A Combined Lookup Table and PI-type Controller for Temperature Control of Thermal Process

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Abstract: This paper presents a combined lookup table technique and PI-type controller. The purpose of the designed controller is applied to control the nonlinear system as thermal process. The proposed controller is easy and convenient to design based on a commercial controller**.** The performances of the proposed controller were studied using the thermal plant model under temperature control. The experimental results included demonstrate the good performance of the proposed controller.

Keywords: feed forward control, PI control, lookup table, temperature control

1. INTRODUCTION

The main purpose of a control system is basically to force the output to follow a reference input with zero steady state error while satisfying certain transient requirements such as the settling time, overshoot, and smoothness of the transient response. Usually, a step or ramp function is used as the reference input. As long as the settling time is short enough, the output can follow any reference input with sufficiently small error. In general, the nonlinear control systems such as temperature control must be investigated on a case by case basis. With the complexity of the heat transfer behavior and long transport delay, the large overshoot and the long rise time may be achieved from the feedback control based on the PID controller. Thus, the feedback control system individually cannot provide the control accuracy without an auxiliary feedforward loop [1]-[4]. The feedforward control measures the disturbances before they enter the process and calculates the required value of the manipulated variable to maintain the controlled variable at its desired value or set point. If the calculation is performed correctly, the controlled variable should remain undisturbed. An application of statistical method based on the lookup table technique can improve the control accuracy [5]-[7].

This paper aims to present the combined controller based on the same principle as in [6]-[7]. However, we develop this idea in a different way to control the temperature of the thermal process that can provide a simple and fast response control using the commercial controller, Yokogawa Electric corporation's Single Loop Programmable Controller (SLPC) [8]. The proposed controller has two modes to control the temperature of thermal process, one is lookup table mode and the other is PI-type control mode. The feedforward control based on the lookup table technique is designed to reduce the delay time while the feedback control based on the PI-type control is applied to achieve the target temperature. The thermal plant model at Process Control Laboratory, King Mongkut's Institute of Technology Ladkrabang (KMITL), Thailand, is used to study the performances of the designed controller, i.e. rise time, fall time and overshoot. The experimental results verify that the proposed controller outperforms (more smoothness and faster response) the system using only the PI-type control**.**

2. TEMPERATURE CONTROL LOOP

The studied thermal plant model under temperature control and its sketched overall structure are shown in Fig. 1 and Fig. 2, respectively. The objective is to maintain the output temperature of the thermal plant model or the oven $T_o(t)$ at its desired value or set point $T_{set}(t)$. The output temperature or controlled variable is monitored and recorded using a thermometer (TI102) and a recorder (TR101), respectively. The phase control is applied to adjust the electric voltage $v_p(t)$ supplied to the oven heating element. The electric current $i_p(t)$ related to the electric voltage passes through the oven heater thus generating heat or the input temperature $T_i(t)$. A thermostat in the system is used to keep the temperature lower than the preset maximum value (200°C). The electric fan is installed to circulate air throughout the oven.

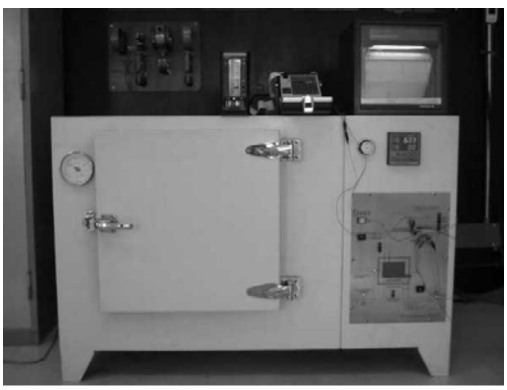


Fig. 1 The studied thermal plant model

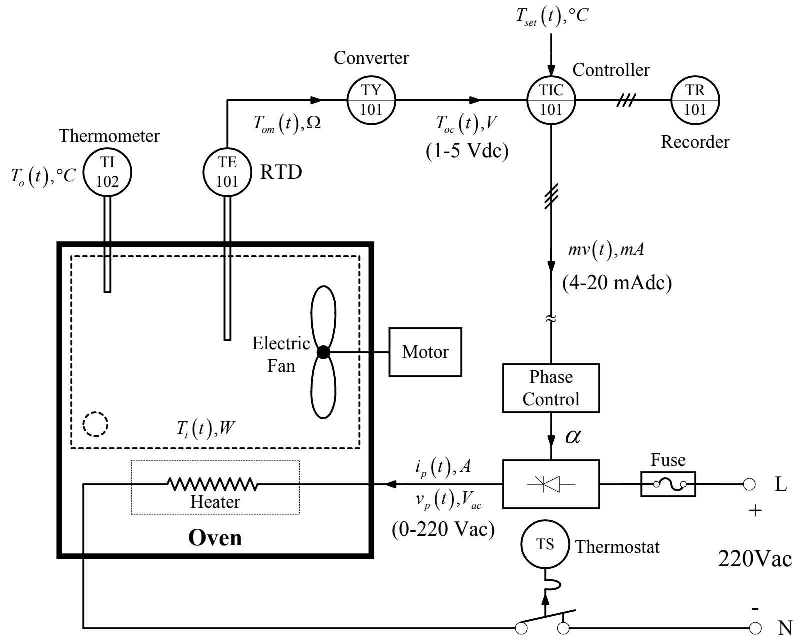


Fig. 2 Temperature feedback control loop

The feedback control scheme works as follows: the output temperature or controlled variable $T_{om}(t)$ is measured using a sensor RTD (TE101) and a converter (TY101) to generate a signal $T_{oc}(t)$ that is proportional to the oven temperature. The converted signal $T_{oc}(t)$ is sent to the controller (TIC101) using the programmable commercial controller as SLPC. The function of the controller is generated an output signal or manipulated variable mv(t), on the basis of the error or the difference between the measured value and the set point. The manipulated variable is then connected to the phase control. The function of the phase control is to adjust the electric voltage $v_p(t)$ so that it is proportional to the controller output signal mv(t), where the electric voltage is varied from 0 to $220V_{ac}$. Thus, the generated heat $T_i(t)$ is a function of the supplied electric voltage $v_p(t)$.

The main disadvantage of feedback control systems [9] is that in order for it to compensate for entering disturbances, the controlled variable must first deviate from set point. Feedback control acts upon an error between the set point and the controlled variable. This means that once a disturbance enters the process, it must propagate through the process and force the controlled variable to deviate from the set point before corrective action can be taken to compensate for the disturbance. Thus, perfect control, defined as no deviation of the controlled variable from the set point in spite of disturbances, cannot be achieved with feedback control.

3. THE PROPOSED CONTROLLER

3.1 Design of the proposed controller

To develop the feedback control as shown in Fig. 2, this paper introduces the two-mode controller, which has the lookup table technique and the PI control. The lookup table technique is designed to reduce the delay time while the PI control is applied to achieve the desired temperature. Fig. 3 shows the block diagram of the proposed controller using the commercial controller SLPC. The proposed concept can be graphically displayed by the following flowchart (see Fig. 4)

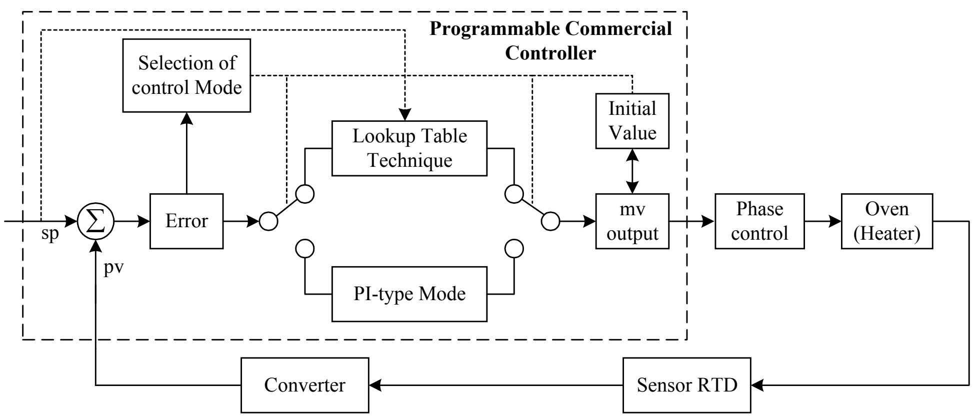


Fig. 3 Block diagram showing the proposed controller concept

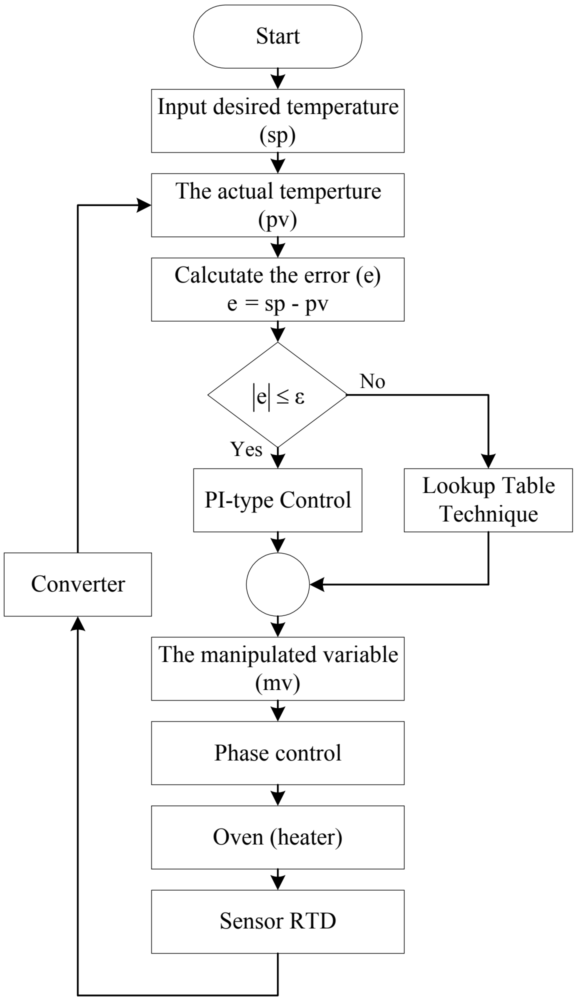


Fig. 4 Flowchart of temperature control

The magnitude of calculated temperature error signal |e| is compared with the preset value ε, which is set to $\pm$ 10% of full scale. If the magnitude error signal is greater than the preset value, the manipulated signal is then controlled using an appropriate value obtained from the lookup table technique. Otherwise, the PI-type controls the temperature to maintain the specified temperature based on the suitable K_p and T_i parameters.

3.2 Lookup Table Technique

The data of lookup table technique was determined by the thermodynamic principles of heat transfer [10]. The three modes of heat transfer are radiation, convection, and conduction. The studied oven in Fig. 1 is based on the convection, which has the heat transfer rate as

$$Q = h \times A\left(T_w - T_b\right) \quad (1)$$

Where:
Q is the heat transfer rate (W)
h is the heat transfer coefficient ($W/m^2 \cdot K$)
A is the surface area of the medium (m^2)
T_w is the temperature of the heating element (°C or K)
T_b is the temperature of the surrounding fluid (air) (°C or K)

The enclosure of studied heater is stainless steel, thus the heat transfer coefficient h is approximately 3.7 $W/m^2 \cdot K$. The surface area of the medium A assuming a free-standing enclosure is about 3.7m^2. The temperature of the surrounding fluid or the ambient temperature is about 27°C or 300K. Substituting these values into the Eq. (1), the heat transfer rate can be written as

$$Q = 13.69\left(T_w - 300\right) \quad (2)$$

From Eq. (2), the temperature of the heating element in Kelvin (K) can be given by

$$T_w = \frac{Q}{13.69} + 300 \quad (3)$$

From section 2, the operation of the studied convection oven is based on the electric current passing through the oven heater, thus generating heat can be written as

$$P = i_p^2 R \quad (4)$$

Where:
P is the generated heat (W)
i_p is the supplied current passing through the oven heater (A)
R is the heater resistance (Ω), 23.4Ω used for the studied oven.

Based on the principle of ideal energy conversion, if we neglect the heat losses, the generated heat is equal to the heat transfer rate as

$$P = Q \quad (5)$$

Substituting Eq. (5) into Eq.(3), the temperature of the heating element can be rewritten as

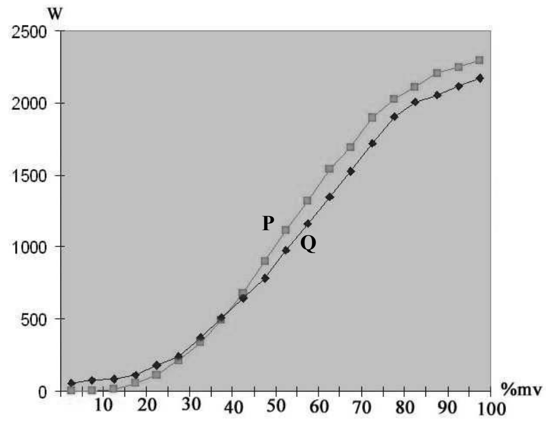
$$T_w = \frac{P}{13.69} + 300 = \frac{\left(i_p^2 R\right)}{13.69} + 300 \quad (6)$$

It is clearly seen that, the temperature of the heating element or the desired temperature $T_o(t)$ can be controlled by the electric current $i_p(t)$ related to the electric voltage $v_p(t)$, which is directly adjusted by the phase control. Table 1 shows the data for lookup table technique. The data in 2nd to 5th columns are measured values from the experimental plant model in Fig. 1, while the data in 6th to 8th columns are calculated values using the Eqs. (2)~(5).

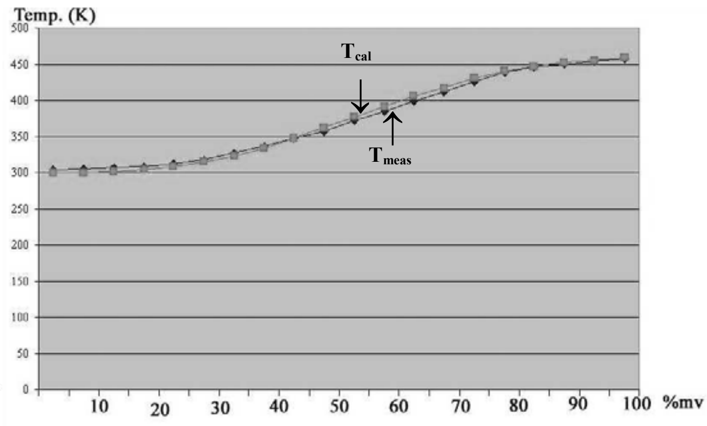
From the lookup table data in Table 1, Fig. 5(a) and Fig. 5(b) show the comparisons between the values P and Q, T_{meas} and T_{cal}, respectively. The percentage of manipulated signal is varied from 0 to 100. It should be noted that the proposed lookup table technique can be applied to improve the control accuracy.

Table 1 Lookup table data of the proposed controller

mv (%)	Measured Voltage [v_p] (V)	Measured Current [i_p] (A)	Measured Temperature [T_{meas}] (C)	Measured Temperature [T_{meas}] (K)	Calculated Generating Heat [P] (W)	Calculated Heat Transfer Rated [Q] (W)	Calculated Temperature [T_{cal}] (K)
5	0.18	0.2	31	304	0.936	54.76	300.065
10	3.63	0.3	32.1	305.1	2.106	75.48	300.14625
15	20	0.8	33.1	306.1	14.976	83.509	301.04
20	33.6	1.5	35.1	308.1	52.65	110.889	303.65625
25	50.6	2.2	39.8	312.8	113.256	175.232	307.865
30	67.9	3	44.4	317.4	210.6	238.206	314.625
35	85.4	3.8	54	327	337.896	369.63	323.465
40	103.1	4.6	64	337	495.144	506.53	334.385
45	120.5	5.4	74	347	682.344	643.43	347.385
50	137.3	6.2	84	357	899.496	780.33	362.465
55	153	6.9	98	371	1114.074	971.99	377.36625
60	167.1	7.5	111.6	384.6	1316.25	1158.174	391.40625
65	180	8.1	125.2	398.2	1535.274	1344.358	406.61625
70	191.4	8.5	138.6	411.6	1690.65	1527.804	417.40625
75	201.3	9	152.4	425.4	1895.4	1716.726	431.625
80	209.4	9.3	166	439	2023.866	1902.91	440.54625
85	215	9.5	173.4	446.4	2111.85	2004.216	446.65625
90	218	9.7	177	450	2201.706	2053.5	452.89625
95	220.5	9.8	181.3	454.3	2247.336	2112.367	456.065
100	222.73	9.9	185.5	458.5	2293.434	2169.865	459.26625



(a)



(b)

Fig. 5 The comparison of Lookup table data as shown in Table 1
(a) the comparison between the values of P and Q
(b) the comparison between the values of T_{meas} and T_{cal} (K)

4. EXPERIMENTAL RESULTS

The performances of the proposed combined controller were observed using the thermal plant model under the temperature control as shown in Fig. 1. The desired temperature is set to 150°C. Using the programmable SLPC based on the proposed technique, the parameters K_p and T_i are set to 5.5 and 420sec, respectively. Fig. 6(a) and Fig. 6(b) show the step responses as the results using only the PI-type control and the proposed technique, respectively.

From the experimental result comparison, it is clearly seen that the response obtained from using the proposed technique outperforms that using only PI-type control. That is, the response is smoother during the initial state and the time to enter the steady state is shorter.

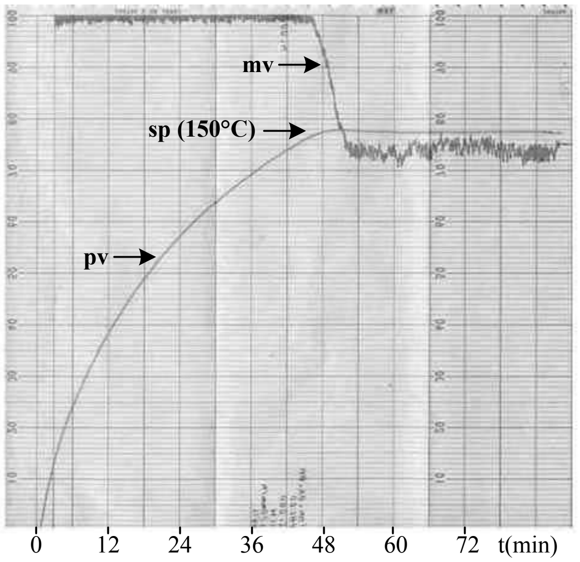


Fig. 5 Experimental result using only PI-type control

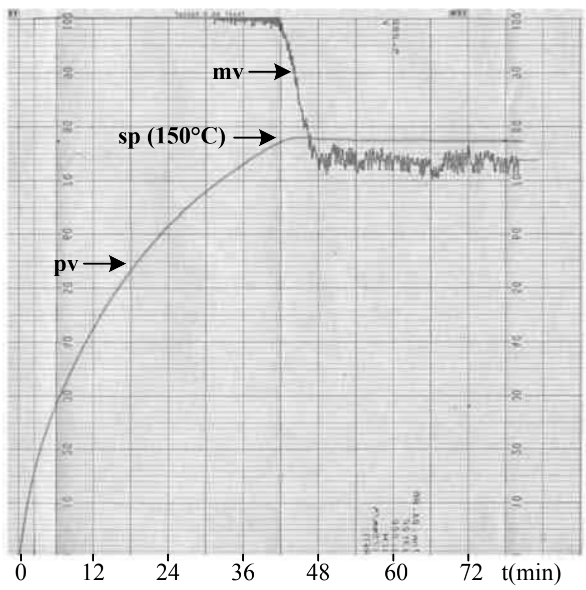


Fig. 6 Experimental result using the proposed technique

5. CONCLUSION

This paper has introduced the temperature control technique, which combines the feedforward-based lookup table and feedback-based PI controls. The proposed technique controls the temperature to maintain the target temperature with fast and smooth response. The experimental results demonstrate that the proposed control technique has sufficient performances for nonlinear system as thermal process.

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