

# A NOVEL APPROACH OF THERMAL PROCESS CONTROL FOR UNIFORM TEMPERATURE

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Abstract: Uniform temperature control of heating plate with a wide thermal conduction area is required in many industrial application fields. In this paper, a novel approach for uniform heating based on the physical property of thermal conduction is proposed. The main idea of the proposed scheme is to control the average and gradient temperatures between arbitrary points whereas in conventional way direct PID control is applied for each heating points. The control system provides the good uniformity not only in steady state but also in transient state. In order to confirm the effectiveness of the scheme, some experimental results are shown and evaluated. *Copyright©2005 IFAC*

Keywords: Temperature control, Thermal interaction, Uniformity, Gradient temperature

## 1. INTRODUCTION

In recent years, in equipments for thermal process, such as developing machines in semiconductor processes, packing machines, and forming/mould machines, management and control of the temperature will be an important issue. Especially in semiconductor processes, the improvement of thermal uniformity is required severely.

In thermal processes heated by the wide heating plate, variance of temperature on the conduction surface is observed in both steady state and transient state. In the steady state, variance of temperature can be suppressed with simple PID controller by fine design of the machines and parameters tuning. Temperature variation in transient state is caused by thermal conduction from the heaters to products. As heating plate is usually attached to enclosure, the thermal inertia is different on each point. This phenomenon is observed drastically in the case that heating plate is wide and thin. From the viewpoint of production, the thermal processing time should be controlled and managed for quality improvement because the thermal energy causing the chemical reaction depends on the temperature and heating time. So, it is required to make the temperatures uniform

on the heating plate as thoroughly as possible, and to shorten the processing time.

For minimizing the variance of temperature, the plate is heated by many heaters, and PID controller is usually applied in each heater as increase of heated product size(Kailath, 1999). However, the thermal interaction among the heaters makes the system quite nonlinear (Seborg, 1989). Also, the nonlinearity of the system depends on the machines and applications, i.e. the shape of heating surface, heater arrangement, dead time, thermal conduction ratio and convection and so on. Thus, it is difficult to realize the precise temperature control system based on conventional PID controllers.

For this difficulty, decoupling control method has been investigated in process engineering (Maciejowski, 1989). Main idea of decoupling control is to compensate the thermal interaction among heaters by decouplers. But, such a decoupler cannot be realized when it contains prediction and ideal derivative terms. Also, the precise identification and modeling of system are quite complicated. So, in general practical applications, statical or partial decoupling using low order information of thermal interaction has been studied considering the trade off of precision and stability.

However, in many cases, such a static or partial decoupling control provides cheap uniformity in the transient state.

In this paper, a novel approach for uniform heating based on the physical properties of thermal conduction is proposed. The main idea of the proposed method is to control the average and gradient temperatures on the surface in order to suppress the thermal interaction among heaters. As a result, the temperature on the heating plate is uniformed not only in steady state but also in transient state. In order to confirm the effectiveness of the proposed method, experimental results are shown and evaluated.

## 2. CONVENTIONAL CONTROL

In the industrial thermal processes, quality of the thermal process is required severely. Especially, temperature control in transient state is important. Fig.1 illustrates a generating mechanism of a transient variation. In the figure, when the outer-side of heat plate is attached to the enclosure, the thermal inertia in outer-side will be bigger than the one in inner-side, and heat flows to the enclosure. Hence, non-uniformity of temperature arises in transient state between the inner-side area and the outer-side area on the heating plate as shown in Fig.2, where PV and SP indicate the present temperature and the reference temperature, respectively. In practical ap-

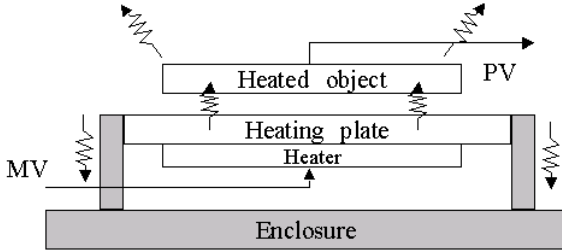


Fig. 1. Construction of heating plate

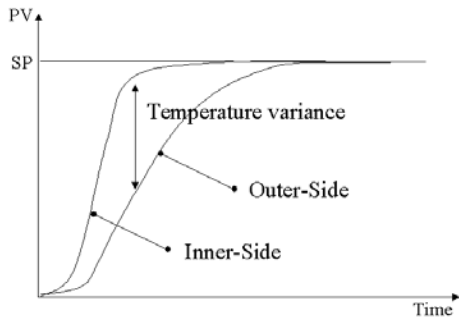


Fig. 2. Temperature variation on heating plate

plications, multi-point temperature controls have been challenged to make the temperature uniform, where PID control with sequential loop closing (Maciejowski, 1989) was conventionally used as

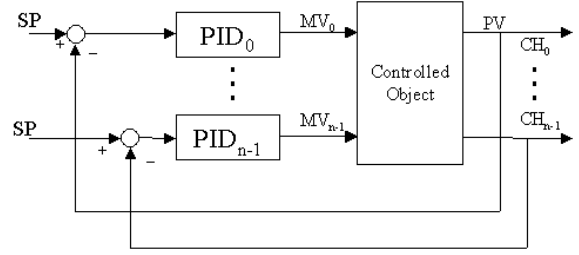


Fig. 3. Block diagram of conventional PID scheme with sequential loop closing

shown in Fig.3. In the figure, the output of  $i$  th -PID controller,  $MV_i$ , affects to the output  $CH_j$  as disturbance. In order to achieve the uniformity, much effort must be paid to adjust the controller parameters. Additionally, modeling of thermal interaction and the parameter adjustment will be difficult because the model parameters change due to reference temperature, the plate and products and environments.

Decoupling control method has been often applied to the system with strong thermal interaction (Maciejowski, 1989). Main idea of decoupling control is to cancel the thermal interaction terms using proper decouplers and to re-construct the plant so as to control easily by PID controllers. It is well known that decoupler cannot be realized when it contains prediction and ideal derivative terms. For this, static decoupling or partial decoupling with low frequency characteristics have been applied to practical applications to guarantee the robust stability.

Detail discussions are omitted, but it was reported that the decoupling control does not provide satisfactory results in terms of uniformity in transient (Suenaga, 2003). Therefore, a new control scheme for uniform heating which is easy to apply to the practical applications is required.

## 3. A NEW SCHEME FOR UNIFORM TEMPERATURE CONTROL

In order to uniform temperature in transient state, a new approach based on physical properties of thermal conduction will be illustrated using a simple impedance model. It is noted that the impedance model cannot express the behavior of system in all frequency because the impedance is defined in arbitrary frequency  $\omega_p$ . However, it will be useful to consider the new scheme.

Fig.4 shows a heat plate model with two-input two-output. In the figure,  $MV1$ ,  $MV2$  and  $PV1$ ,  $PV2$  are inputs and outputs, respectively. In thermal applications, as the heaters are attached to the thermal plate, time constant  $T_A$  of the interaction dynamics between two heaters is smaller than the time constant of whole plate  $T$ , i.e.,

it is generally assumed that  $T_a \ll T$ . Fig.5 is

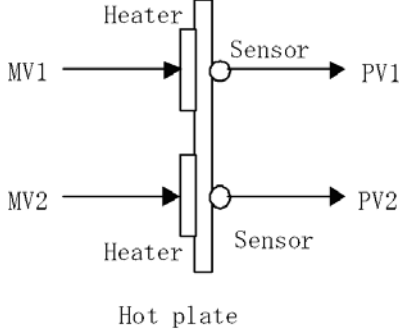


Fig. 4. 2-input 2-output thermal interaction model

the impedance model of Fig.4 at arbitrary frequency  $\omega_p$ . In the figure,  $MV$ ,  $PV$  are expressed by the current  $I$  and voltage  $V$ , respectively.  $I_A$  means the thermal flow between two heaters. And, the thermal impedances of heater1 and heater2 are expressed as  $Z_1$  and  $Z_2$ , and the thermal impedance between heater1 and heater2 is expressed as  $Z_A$ . In the physical property of thermal

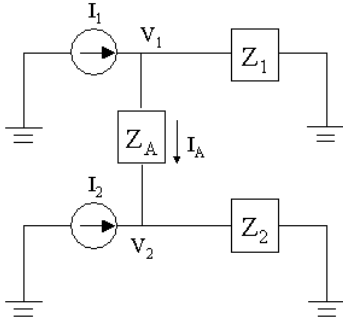


Fig. 5. Impedance expression of Fig.4

conduction, thermal flow  $I_A$  is zero in case that  $V_1 = V_2$ . This implies that the thermal interaction of the system can be reduced by regulation of difference of temperature between two points.

The difference of temperature between two heaters is expressed as follows.

$$\begin{aligned} t_{grad} &= V_1 - V_2 = \frac{Z_1 I_1 - Z_2 I_2}{Z_1 + Z_2 + Z_A} Z_A \\ &\approx \frac{Z_1 Z_A}{Z_1 + Z_2} I_1 - \frac{Z_2 Z_A}{Z_1 + Z_2} I_2 \end{aligned} \quad (1)$$

which we call as ‘‘gradient temperature’’.

The average temperature  $t_{ave}$  of two heaters is as

$$\begin{aligned} t_{ave} &= \frac{V_1 + V_2}{2} \\ &= \frac{Z_1}{2} \left(1 - \frac{Z_1 - Z_2}{Z_1 + Z_2 + Z_A}\right) I_1 \\ &\quad + \frac{Z_2}{2} \left(1 + \frac{Z_1 - Z_2}{Z_1 + Z_2 + Z_A}\right) I_2 \end{aligned} \quad (2)$$

When  $Z_1 \approx Z_2$ , i.e. the characteristics of two heaters are almost equivalent, the followings are obtained from eq.(1) and eq(2).

$$t_{grad} \approx \frac{Z_A}{2} (I_1 - I_2) \quad (3)$$

$$t_{ave} \approx \frac{Z_1}{2} (I_1 + I_2) \quad (4)$$

Thus,  $t_{grad}$  is mainly affected by interaction impedance  $Z_A$ , and the average temperature  $t_{ave}$  is affected by  $Z_1$ .

In case that the interaction impedances  $Z_A$  are large and the impedance  $Z_1$  and  $Z_2$  are small, the time constant  $T_a$  is small. So, slow mode of average and fast mode of gradient are appeared in the response. As  $t_{grad}$  means thermal variance on the surface, it is required to control  $t_{grad}$  to zero as fast as possible in transient state for uniform heating.

Thus, we will divide the control objective into two sub-objectives, explicitly (Nanno, 2002).

- (1) The gradient temperature between arbitrary two points is controlled to zero for minimizing the thermal interaction.
- (2) The average temperature of arbitrary points is controlled to the reference.

Direct feedback of gradient temperature provides the uniformity of dynamics at controlled points. Furthermore, uniformity of temperature prevents the thermal flow between the controlled points. This implies that control of the gradient temperature can suppress the thermal flow and will be effective to thermal process with strong thermal interaction.

### 3.1 A New Uniform Temperature Control System

The block diagram of the proposed temperature control system is shown in Fig. 6. The temperature controller consists of PID controllers, mode-converter  $G_m$  and pre-compensator  $G_c$ . Mode-converter  $G_m \in R^{n \times n}$  has the function of converting the measured temperature into the average and gradient temperatures, where  $n$  is the number of control channels. The references are given as reference average and reference gradient of temperature.

Let the temperature in the point  $x_i$  is measured as  $t_i$ . Then the average temperature of all points  $t_{ave}$  and the gradient temperature between adjoining points  $t_{grad}$  can be expressed as follows,

$$t_{ave} = \sum_{j=0}^{n-1} t_j / n \quad (5)$$

$$t_{grad} = [t_1 - t_0, \dots, t_{n-1} - t_n] \quad (6)$$

From eqns.(5), (6), the mode-converter  $G_m$  is expressed as

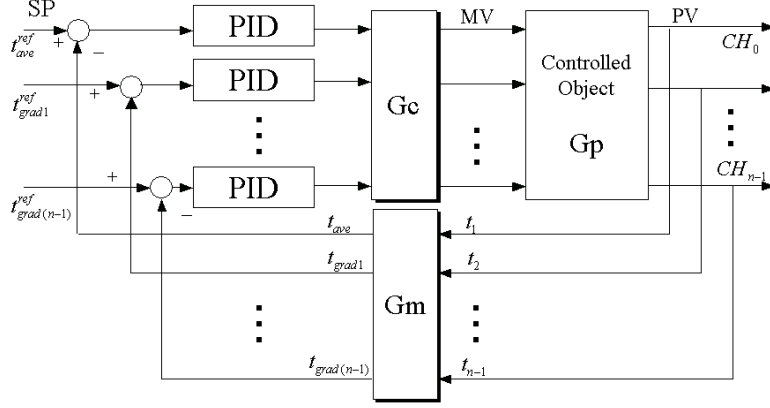


Fig. 6. Block diagram of proposed scheme

$$G_m = \begin{bmatrix} 1/n & 1/n & 1/n & \dots & 1/n \\ -1 & 1 & 0 & \dots & 0 \\ 0 & -1 & 1 & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & -1 & 1 \end{bmatrix} \quad (7)$$

Whereas, the reference vector  $t^{ref}$  consists of the reference average temperature and reference gradient temperature between arbitrary points as

$$t^{ref} = [t_{ave}^{ref}, t_{grad}^{ref}]^T \quad (8)$$

It is remarked that  $t_{ave}$  and/or  $t_{grad}$  can be selected arbitrarily under the condition discussed later.

### 3.2 Design of Pre-compensator $G_c$

Pre-compensator  $G_c$  has two functions ; the one is to convert the PID output to MV, and the other is to decouple thermal interaction in  $G_p$ . For the converting function,  $G_m$  is required to convert the PID output calculated from average and gradient of temperatures to real output MV.

In the design of control system, we regard  $G_m G_p$  as the extended plant with outputs of  $t_{ave}$  and  $t_{grad}$ . Then, pre-compensator  $G_c$  is designed so as to cancel the off-diagonal terms of the extended plant. A simple design of  $G_c$  is as follows

$$G_c = (G_m \cdot G_p)^{-1} \quad (9)$$

### 3.3 Modeling of $G_p$ and Design of $G_m$

When the step input is added to the controlled object in order, and the plant model  $G_p$  is obtained as transfer function matrix using the input/output relationship (Matsunaga, 2003). The  $(i, j)$  element of  $G_p$  is described as

$$G_{p_{ij}} = \frac{K e^{-L_{ij}s}}{T_{ij}s + 1} \quad (10)$$

As transient temperature uniformity is required in this paper, the constant matrix  $G_p(\omega_p)$  at cross over frequency  $\omega_p$  is used to design  $G_c$ . As the hunting cycle is a few times of time lag of the system,  $\omega_p$  can be determined roughly using the measured time lag, where the time lag is defined as a biggest delay among elements of the transfer function matrix.

Mode-converter  $G_m$  is selected so that the  $G_m G_p$  is nonsingular, and pre-compensator  $G_c$  is designed using eq.(9). In general, as heating elements and thermal sensors are collocated, the diagonal parts of  $G_p$  are dominant and the matrix will be nonsingular. However, in non-collocated case, we must pay attention to selection of  $G_m$  carefully (Nanno, 2004). From the viewpoint of construction of heating plate,  $t_{grad}$  should be selected so as to  $T_a$  will be small considering the geometric distance of points, heater power and thermal resistance, so that the gradient temperature should be control zero rapidly.

For determination of  $G_m$ , following points will be important.

- (1) Select the points for the gradient calculation where time constant of thermal interaction is small and time lags are close.
- (2) Define eq.(5), e.g. average of all points, zone average, arbitrary points, so as to  $G_m G_p$  is nonsingular.

### 3.4 PID Gains

The most important point of the proposed scheme is to minimize thermal interaction among many heaters by controlling the gradient temperature in arbitrary points. So, how to design PID gains for gradient control are important. Ziegler-Nichols, CHR and other traditional methods can be available to determine PID gains (Astrom and T.Hagglund, 1995).

#### 4. EXPERIMENTAL RESULTS

Fig.7 shows an experimental heater with strong thermal interaction which was used in this study. Seven heaters of 20W are arranged in line. The heating plate is made of aluminum and the size is  $140 \times 100 \times 4[mm]$ . Both ends of plate are attached to the enclosure made of iron. Seven of thermal sensors and heaters are arranged in line with separation distance  $15[mm]$ . The stick made of aluminum emulates the thermal disturbance.

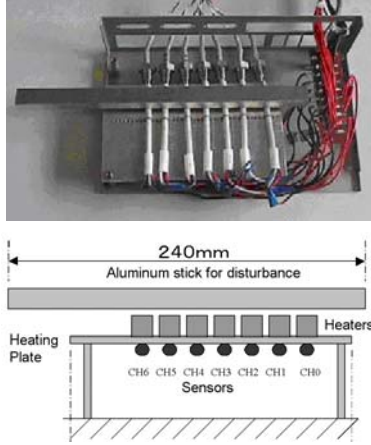


Fig. 7. Construction of plant

The reference of average is set to  $t_{ref}^{ave} = 120$  degrees centigrade. And the reference gradient is set to  $t_{ref}^{grad} = [0, 0, 0, 0, 0, 0]$ . The controller is implemented to multi-point temperature controller (type E5ZE by Omron). The control and sampling period is  $1.0[sec]$ . All the PID gains were determined by Ziegler-Nichols method.

The step responses using the conventional and the proposed methods are shown in Fig.8 and Fig.9, respectively. It is observed from these figures that the performance of convergence time is improved from  $200[s]$  to  $83[s]$ . Also, the disturbance re-

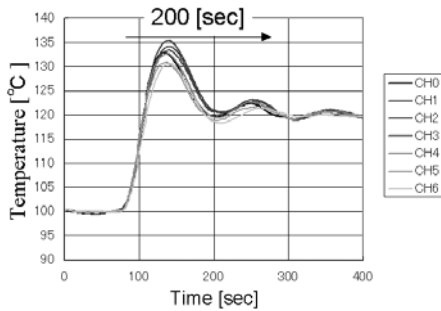


Fig. 8. Step response using the conventional control

sponses are shown in Fig.10 and Fig.11. In these figures, disturbance is added at the time  $80[s]$  by contacting the aluminum stick to the heaters. Comparing with these figures, it is observed that the convergence is improved from  $144[s]$  to  $63[s]$ . In Fig.10, large variation is observed in each point. Especially, the temperature at the point CH0 is

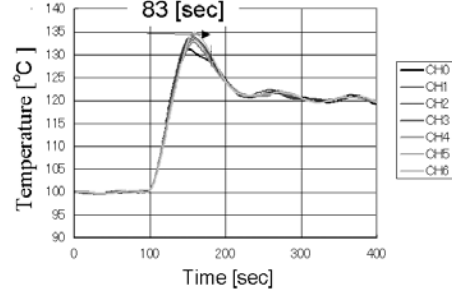


Fig. 9. Step response using the proposed control

quickly returned to the reference. Fig.11 shows that the variation is very small until  $50[s]$  after disturbance added. By the proposed temperature control, the temperature at the point CH0 behaves the cooperative action with other channels.

Fig.12 shows the maximum absolute of temperature variation comparing proposed controller with the conventional PID. The maximum absolute of temperature is defined as

$$\max T_{grad} = \max t_i - \min t_j \quad (i, j = 1 \sim 7) \quad (11)$$

The dashed and solid lines indicate the maximum variances using conventional method and the proposed method respectively, where the maximum variance is related to the thermal energy variation in production. From the figure, it is observed that the variation of the proposed method decreases to about half of one of conventional method area.

From the above experimental results, it is seen that the proposed control scheme gives great improvement in the performance of uniformity. This implies that it is expected that the proposed controller will provide good quality.

Finally, Fig.13 and Fig.14 show the difference of temperatures between adjacent points using conventional PID controller and the proposed controller, respectively. From these figures, it is observed that the proposed controller yields  $10 \sim 50\%$  reduction in the difference of temperatures over the conventional PID controller, and rapid uniformity can be achieved.

#### 5. CONCLUSION

In this paper, a new scheme of temperature controller for uniform heating has been proposed. The main idea of the proposed scheme is to control the average and the gradient of temperatures on the surface. The proposed scheme was applied to experimental in-line heater and the effectiveness for thermal interaction system was confirmed. The improvement of uniformity is achieved, e.g.  $43\%$  improvement in convergence time shortening and  $50\%$  improvement in thermal variance.

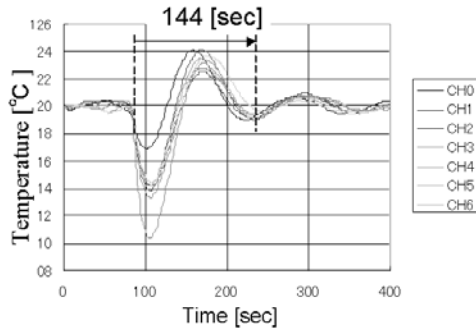


Fig. 10. Disturbance response using the conventional control

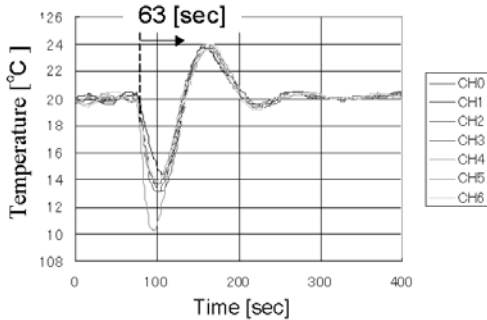


Fig. 11. Disturbance response using the proposed control

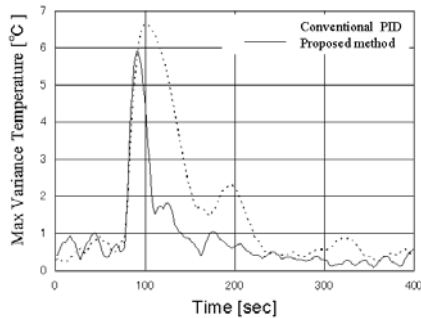


Fig. 12. Absolute of variance

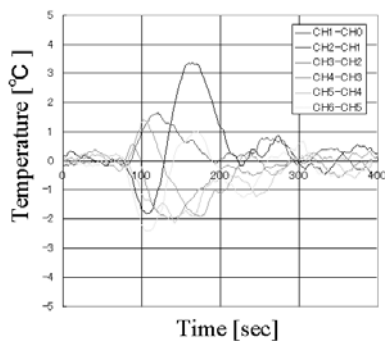


Fig. 13. Gradient temperature by conventional control

The feature of the proposed scheme is to divide the plant into two sub-systems by mode-converter  $G_m$ , i.e. slow-mode expressed by average and the fast-mode expressed by gradient. Although the idea in this method is simple, the controller can provide remarkable improvement. As the proposed method has the advantages that it can be implemented easily to traditional PID scheme, it is expected to be effective to distributed paramete-

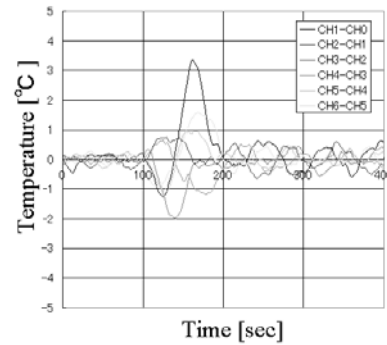


Fig. 14. Gradient temperature by proposed control

ter system and be used in the various applications. The proposed controller has been tested in the semiconductor processes and very high uniformity was obtained. The systematic design and experimental verification for the practical application will be the future investigation.

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