Temperature Control of Deionized Water Heater as a Class of Serial Processes

Kazuhiro MIMURA *, Tetsuo SHIOTSUKI **, and Shigeyasu KAWAI ***

Abstract: One of the important classes of MIMO processes is that of serial processes. We propose a combined control technique of PID control and disturbance observer for the temperature control of a deionized (DI) water heater that has the structure of a serial process. The results of both simulation and actual equipment experiment verify that the proposed method enables us not only to use fewer temperature sensors than the conventional system but also to solve the offset problem that is typical for the serial processes.

Key Words: serial process, PID control, temperature control, disturbance observer, robustness.

1. Introduction

Proportional-integral-derivative (PID) control is categorized as a “classical” control method. However, because of its simplicity, tractability, and yet powerful control ability, it is still the most widely used control technique in practical control systems [1].

One of the important classes of MIMO processes is that of serial processes in which multiple units having the same configuration are connected in series. These processes are very common in process industries, which enable their output to reach a further set point that is not achievable by a single control unit. A typical application is the neutralization performed in multiple tanks in series. Faanes and Skogestad [2] proposed a 3x3 MPC controller with a disturbance observer and applied to a pH neutralization process. Their method improved the MPC’s integral controller with a disturbance observer. The disturbance observer is not used for the ordinal purpose, that is, to cancel disturbance by the estimate and canceling disturbance. However, since the states of upstream units only affect the states of downstream units, the accumulation of the error for the upstream units causes an overcompensation of the downstream units, which finally causes the actuator saturation and offset of the final unit output. Such an offset problem that comes from the error accumulation and actuator saturation commonly appears in serial processes, but was not discussed in Faanes and Skogestad [2] because designing their controller needs an assumption of no constraints to derive the optimum of the control input [3].

A DI water heater supplies heated deionized (DI) water to a semiconductor cleaning machine, which has a structure of the serial process and hence has the same problem. The DI water heater consists of multiple units that have a heating function and heat up DI water to the desired temperature step by step. Therefore, if one unit cannot heat up with its limited power, other downstream units will compensate its shortage. However, if the necessary power is beyond the unit’s ability, its final output has an offset to the desired temperature. In addition to this problem, the DI water heater cannot have the outlet temperature sensor for each unit except the most downstream one due to the design and/or cost limitation.

In this paper, we propose a controller design for a class of serial processes that have an actuator saturation for each unit and an output sensor only at the most downstream. The proposed method consists of a PID controller for each unit and a disturbance observer. The disturbance observer is not used for the ordinal purpose, that is, to cancel disturbance by the estimate but is used to assign a proper command signal for each unit.

2. Serial Process

Faanes and Skogestad [2] defined a serial process as follows: A serial process can be divided into a series of sub-process or units, where the states in each unit depend on the states in the unit itself (xi), the states in the upstream unit (xi−1), and the exogenous variables (ui, di) to the unit.

We basically follow their definition but address two assumptions. A1. Disturbances are added to the inputs. A2. Each unit has actuator saturation.

Figure 1 shows the block diagram of the serial process defined above. Suffix i is a unit number. Transfer function G_{i1}(s) represents a transfer dynamics of mass and/or energy flow and G_{2i}(s) represents dynamics acting on the flow.

This structure is suitable especially when its desired value is much higher than the achievable value of single unit. However,
the accumulation of the error for the upstream unit cause to the over compensation of the downstream unit, which finally cause to the actuator saturation and offset of the entire system output. For example, let consider three unit 0, 1, and 2, are connected in series and each unit is controlled by PID controller, $C_0, C_1, C_2$, as shown in Fig. 2. Suppose each unit needs 70% of power to reach its desired value, $S V_0$. If the unit 1 had some trouble and could output only 20% of power, 50% of power will run short. In this case, the unit 2, that is downstream of the unit 1, has to compensate 50% of shortage because the error of the unit 1 affects to the unit 2. The unit 2, however, can only compensate 30% due to the actuator saturation and as a result the offset remains. On the other hand, the unit 0, that is the upstream of the unit 1, doesn’t care anything about the downstream and does nothing since its output reaches $S V_0$. To overcome this problem, all command value $u_0, u_1, u_2$ should be assigned properly under the model uncertainties.

Decoupling is one of the most popular topics to control MIMO system with multiloop PID controller [4]–[6]. So one would consider decoupling control applying to a serial process. However, decoupling control is not suitable for this process because this example shows the unit 0 can be regarded as a decoupled system and it is clear that the unit 0 can’t do any further compensation without adding extra functions to sense the downstream states.

3. Modeling

3.1 DI Water Heating System

Here, a DI water heating system will be introduced which is mainly used to supply heated DI water for silicon wafer cleaning equipment. Figure 3 shows a simplified sketch of the three-bottle heating system which consists of three heating units. One unit consists of a quartz bottle, six halogen lamps and a power module that includes output saturation. Each bottle has one inlet and one outlet for DI water flow, and they are connected in series. They are labeled as 0, 1 and 2 for upstream, mid-stream and downstream. The water flows inside of the bottles and heated by radiation from halogen lamp attached outside of the bottles. Each unit can supply heating power up to 24[kW] through the power module, whose input are also labeled as $p_i$, $i = 0, 1, 2$ (command value). The three-bottle heating system can supply maximum power of 72[kW] by using three heating units. These heating units can be manipulated independently.

The temperatures at the inlet and the outlet are labeled as $T_{in i}$ and $T_{out i}$. The connected tubes between each bottles are so short that the following constraints are addressed.

C1. Energy loss between bottles can be ignored, i.e. $T_{in i} = T_{out i}$, $T_{in 2} = T_{out 1}$

C2. Design and cost limitation prevents the direct measurement of $T_{out 0}$ and $T_{out 1}$.

If each temperature at the outlet of the bottle can be obtained three SISO-PID feedback control loops can be constructed and the temperature of each bottle can be controlled independently. But here we consider the case of only two temperature sensors : $T_{in i}$ and $T_{out i}$. Thus the three-bottle heating system can be considered as 3 inputs and 2 measurement outputs MIMO system with serial structure.

![Fig. 2 Serial process with independent controllers.](image)

![Fig. 3 Simplified sketch of a three-bottle heating system.](image)

3.2 Mathematical Model of a Single Heating Unit

Figure 4 shows a simplified schematic diagram of single heating unit which consists of a quartz bottle, halogen lamp heaters and a power module. $T_{in i}$ and $T_{out i}$ indicate the temperatures at the inlet and the outlet of the bottle-$i$. $p_i$ shows the command value to power module-$i$, and $\bar{p}_i$ the actual energy flow from halogen lamp heaters to DI water in the bottle-$i$. Here, the suffix $i$ indicates the position as 0: upstream, 1: mid-stream and 2: downstream.

We address the following assumptions.

A3. There is no heat loss on the surface of the bottles.

A4. All the bottles have the same physical characteristics.

Applying the lumped capacitance method [7] the following energy balance equation is obtained.

\[
V_p C_p \frac{dT_{out i}(t)}{dt} = \bar{p}_i (t - \tau_2)
\]

\[-q_p C_p (T_{out i}(t) - T_{in i}(t - \tau_1)) \quad i = 0, 1, 2 \quad (1)
\]

where the variables and the parameters are listed in Tables 1 and 2, respectively. Moreover the dynamics of halogen lamp heater is assumed as FOPD (First Order plus Delay)

\[
T_p \frac{d\bar{p}_i(t)}{dt} = \bar{p}_i(t) - p_i(t - \tau_0), \quad |p_i(t)| \leq p_{MAX} \quad (2)
\]

The Laplace transform of (1)(2) give us the following equations, where saturations of $p_i$’s are ignored because the inputs to the plant are automatically restricted by the PID controller.
3.3 Empirical Model of a Single Heating Unit

In order to identify the parameters in (3), two step response experiments were conducted. The first experiment was arranged to get the characteristic from the inlet temperature \( T_{in} \) to the outlet temperature \( T_{out} \), and the second, from the power module command \( p_i \) to the outlet temperature \( T_{out} \). Figure 6 (a) shows the experimental setups for the first experiment. Heated DI water and unheated DI water were switched by switching valve and the temperatures at the inlet and the outlet were measured simultaneously. The time constant of the temperature sensors are less than 0.5[sec], which is small enough to be ignored for total dynamics. Figure 6 (b) shows experimental setup for the second experiment. Step command signal was applied to the power module and the response of the outlet temperature was measured.

The results were normalized and approximated to the FOPD model, and then compared with the mathematical model. Figure 7 (a) shows the experimental measurements \( T_{out}(t) \) (bold line) and the time response of FOPD empirical model, \( G_{emp}(s) \) (thin line) with the parameters listed in Table 3. The time constant of the empirical model, \( T_{em1} = 15.7[sec] \), is fairly close to the time constant of the mathematical model, \( T_{th} = 16.8[sec] \).

Figure 7 (b) shows the response from the power module command \( p_i \) to the temperature at the outlet. In previous sections \( G_{in}(s) \) was derived as second order system. But in order to make the design procedure simple we adopt a FOPD approxi-

![Fig. 4 Schematic diagram of one heating unit. Water flow and energy flow.](image)

![Fig. 5 Block diagram of quartz bottle with halogen lamp heater.](image)

![Fig. 6 Experimental set up for two step response test: (a) Response of outlet temperature to inlet temperature and (b) response of outlet temperature to lamp heater power.](image)
mated transfer function model $G_{em2}(s)$. The gain of the $G_{em2}(s)$ is equal to the gain of the mathematical model, $G_{th2}$, which is $K_{th}$.

From these results, the empirical model is expressed as a sum of two FOPD models, with the parameters listed in Table 3,

$$T_{out}(s) = \frac{1}{T_{em1}s + 1} e^{-\theta_1 s} T_{in}(s) + \frac{K_{th}}{T_{em2}s + 1} e^{-\theta_2 s} p(s)$$

$$= G_{em1}(s) T_{in}(s) + G_{em2}(s) p(s). \quad (7)$$

Table 3 Parameters of heating unit.

<table>
<thead>
<tr>
<th>notation</th>
<th>description</th>
<th>value</th>
<th>unit</th>
</tr>
</thead>
<tbody>
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<td>$T_{em1}$</td>
<td>Time constant of $G_{em1}$</td>
<td>15.7</td>
<td>[sec]</td>
</tr>
<tr>
<td>$\theta_1$</td>
<td>Time delay of $G_{em1}$</td>
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<td>[sec]</td>
</tr>
<tr>
<td>$T_{em2}$</td>
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<td>[sec]</td>
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<td>$\theta_2$</td>
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<td>[sec]</td>
</tr>
<tr>
<td>$K_{th}$</td>
<td>Gain of $G_{em2}$</td>
<td>9.61E-4</td>
<td>[°C/W]</td>
</tr>
</tbody>
</table>

### 3.4 Model for Control Design

To design disturbance observer and PID controller, we define a model for control design by expressing (7) through multiplicative uncertainty.

$$T_{out}(s) = \frac{1}{T_{em1}s + 1} e^{-\theta_1 s} T_{in}(s) + \frac{K_{th}}{T_{em2}s + 1} e^{-\theta_2 s} p(s)$$

$$= \frac{1}{T_{em2}s + 1} \left[ 1 + \frac{K_{th}}{T_{em2}s + 1} e^{-\theta_2 s} - 1 \right] T_{in}(s)$$

$$+ \frac{K_{th}}{T_{em2}s + 1} \left[ 1 + \left( e^{-\theta_2 s} - 1 \right) \right] p(s)$$

$$= \frac{1}{T_{em2}s + 1} \left[ (1 + \delta_1(s)) T_{in}(s) + (1 + \delta_2(s)) K_{th} p(s) \right]$$

$$= G_{de}(s)(T_{in}(s) + K_{th} p(s)) + \Delta, \quad (8)$$

where

$$G_{de}(s) = \frac{1}{T_{em2}s + 1}$$

$$\Delta = G_{de}(s) (\delta_1(s) T_{in}(s) + \delta_2(s) K_{th} p(s)). \quad (9)$$

Here, we exclude time delays, $\theta_1$ and $\theta_2$, and equalize time constant of two transfer functions, $T_{em1}$ to $T_{em2}$ in order to reduce the model order. The effect of this model uncertainty on the stability of entire system is considered later in section 4.5.

### 3.5 Model of the Three-Bottle Heating System

The three-bottle heating system model is considered here. It has three command inputs for power modules $p_i$, $i = 0, 1, 2$, and one water flow input where inflow temperature is $T_{in}(= T_{s1})$, which is assumed constant. The temperature of the outflow water $T_{out2}$ is obtained through the temperature sensor which has dynamics as

$$T_{out} = \frac{1}{T_{sen}s + 1} T_{out2} = G_{sen}(s) T_{out2} \quad (10)$$

where $T_{sen}$ is sensor output and $T_{out}$ is time constant of temperature sensor that value is 11[sec].

The block diagram of three-bottle heating system is shown as Fig. 8. Three empirical models (7) and temperature sensor (10) are connected in series. This model is used as an actual plant model in simulation.

![Block diagram of three-bottle heating system as the actual plant model.](image)

Fig. 8 Block diagram of three-bottle heating system as the actual plant model.

For disturbance observer design, three nominal models (8) and temperature sensor (10) are connected in series as shown in Fig. 9.

![Block diagram of three-bottle heating system to design disturbance observer.](image)

Fig. 9 Block diagram of three-bottle heating system to design disturbance observer.

This plant model can be described by a state space form as

$$\dot{x}(t) = A_{de} x(t) + B_{de1} u_1(t) + B_{de2} u_2(t)$$

$$y(t) = C_{de} x(t) \quad (11)$$

where

$$y = T_{out2},$$

$$u_1 = \begin{bmatrix} p_0 & p_1 & p_2 \end{bmatrix}^T, \quad u_2 = T_{in0},$$

$$A_{de} = \begin{bmatrix} A_{de1} & A_{de2} & A_{de3} \\ A_{de4} & A_{de5} & A_{de6} \\ A_{de7} & A_{de8} & A_{de9} \end{bmatrix},$$

$$B_{de1} = \begin{bmatrix} B_{de11} & B_{de12} & B_{de13} \end{bmatrix},$$

$$B_{de2} = \begin{bmatrix} B_{de21} & B_{de22} & B_{de23} \end{bmatrix},$$

$$C_{de} = \begin{bmatrix} C_{de1} & C_{de2} & C_{de3} \end{bmatrix}.$$
reference temperature, TSV can be considered as a sum of equilibrium relation and its deviation (14). and

heaters should supply appropriate energy depending on the temperature simple, we chose equal energy assignment in this study. However, to make the controller structure simple, we chose equal energy assignment in this study. Temperature difference between TSV and Tin is divided by the number of heating unit so that each heating unit controls equal temperature difference. For example, if the TSV is 65[°C] and Tout is 20[°C], the TSV0 is 35[°C] and the TSV1 is 50[°C]. G(x) is a temperature sensor model for mid- and upstream heating unit. It has the same dynamics as the actual temperature sensor expressed by Eq. (10).

Assuming that the constant input \([u_1, u_2]^T = [0, T_{in}]^T\) drives the entire system to the equilibrium point. The equation (11) can be considered as a sum of the equilibrium relation and its deviation such that \(x = x_{eq} + \delta x, u = u_{eq} + \delta u, y = y_{eq} \). For simplicity, we use the notations as \(\delta x \rightarrow x, \delta y \rightarrow y, \) and \(\delta u \rightarrow u\). Thus, the deviation system is represented as equation (14).

\[
x(t) = A_{dx} x(t) + B_{dx1} u_1(t)
y(t) = C_{dx} x(t)
\]

4. Controller Design

4.1 Strategy of Control Design

The requirement of the control system is to drive the outlet temperature, Tout from initial value, in general it is Tin, to reference temperature, TSV as fast as possible. Moreover the controller is required to be robust with respect to unexpected variation of power supply voltage and/or failure of electrical heater. Tin is measurable but not manipulatable. Thus the heaters should supply appropriate energy depending on the temperature difference Tout - Tin.

Here we adopt a combination of traditional PID control, state/disturbance observer that estimates disturbance and unmeasurable temperature and set-point distributor which assigns bottle output references.

4.2 Structure of Control System

Figure 10 shows the block diagram of three-bottle DI water temperature control system. Each heating unit has PID controller that heats up DI water up to its set point, TSVi calculated by a set point distributor. The heating unit of the top (downstream) has the outlet temperature sensor to feedback the outlet temperature to the PID controller. In this study, the rest of two heating units, midstream and upstream use estimated outlet temperature by observer. In this way, we are able to use outlet temperatures for all heating units. There are various ways to assign set point for the each heating unit to achieve optimal energy distribution. However, to make the controller structure simple, we chose equal energy assignment in this study. Temperature difference between TSV and Tin is divided by the number of heating unit so that each heating unit controls equal temperature difference. For example, if the TSV is 65[°C] and Tin is 20[°C], the TSV0 is 35[°C] and the TSV1 is 50[°C]. G(x) is a temperature sensor model for mid- and upstream heating unit. It has the same dynamics as the actual temperature sensor expressed by Eq. (10).
ues and then all command values settle equal values.

laborate. The integrated error compensates for all heating units
cases. As shown Fig. 13, let consider the plant model to be con-
Figure 12 shows the structure of the disturbance observer.
Since we assume that an equal disturbance is added to the all
inputs, the number of the integrator is only one. This structure
enables the effect that the all actuators behave as if they col-

![Image](image1)

**Fig. 11** Block diagram of the three-bottle heating system with disturbance.

$$
\begin{bmatrix}
T_{\text{err}0}(t) \\
T_{\text{err}2}(t) \\
T_{\text{err}4}(t) \\
T_{\text{err}6}(t)
\end{bmatrix}
A_d =
\begin{bmatrix}
a_1 & 0 & 0 & 0 & a_2 + a_3 \\
a_2 & a_1 & 0 & 0 & a_3 \\
0 & a_2 & a_1 & 0 & a_3 \\
0 & 0 & a_5 & a_4 & 0 \\
0 & 0 & 0 & 0 & 0
\end{bmatrix}
$$

where \( a_1, a_2, a_3, a_4, a_5 \) are the same as (13),

$$
\begin{bmatrix}
a_1 \\
a_2 \\
a_3 \\
a_4 \\
a_5
\end{bmatrix}
= \begin{bmatrix}
1/T_{\text{em}2} \\
0 \\
0 \\
0 \\
0
\end{bmatrix}
$$

![Image](image2)

**Fig. 12** Disturbance observer structure.

where \( K_{\text{th}} \) and \( T_{\text{em}2} \) are gain and time constant of the nominal
model, \( G_{\text{de}} \) and \( T_{\text{sen}} \) is time constant of the temperature sensor.
According to the [10], the plant model (19) is

$$
G_p(s) = \frac{K_{\text{th}}}{(T_{\text{em}2}s + 1)(T_{\text{sen}}s + 1)}, \quad G_p(s) = 1
$$

(21)
since the model has no positive zero and/or time delay. With a
low pass filter, \( F(s) = \frac{1}{a s + 1} \), the IMC controller \( G_{\text{IMC}}(s) \) is

$$
G_{\text{IMC}}(s) = \frac{1}{G_p(s) \lambda s + 1} = \frac{(T_{\text{em}2}s + 1)(T_{\text{sen}}s + 1)}{K_{\text{th}}(\lambda s + 1)}
$$

The IMC structure can be modified to a simple closed loop
structure.

$$
\frac{G_{\text{IMC}}(s)}{1 - G_{\text{IMC}}(s) G_p(s)} = \frac{G_p^*(s)^{-1} F(s)}{1 - G_p(s) F(s)}
\frac{1}{\frac{(T_{\text{em}2}s + 1)(T_{\text{sen}}s + 1)}{K_{\text{th}}(\lambda s + 1)}}
\frac{1}{1 - \frac{K_{\text{th}}}{\lambda s}}
$$

Comparing (23) with the PID controller,

$$
C(s) = K_p (1 + \frac{1}{T_i s} + T_d s),
$$

where \( K_p \) is proportional gain, \( T_i \) is integral time, and \( T_d \) is
derivative time, PID parameter can be derived as

$$
K_p = \frac{1}{K_{\text{th}} A}, \quad T_i = T_{\text{em}2} + T_{\text{sen}}, \quad T_d = \frac{T_2 \cdot T_{\text{sen}}}{T_{\text{em}2} + T_{\text{sen}}}
$$

![Image](image3)

**Fig. 13** IMC-PID controller and plant model.

\[\text{SICE JCMSI, Vol. 3, No. 4, July 2010}\]

**4.4 PID Controller Design**

Since we have the plant model, IMC-PID tuning [10] is suit-
able design method. Compare to the other method, it is easy to
tune because we can adjust only a filter parameter, \( \lambda \) in many
cases. As shown Fig. 13, let consider the plant model to be con-
trolled is the heater side of the nominal model (8) with sensor
model, which is second order.

$$
G_p(s) = \frac{K_{\text{th}}}{(T_{\text{em}2}s + 1)(T_{\text{sen}}s + 1)}
$$

(19)
As noted before, the nominal model Eq. (11) is used for designing observer. This yields model uncertainty between the nominal model and the actual plant. At the same time, the fluctuations of the lamp power, flow rate, and power supply voltage in the actual plant cause to the additional uncertainty of the time constant, gain, and time delay. To investigate the robust stability of the whole system, three kinds of model uncertainties (time constant, gain, and time delay) were considered. Figure 14 shows total control system. The plant and sensor consist of three-bottle heating system as shown in Fig. 8, where we add the model uncertainties to the empirical model. The PID controller and the disturbance observer are the same as (24) and (17), respectively.

Plus or minus 20% of fluctuations of the time constant and gain were considered, which are reasonable value for the actual plant. For the time delay, five times as long as the nominal value was considered. This results eighteen combination of model uncertainties. Figure 15 shows Nyquist plots of the open-loop transfer function for each heating unit. Solid line shows the nominal plant and dotted line shows the worst case of eighteen combinations, which is 120% of nominal plant gain, 80% of nominal time constant, and 500% of nominal time delay. All plots show enough stability margins [11]. Even though the time delay is five times longer than the nominal value the disturbance

Fig. 15 Nyquist plots of the open loop transfer function for each heating unit (a) unit2 (in2 to $T_{out2}$) (b) unit1 (in1 to $T_{out1}$) (c) unit0 (in0 to $T_{out0}$), and two circles representing sensitivity Ms 1.3 and 2.0.

Fig. 16 Comparison of simulation results: (a) Proposed method and (b) actual outlet temperature feedback.
The case of disturbance observer, (a), using actual outlet temperature feedback. At 100[sec] after the outlet temperature reached to the set point, the lamp heaters of the middle unit are all off. The set point of the top bottle is 63[°C]. Figure 17 shows the case of disturbance observer, (a), using actual outlet temperature of each heating unit, (b), respectively. The actual experiment result showed that case (a) had robustness against burn out of the lamp heater. Despite the two-heating unit operation, the outlet temperature $T_{\text{out},2}$ recovers to the set point about 150[sec] after the burn out, behaving as if two heating units collaborate. On the other hand, case (b), $T_{\text{out},2}$ could not reach the $T_{\text{SV2}}$ because the PID controller for the heating unit 0 had reached set point and could not compensate a shortage of the lamp heater power.

6. Actual Equipment Experiment Results

Using the actual equipment, the same experiment as simulation was conducted. Figure 17 shows the result of lamp heater failure experiment. In the same as the simulation, at 100[sec] after the outlet temperature reached to the set point, the lamp heaters of the middle unit are all off. The set point of the top bottle is 63[°C]. Figure 17 shows the case of disturbance observer, (a), using actual outlet temperature of each heating unit, (b), respectively. The actual experiment result showed that case (a) had robustness against burn out of the lamp heater. Despite the two-heating unit operation, the outlet temperature $T_{\text{out},2}$ recovered to the set point about 150[sec] after the burn out, behaving as if two heating units collaborate. On the other hand, case (b), $T_{\text{out},2}$ could not reach the $T_{\text{SV2}}$ because the PID controller for the heating unit 0 had reached set point and could not compensate a shortage of the lamp heater power. In conclusion, the proposed method has superior robustness.

7. Conclusion

We have proposed a combined technique of PID control and disturbance observer that is effective for MIMO plants with a series structure. We applied the proposed method to the temperature control of the DI water heater. The results of both simulation and actual equipment experiment verified that the proposed method enabled us not only to use fewer temperature sensors than the conventional system but also to have robustness by balancing actuations against model uncertainty of a lamp heater such as a nonlinear input-output relation, power variation, and sudden burnout.

References


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