n-Steps On-Off Temperature Controller

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Abstract: This paper presents an n-steps on-off controller to maintain the desired temperature of the thermal process. The proposed technique is simple and convenient to implement based on the programmable commercial controller. The thermal plant model is experimented to observe the performances of the proposed controller. The experimental results included demonstrate the good performance of the proposed controller.

Keywords: on-off control, temperature control, feedback control, thermal process

1. INTRODUCTION

The temperature control of the thermal process is the important in industrial systems. In general, the temperature control must be investigated on a case by case basis to achieve the good control performance. Three widely used methodologies are two-position (on-off), time proportional (throttling), and Proportional-Integral-Derivative (PID) algorithm [1]-[2]. The PID algorithm is suitable for the systems having small mass or small capacity. It provides the high precision and stable control. However, the long rise time may be obtained from this conventional control. The on-off and time proportioning controls are the most common methods and used when the mass of the system is so huge causing the extremely slowly changes in temperature. In addition, the large overshoot and the offset obtained from the on-off control and the proportioning action occur within a proportional band around the desired temperature or set point [3]. The time proportional control methodology may require an operator to make a small manual adjustment to bring the temperature to the desired temperature at the initial state. To eliminate the overshoot and reduce the offset associated with on-off and proportional controls, the multiple step operations on-off controller is proposed in this paper.

This paper aims to design the n-step on-off controller for temperature control, which is based on the use of the commercial controller, Yokogawa Electric corporation's Single Loop Programmable Controller (SLPC) [4]. The performances of the proposed temperature controller were observed using the experimental thermal plant model at Process Control Lab, KMITL, Thailand. The experimental results included demonstrate the good performance of the proposed controller

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

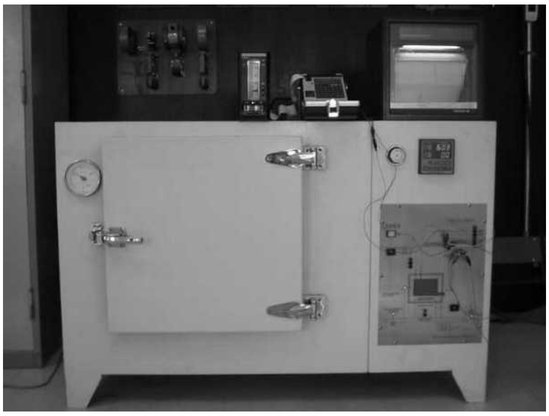


Fig. 1 The studied thermal plant model

keep the temperature lower than the preset maximum value (200°C). The electric fan is installed to circulate air throughout the oven.

The feedback control scheme works as follows: the output temperature or controlled variable $T_{om}(t)$ is measured by 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 to generate an output signal or manipulated variable mv(t), on the basis of the error or difference between the measurement 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 $v_p(t)$ in 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 $v_p(t)$.

3. THE PROPOSED CONTROLLER

3.1 Design of the proposed controller

Fig. 3 shows the block diagram of the proposed controller. The design of proposed controller based on the use of the programmable commercial controller as SLPC can be explained as follows.

The rate percent on-off of manipulated signal is assigned to each step, where the number of step operations n depend on the characteristic of temperature control system and the desired precision. The temperature deviation or error signal is

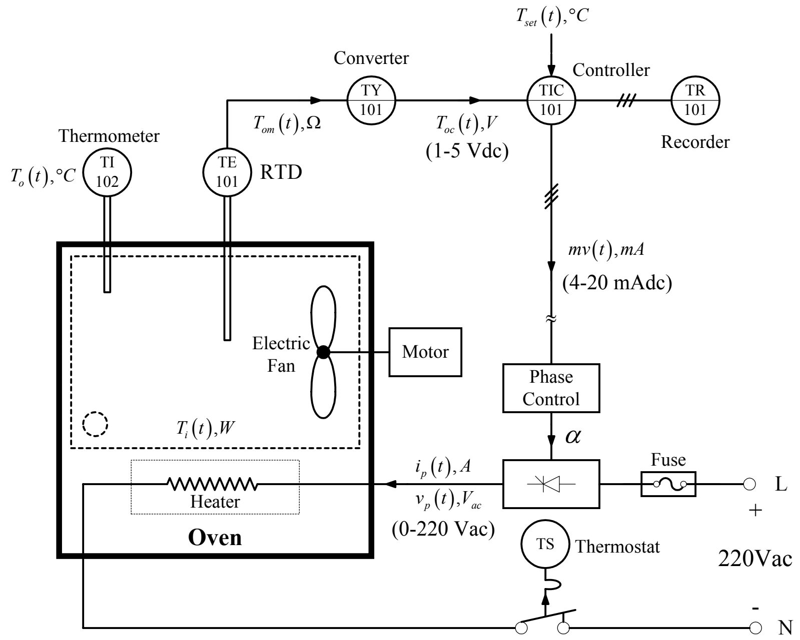


Fig. 2 Temperature feedback control loop

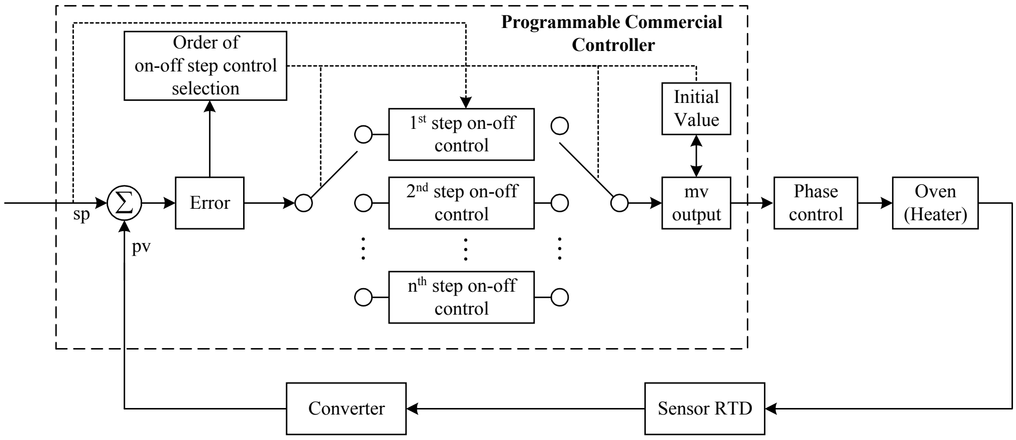


Fig. 3 Block diagram showing the proposed technique

used to decide the suitable rate percent on-off of manipulate signal. When the error signal is further from the desired temperature or set point, the manipulated signal is high rate percent on-off. On the contrary, if the error signal is near the set point, the manipulate signal is low rate percent on-off.

The temperature control system must be investigated on a case by case to provide the output temperature at its set point. The appropriate manipulated signal to control the temperature was determined by the thermodynamic principles of heat transfer [5]. 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•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•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 generated heat can be written as

$$P = i_p^2 R \tag{4}$$

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

$$P = Q \tag{5}$$

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

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

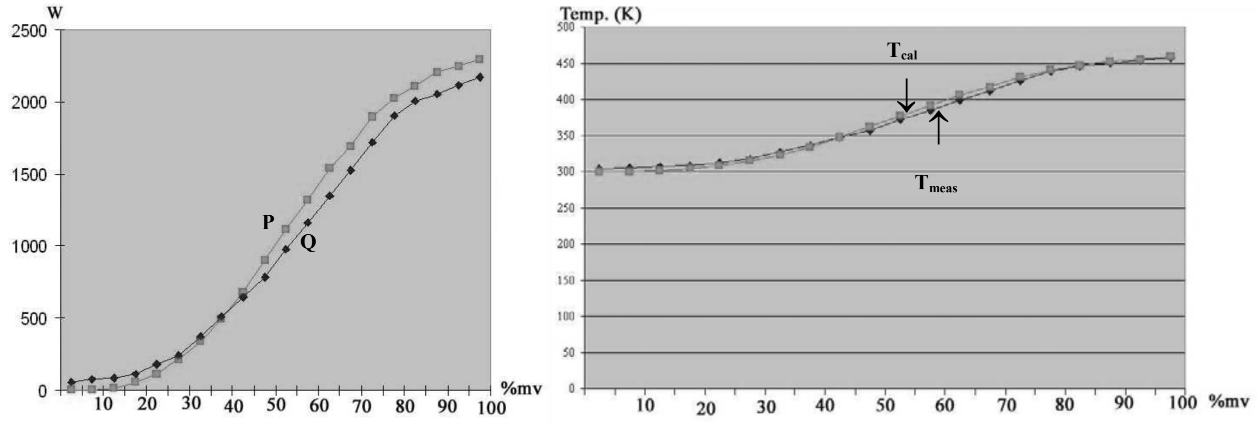
It is clearly seen that, the temperature of the heating element or the desired temperature $T_o(t)$ can be controlled by the electric current $i_p(t)$ related to the electric voltage $v_p(t)$, which is directly adjusted by the phase control. Table 1 shows the data for lookup table technique. The data 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 from Eqs. (2)~(5).

From data in Table 1, Fig. 4(a) and Fig. 4(b) show the comparisons between the values, P and Q, T_{meas} and T_{cal}, respectively. Where the percentage of manipulated signal is varied from 0 to 100. It should be noted that the number of step operations n of the proposed technique can be considered based on the characteristics of thermal process as shown in Fig 4.

In this paper, the number of step operations n is equal to 5, which are 0% - 100%, 0% - 90%, 0% - 80%, 0% - 70%, and 0% - 60% of on-off manipulate signals. The high error signal (0% < e < 2%) during the first step causes the 100% on-off manipulate signal, while the low error signal (0% < e < 2%) during the fifth step causes only 60% on-off control signal. The proposed technique can be graphically displayed by the following flowchart as shown in Fig.5.

Table 1 The experimental thermal process data

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. 4 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)

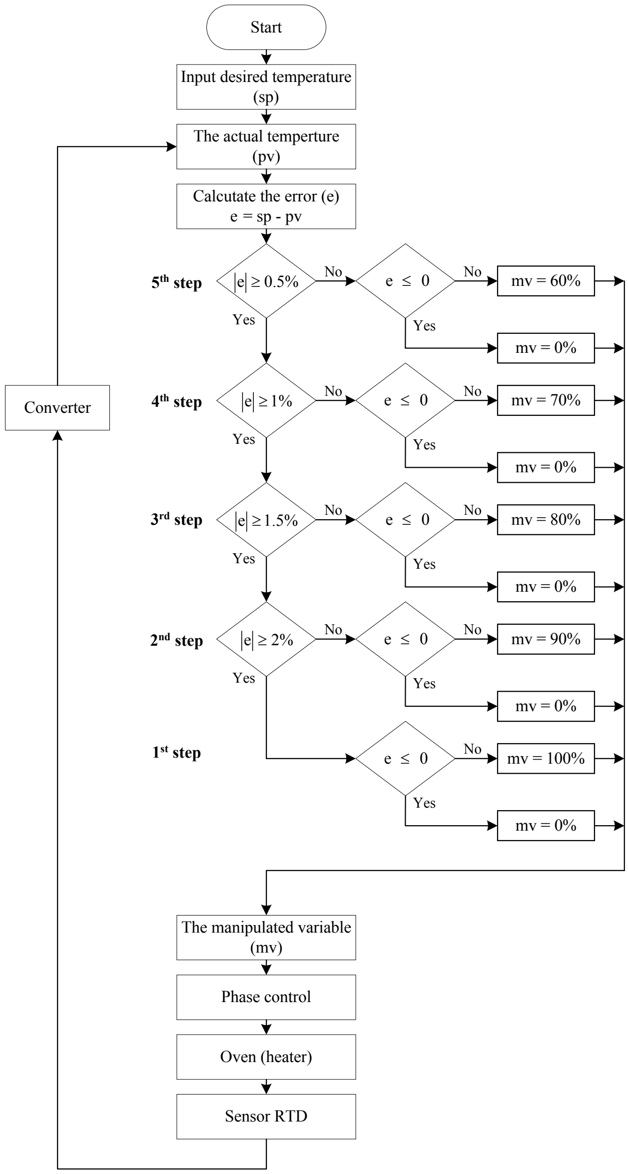


Fig. 5 Flowchart of temperature control

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 120°C. Fig. 6 - Fig.8 show the step responses based on the use of the conventional on-off control, the P-type control, and the proposed technique.

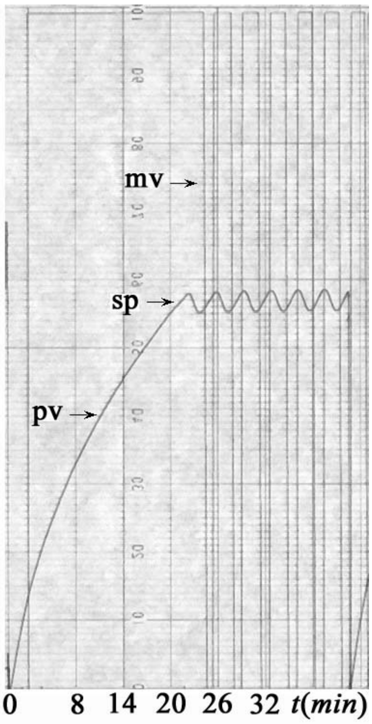


Fig. 6 Experimental result using on-off control

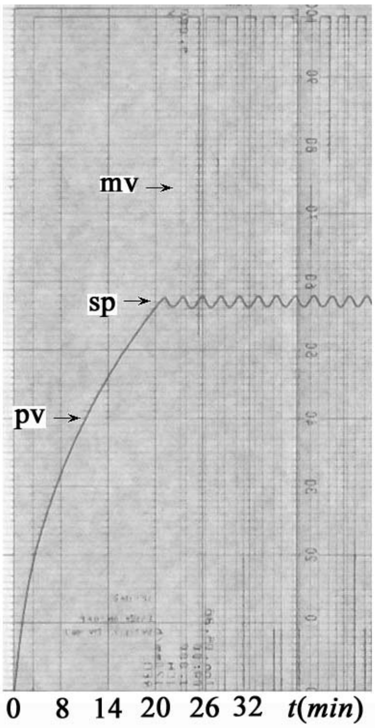


Fig. 7 Experimental result using the P-type control

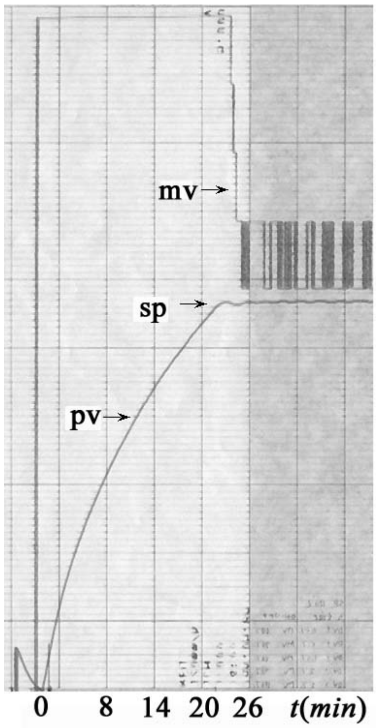


Fig. 8 Experimental result using the proposed technique

From the experimental-results comparison, it is clearly seen that the five steps on-off controller outperforms that using only the on-off and proportional control and the P-type control. That is, the response has more smoothness and lowest oscillator during steady state.

5. CONCLUSION

This paper described the design of n-steps on-off controller. The proposed controller is simple and convenient to design based on the use of the programmable commercial controller. The experimental results demonstrating that the proposed controller has sufficient performances for temperature control system.

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