smooth without random noise, and so it is preferable to use the dynamic predictive model of noise-heat-generation at the position C. The averaged step response pattern obtained by experiment is accurate entirely even though it has random noise, and so it is preferable to use the dynamic predictive model of control-heat-generation at the position B. Both step response patterns are combined to use. Figure 15 shows the experimental result of the temperature change at the object position-a. The temperature change at the object position-a is 0.06 ℃, which is 1/50 times smaller than that without control-heat-generation (3 ℃).

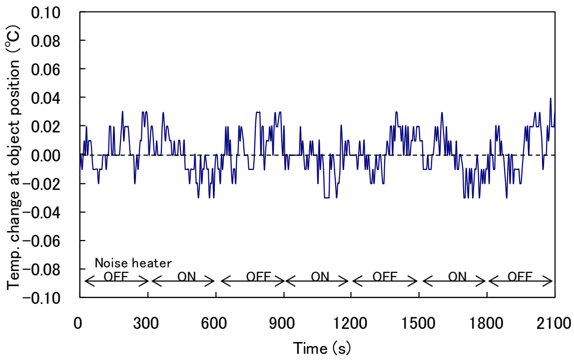

Fig. 15 Temperature change at position-a for control with combined pattern by experiment and calculation

VII. SUMMARY

The effect error in the dynamic predictive model of the model predictive control was examined analytically and experimentally to minimize temperature change at an object position in a 2-dimensional vertical plate with a varying noise-heat-generation, and following results were obtained.

(1) Artificial error in the dynamic predictive model causes various patterns of temperature change at the object position such as periodical error and oscillation error.

(2) The step response pattern obtained by experiment has the random noise error and averaging 21 data along the time steps is effective to reduce effect of the random noise error. Temperature change at the object position-a is 0.08 ℃ using the model

predictive control with the averaged step response pattern obtained by experiment. The temperature change at the object position has periodical error of 300 s period.

(3) The step response pattern obtained by the network model calculation is smooth without random noise but has some modelling errors entirely. The temperature change at the object position-a is 0.07 ℃ using the step response pattern obtained by the network model calculation. The temperature change at the object position-a has periodical error of 600 s period.

(4) When the step response patterns obtained by the network model calculation and experiment are combined to use, the temperature change at the object position-a is 0.06 ℃, which is 1/50 times smaller than that without control-heat-generation (3 ℃).

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Shigeki Hirasawa is Ph.D. from Department of Physical Engineering, Tokyo Institute of Technology, Japan. He is working as Professor in Kobe University, Japan. His area of research is thermal engineering and heat transfer in manufacturing process.

Kazuya Koike is M.Eng. from Department of Mechanical Engineering, Kobe University, Japan.

Tsuyoshi Kawanami is Ph.D. from Department of Mechanical Engineering, Hokkaido University, Japan. He is working as Associate Professor in Kobe University, Japan. His area of research is thermal engineering, refrigeration and air conditioning.

Katsuaki Shirai is Ph.D. from Fakultät Elektrotechnik und Informationstechnik, Technische Universität Dresden, Germany. He is working as Assistant Professor in Kobe University, Japan. His area of research is flow measurement and laser diagnostics.