Metal Chamber Temperature control by Using Fuzzy PID Gain Auto-tuning strategy

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Abstract: - Although PID control scheme is widely employed in industrial control systems, it is hard to search the model-free appropriate control gains for achieving good dynamic performance. The selected constant PID control gains can not achieve consistent control accuracy for different temperature setting points or testing runs. In addition, the temperature control system has nonlinear time-delay, time-varying, slow response speed and one-way control input characteristics, it is also difficult to accurately estimate the dynamic model for designing a model-based general purpose temperature controller to achieve good control performance. Recently, temperature is become an important production control parameter in chemical and semiconductor industry. How to design an appropriate gains auto-tuning control strategy for achieving accurate temperature control accuracy has become an interesting research topic. Here two model-free auto-tuning PID and fuzzy PID control strategies are introduced to design a general temperature controller for different plants. The designed temperature control plants have heater control phase only without cooling control function. The experimental results show that these control schemes can obtain reasonable control performance. The steady state error of the step input response is less than 0.2 $^{\circ}C$ without overshoot. The setting point dynamic response behaviour is better than that of the model-based IMC-PID due to the modelling uncertainty and modelling error.

Key-Words: - Temperature control, gain auto-tuning, fuzzy PID and one-way control input.

1 Introduction

Temperature is an important control parameter in chemical, material and semiconductor manufacturing processes. For example, material annealing, thin film deposition, laminator operation and TV glass melting furnace all need appropriate temperature control system. Some of the temperature control systems have heating and cooling control phases and others only have heating input control phase. Their dynamic behaviours have significant difference. The temperature control system with heater input only is more difficult to monitor than two phases control systems for obtaining good control performance. How to design a general purpose temperature controller with good response speed, smaller steady state error and overshoot for industrial implementation is still a challenge work in control research field. Currently, the on-off control and PID control schemes are employed in the commercial products. PID controller was proposed in 1936. It has been widely used in industrial automatic control systems. However, how to adjust the control gains is the key factor of implementing a PID controller. If the accurate dynamic model of a control system is available, the Ziegler and Nichols rule [1] and IMC control strategy [2,3] can be used to calculate the appropriate gains. However, the heating plant has time-delay and temperature dependence nonlinear behaviours. It is hard to establish an accurate dynamic model for a PID controller design. Generally, it needs a trial-and-error process for obtaining a good control response. When the system has external disturbance or set-point change, its transient response may deteriorate. It needs an online operator to readjust it or switch it to the manual control. This is not a convenient application and the production parameters may not maintain in a good level during manufacturing process. Hence the model-free intelligent control schemes have gained the researcher attention.

Auto-tuning PID control strategy was proposed by Astrom and Hagglund[4]. Hang et al. [5-7] proposed some adjusting rules for the auto-tuning PID controller by employing the adaptive control technique and worked out the performance comparison for those methods [8,9]. The appropriate gains searching of this approach is based on the system output response of an on-off open loop relay control. The critical period and critical gain are found first, and then the appropriate PID gains can be calculated by using the Ziegler and Nichols rule.

In addition, adaptive predictive temperature control strategy is employed to design the nonlinear HVAC system for improving the temperature control performance for a wide range of operating points [10]. Fuzzy control has been successful employed in a lot of industrial process. It has model-free intelligent characteristic. It has been implemented on the industrial temperature controller based on FPGA hardware structure [11], too. Recently, the fuzzy control theory is used to improve the adaptivity and robustness of a PID controller. There has a lot of fuzzy PI, fuzzy PD and fuzzy PID control schemes were proposed in literature [12-16]. The PID gains are nonlinear functions of tracking control performance. They can be adjusted automatically based on the output error. It can achieve better robustness, quick response and smaller overshoot than that of a traditional PID controller. Usually, the heater input only one-way temperature control problem has nonlinear time-delay and un-symmetric control behaviour. It is difficult to estimate an appropriate dynamic model for model- based controller design for achieving precise temperature control accuracy with good transient response. Hence the model-free PID control scheme with auto-tuning or gain adjustment mechanism is the suitable approach to develop the heater input only temperature controller. Here auto-tuning and fuzzy PID control strategies are employed to design general purpose temperature controller for monitoring the temperature of one hollow metal cylinder and one hollow metal block with heater input only.

2 Metal Block Chamber Temperature Control System Structure

The control system structure of this temperature monitoring system is shown in Fig. 1. It is a PC based structure. PC sends the control current into a SCR driver through the D/A card. This SCR can monitor the power output of a single phase 220 V and 20A alternative current power source. It regulates the current input of the heating rod for raising the temperature of the hollow metal cylinder or hollow aluminum rectangular block. The medium inside the hollow cylinder hole is air. The temperature of the hollow metal cylinder is measured by using a RTD resistance temperature sensor and fed back into the PC through A/D card. The control algorithm is implemented with C++ program. In order to develop a general purpose temperature controller, two different control plants are prepared for evaluating the control performance. The dimension of the hollow iron cylinder is 250 mm height and 51 mm diameter with 10 mm diameter hollow hole for installing the heating rod and RTD PT100 temperature sensor. The dimension of the hollow aluminum rectangular block is $150\times50\times25$ mm with 10 mm diameter hollow hole for installing the heating rod and RTD PT100 temperature sensor. The accuracy of the selected PT100 RTS sensor is about $0.2^\circ C$ for the measuring temperature under $120^\circ C$. The sensitivity of this RTD sensor is 0.0015 per $^\circ C$. The sensing delay is about 0.1 second which is acceptable with respect to the 4Hz sampling frequency.

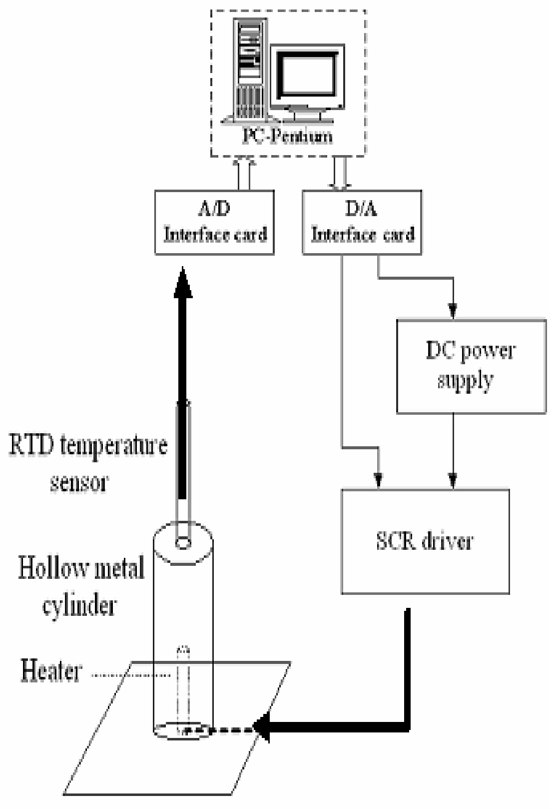

Fig. 1 The experimental system set-up.

3 Auto-tuning PID Control

The key role which influences the system control performance of a PID controller is how to find the optimal proportional gain, integral time constant and derivative time constant. Since, the temperature control system has nonlinear time-delay, time-varying, slow response speed and one-way control input characteristics, it is difficult to accurately estimate the dynamic model for designing a model-based PID general purpose temperature controller to achieve good control performance. For practical implementation, these model-free gains adjustment is achieved by expertise experience and trial-and-error modification. It is a time consuming work and the dynamic response behaviour can not be guaranteed. Each control case may have different dynamic performance due to system nonlinear and time-varying behaviours. Hence, Astrom and Hagglund [4] proposed a relay feedback evaluating method to find the gain parameters for a PID controller. Firstly, On-Off switching control is employed for the beginning two cycles. When the system temperature is below the setting command, the control power is fully opened to drive the temperature up. When the temperature reaches the setting value, the control input is switched off immediately. Then the critical gain, K_u , and critical period, P_u , can be found from these input-output response curves as Fig. 2.

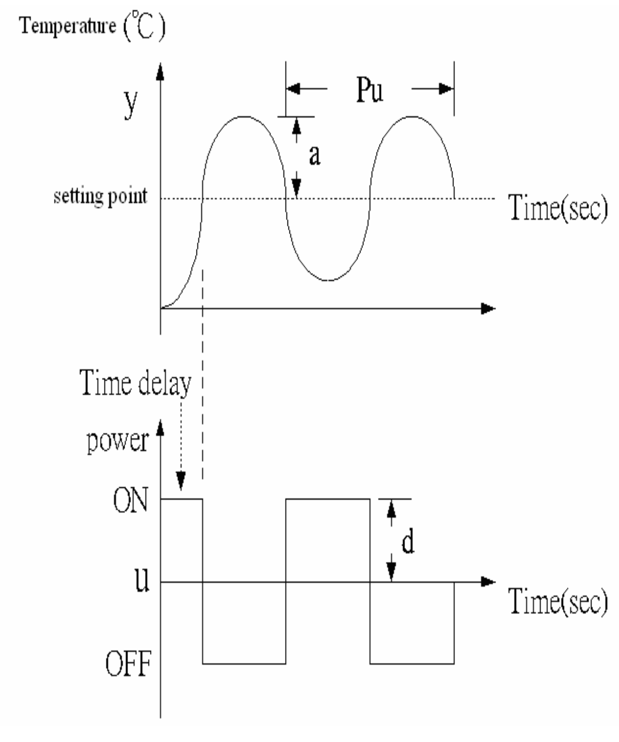

Fig. 2 The estimating of critical period and critical gain from on-off control.

Where

$$K_u = \frac{4d}{a} \tag{1}$$

Hence, the gain parameters can be calculated by using the experience formula of Ziegler-Nichols.

$$K_p = 0.6K_u, T_i = \frac{P_u}{2}, \text{ and } T_d = \frac{P_u}{8} \tag{2}$$

That means

$$K_p = 0.6K_u,\ K_i = K_p/T_i \text{ and } K_d = K_p T_d \tag{3}$$

Based on this algorithm, the appropriate PID control gains can be easily obtained for each control cases. It is a convenient application scheme.

4 Fuzzy PID Controller

Usually the motivation of a fuzzy approach is that the knowledge is insufficient and the dynamic model has uncertainty. Fuzzy set theory was employed to simulate the logic reasoning of human beings. The major components of a fuzzy controller are a set of linguistic fuzzy control rules and an inference engine to interpret these rules. These fuzzy rules offer a transformation between the linguistic control knowledge of an expert and the automatic control strategies of an activator. Every fuzzy control rule is composed of an antecedent and a consequent, a general form of the rules can be expressed as

$$R_i: \text{If X is } A_1 \text{ and Y is } A_2, \text{ Then U is } C_1 \tag{4}$$

Where R_i is the i^{th} rule, X and Y are the states of the system output to be controlled and U is the control input. A_1, A_2 and C_1 are the corresponding fuzzy subsets of the input and output universe of discourse, respectively.

The output importance of each rule depends on the membership functions of the linguistic input and output variables. In this system, two input indices of the fuzzy gain regulator are temperature error e and error change $\Delta e(t)$, and the output index is parameter α updating value $h(t)$. In order to simplify the complicated computation of this fuzzy gain regulator, seven equal span triangular membership functions are employed for fuzzy controller input and output variables e and $\Delta e(t)$, and $h(t)$.

Since the temperature control system has time varying behaviour and the dynamic response may depend on the temperature setting value, it is not easy to establish the appropriate PID gains. Fuzzy self-tuning PID controller [17] was proposed to solve this problem and obtaining the controller adaptability. The main idea of their approach is employed a parameter α to parameterize the Ziegler-Nichols tuning formula for getting faster set point dynamic response. This parameter is adjusted by using a fuzzy strategy based on the system temperature output error and the error change. The system control block diagram is shown in Fig. 3. The control law formula for a standard PID controller is

$$u(t) = K_p[e(t) + \frac{1}{T_i}\int_0^t e(t)dt + T_d\frac{de(t)}{dt}] \quad (5)$$

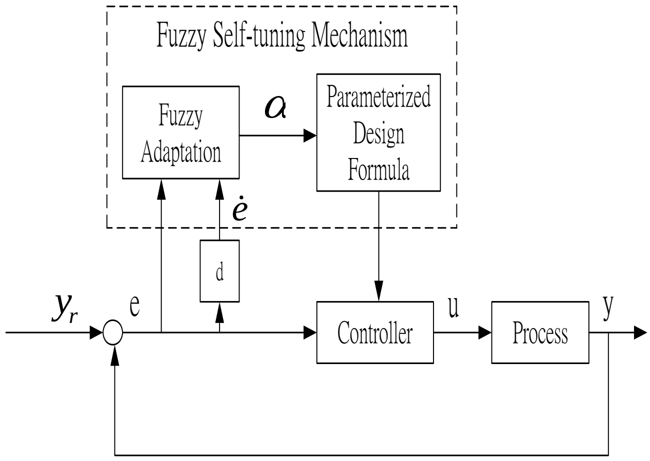

Fig. 3 Fuzzy-PID control system block diagram.

Where $e(t)$ is the system output error, T_i and T_d are the resetting and derivative times, respectively. Then the relationship between fuzzy PID control gains and the parameter α can be represented as

$$\begin{aligned} K_p &= 1.2\,\alpha K_u \\ T_i &= 0.75\frac{1}{1+\alpha}P_u \\ T_d &= 0.25\,\alpha P_u \end{aligned} \quad (6)$$

Where K_u and P_u parameters are obtained from the auto-tuning process. This Fuzzy-PID controller will become a basic Ziegler-Nichols formula, when $\alpha = 0.5$.

The output error $e(t)$, error change $\Delta e(t)$ and the parameter α updating value $h(t)$ are classified into seven membership functions [-3, -2, -1, 0, 1, 2, 3]. Three appropriate gain factors ge, gce and gu are selected to map these variables, $e(t)$, $\Delta e(t)$ and α, into the specified range of the fuzzy universe of disclose [-3, -2, -1, 0, 1, 2, 3]. The values of these parameters are not critical for this fuzzy logic gain regulator. They can be roughly determined by simple experimental tests. Hence the same values can be employed for both temperature control plants and used in different temperature setting points. For simplifying the computation effort, the triangular membership function is employed for those fuzzy variables.

$$\mu(x) = \frac{1}{W}(-|x-a|+W) \quad (7)$$

Where a is the tip point value of each membership function and W is one-half of the width of the membership function. The fuzzy rule table for adjusting the Fuzzy–PID controller parameter α is shown in Table 1. Here, 49 fuzzy rules are employed to regulate the PID control gains of the heater input only one-way temperature control systems on-line based on the temperature output error $e(t)$ and error change $\Delta e(t)$. This rule table is designed based on fuzzy control knowledge and a minor trial-and-error checking process. The weight method is used to de-fuzzilize the updating value.

$$h(t) = \frac{\int x\mu(x)dx}{\int \mu(x)dx} \quad (8)$$

Then the parameter α can be updated by the following recursive formula

$$\begin{aligned} &\alpha(t+1) = \alpha(t) + \gamma h(t)[1-\alpha(t)] \text{ for } \alpha(t) > 0.5 \\ &\alpha(t+1) = \alpha(t) + \gamma h(t)\alpha(t) \text{ for } \alpha(t) \le 0.5 \end{aligned} \quad (9)$$

Where γ is a positive learning rate constant. It can be chosen between [0.2, 0.6] for most dynamic system. The initial value of α is set to 0.5 for matching the situation of auto-tuning PID controller statement.

Table 1 Fuzzy rule bank for the adjusting parameter.

H		R						
		-3	-2	-1	0	1	2	3
E	-3	-3	-3	-2	-2	-1	-1	0
	-2	-3	-2	-2	-1	-1	0	1
	-1	-2	-2	-1	-1	0	1	1
	0	-2	-1	-1	0	1	1	2
	1	-1	-1	0	1	1	2	2
	2	-1	0	1	1	2	2	3
	3	0	1	1	2	2	3	3

5 Experimental Results

In order to evaluate the control performance of the auto-tuning and Fuzzy-PID control schemes, two small temperature control plants are built for the experimental purpose. One is a hollow iron cylinder and the other is a hollow aluminum rectangular block. The dimensions of these two metal plants are described in previous section. Both have a heating coil to input energy and a RTD temperature sensor to measure the temperature. The time-delay of these control plants is about 20 second measured from the transient response of auto-tuning process. The 4 Hz slow sampling frequency is chosen for the following experiments. Two different temperature changes are specified for each control plant in the following experiments to investigate the performance and robustness of the proposed controllers. The control gains of the auto-tuning PID control scheme are calculated from the Ziegler-Nichols formula based on the critical gain, K_u , and critical period, P_u , obtained from the auto-tuning process. These parameters and the auto-tuning PID control gains of following four experimental cases are listed in Table 2.

5.1 Hollow iron roller with Auto-tuning PID control:

The parameters K_u and P_u are estimated from the auto-tuning process with the specified temperature change between $50^\circ C$ and $80^\circ C$. Then the PID control gains can be calculated based on the Ziegler-Nichols formula. They are listed in Table 2. The temperature response and the heating current for an $80^\circ C$ setting point are shown in Fig. 4(a) and (b), respectively. It can be observed that the temperature response reaches steady state within 3.5 minute and the steady state error is less than $0.1^\circ C$ without overshoot.

Table 2 Auto-tuning PID control parameters.

Control plant	Temperature variation range	K_u	P_u	K_p	T_i	T_d
Hollow iron cylinder	$50^\circ C \sim 80^\circ C$	6.35	242	3.81	121	30.25
Hollow iron cylinder	$90^\circ C \sim 120^\circ C$	5.8	162	3.48	81	20.25
Hollow aluminum rectangular block	$45^\circ C \sim 80^\circ C$	3.38	424	1.0	212	53
Hollow aluminum rectangular block	$25^\circ C \sim 100^\circ C$	3.83	266	2.29	133	33.25

For the specified temperature change between $90^\circ C$ and $120^\circ C$, $K_u = 5.8$ and $P_u = 162$ are obtained. The temperature response and the heating current for a $120^\circ C$ setting point are shown in Fig. 5(a) and (b), respectively. It can be observed that the temperature response reaches steady state within 4.5 minute and the steady state error is less than $0.1^\circ C$ with $0.5^\circ C$ overshoot.

5.2 Hollow aluminum rectangular block with auto-tuning PID control:

The parameters K_u and P_u are estimated from the auto-tuning process with the specified temperature change between $45^\circ C$ and $80^\circ C$. Then the PID control gains can be calculated based on the Ziegler-Nichols formula and listed in Table 2. The temperature response and the heating current for an $80^\circ C$ setting point are shown in Fig. 6(a) and (b), respectively. In this case, the heater input current is switched from the saturation (20A) to the PID control law at $20^\circ C$ ahead the setting point. The proportional gain K_p is chosen as one-half of the value calculated from the Ziegler-Nichols formula to evaluate the system performance and transient response variation. It can be observed that the system temperature has slow rising response. The temperature response reaches steady state within 13 minute and the steady state error is less than $0.1^\circ C$

without overshoot. It still can obtain good control performance.

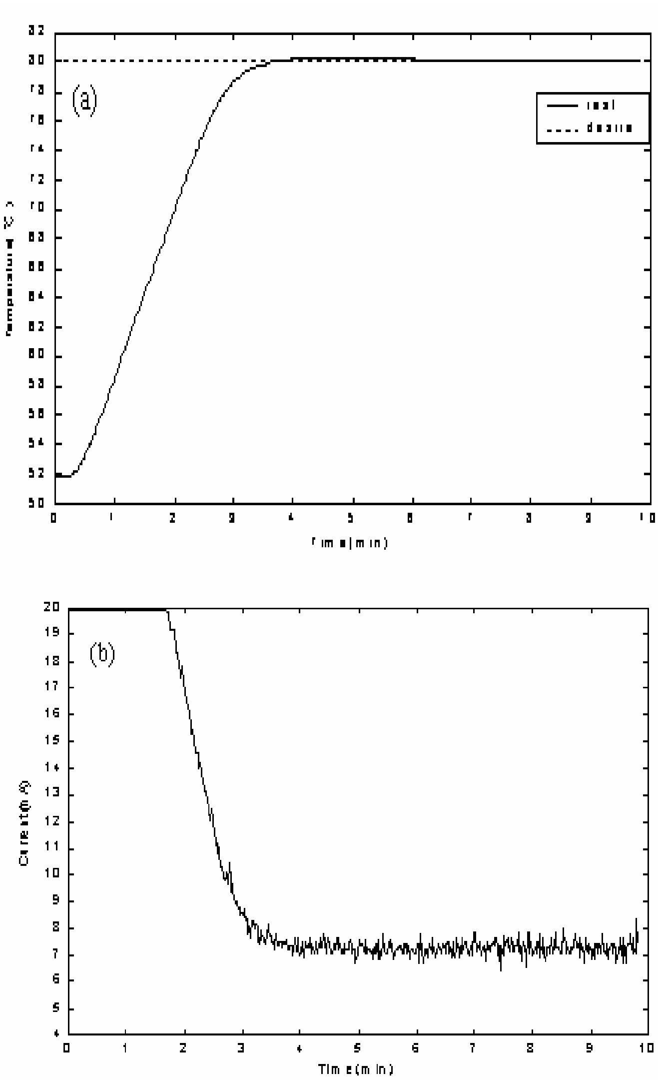

Fig. 4 (a) Temperature $80^\circ C$ step response and (b) the heater input current of an iron cylinder with auto- tuning PID control.

For the specified temperature change between $25^\circ C$ and $100^\circ C$, $K_u = 3.83$ and $P_u = 266$ are obtained. The temperature response and the heating current for a $120^\circ C$ step setting are shown in Fig. 7(a) and (b), respectively. It can be observed that the temperature response reaches steady state within 18 minute and the steady state error is less than $0.2^\circ C$ without overshoot.

5.3 Hollow iron roller with Fuzzy PID control:

The parameters K_u and P_u are estimated from the auto-tuning process. $K_u = 3.68$ and $P_u = 448$ are obtained from the auto-tuning test with the specified temperature change between $24^\circ C$ and $80^\circ C$. The gain factors of the fuzzy variables are selected as: $ge = gec = 0.01$, and $gu = 0.2$. The learning rate constant γ is chosen as 0.1. The temperature response and the heating current for an $80^\circ C$ setting point are shown in Fig. 8(a) and 8(b), respectively. It can be observed that the temperature response reaches steady state within 12 minute and the steady state error is less than $0.2^\circ C$ with $0.45^\circ C$ overshoot. The steady state error will converge into $0.1^\circ C$ within 14 minutes. The variation history of the fuzzy control parameter α is shown in Fig. 8(c).

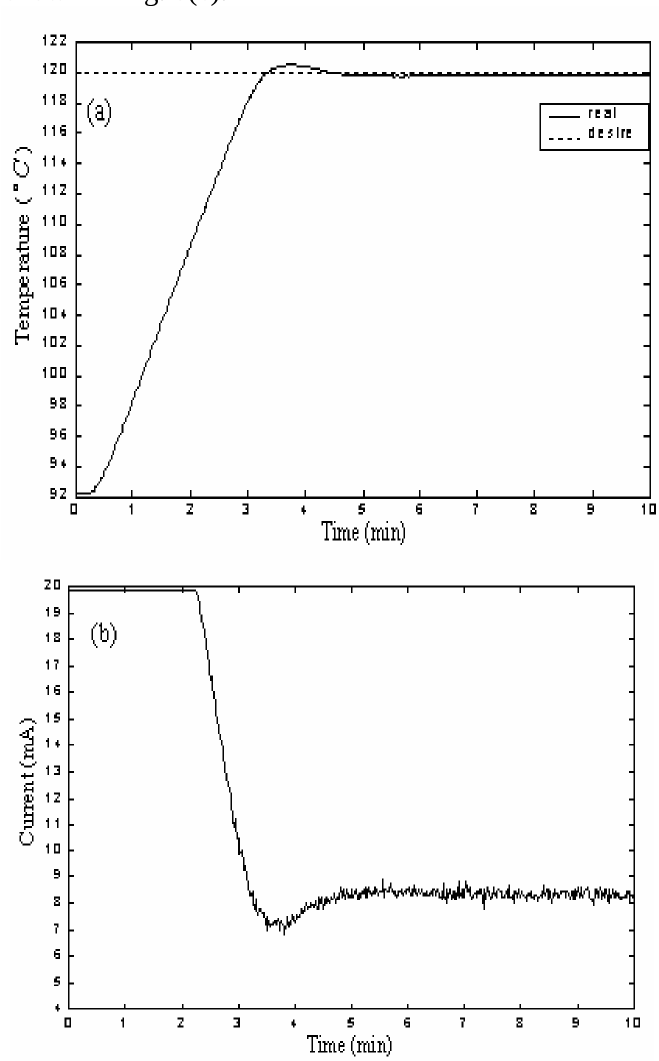

Fig. 5 (a) Temperature $120^\circ C$ step response and (b) the heater input current of an iron cylinder with auto-tuning PID control.

$K_u = 5.8$ and $P_u = 162$ are obtained from the auto-tuning test with the specified temperature change between $70^\circ C$ and $120^\circ C$. The gain factors of the fuzzy variables are: $ge = gec = 0.01$, and $gu = 0.2$. The learning rate constant γ is chosen as 0.1. The temperature response and the heating current for a $120^\circ C$ setting point are shown in Fig. 9(a) and 9(b), respectively. It can be observed that the temperature response reaches steady state within 8 minute and the steady state error is less than $0.2^\circ C$ with $0.7^\circ C$ overshoot. The variation history of the fuzzy control parameter α is shown in Fig. 9(c).

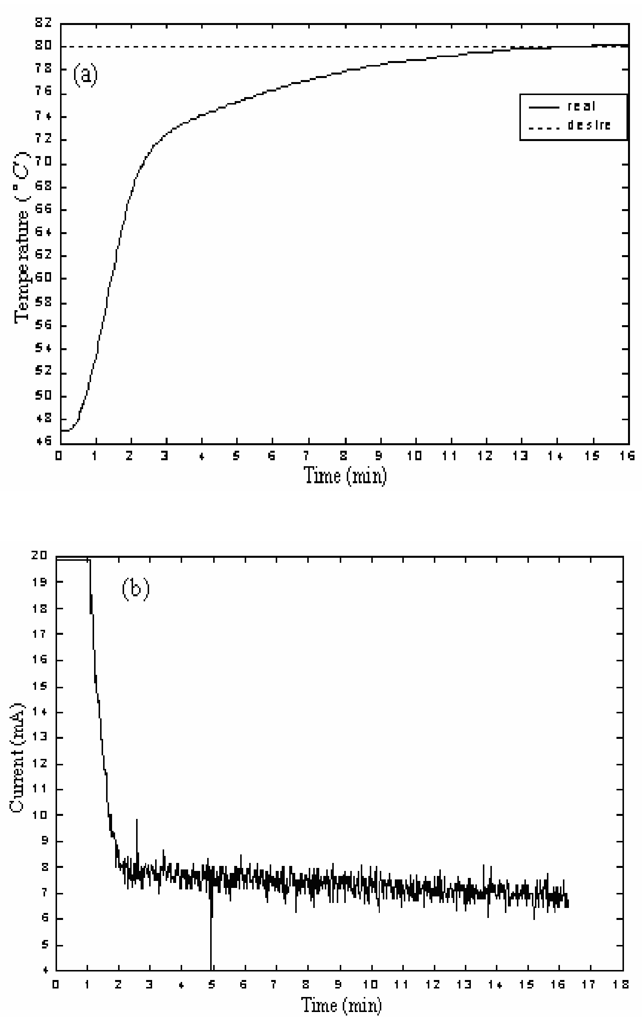

Fig. 6 (a) Temperature $80^\circ C$ step response and (b) the heater input current of a aluminum rectangular block with auto-tuning PID control.

5.4 Hollow aluminum rectangular block with Fuzzy-PID control:

In order to develop a general-purpose fuzzy PID controller, the same fuzzy variables gain factors and learning rate constant γ as the iron cylinder case are selected for this control plant. $K_u = 3.38$ and $P_u = 424$ are obtained from the auto-tuning test with the specified temperature change between $45^\circ C$ and $80^\circ C$. The temperature response and the heating current for a $80^\circ C$ step setting are shown in Fig. 10(a) and 10(b), respectively. It can be observed that the temperature response reaches steady state within 15 minute and the steady state error is less than $0.1^\circ C$ with $0.4^\circ C$ overshoot. The variation history of the fuzzy control parameter α is shown in Fig. 10(c).

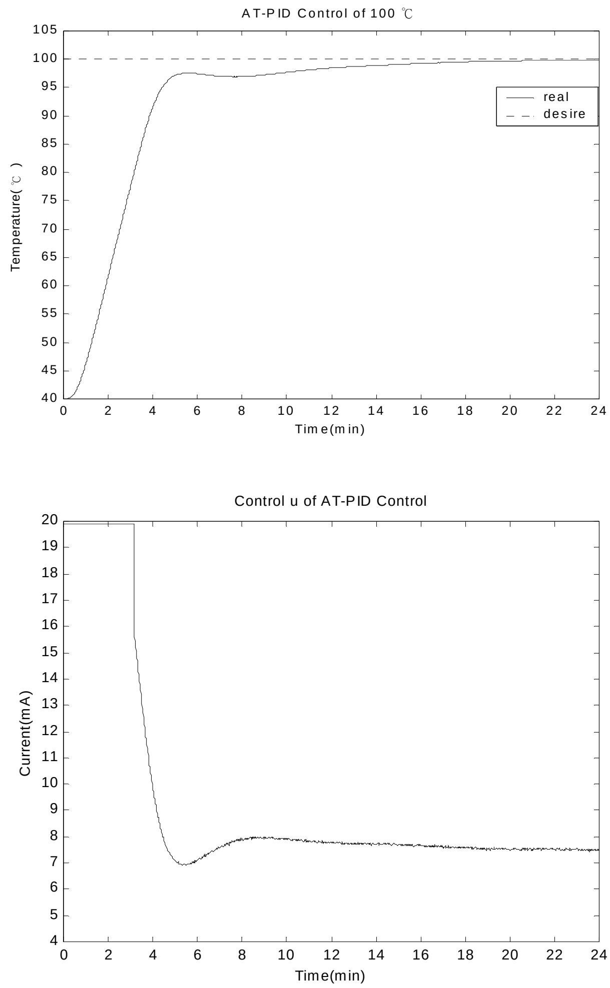

Fig. 7 (a) Temperature $120^\circ C$ step response and (b) the heater input current of a aluminum rectangular block with auto-tuning PID control.

$K_u = 3.83$ and $P_u = 266$ are obtained from the auto-tuning test with the specified temperature change between $25^\circ C$ and $100^\circ C$. The temperature response and the heating current for a $100^\circ C$ setting point are shown in Fig. 11(a) and 11(b), respectively. It can be observed that the temperature response reaches steady state within 12 minute and the steady state error is less than $0.2^{\circ}C$ with $1.0^{\circ}C$ overshoot. The variation history of the fuzzy control parameter α is shown in Fig. 11(c).

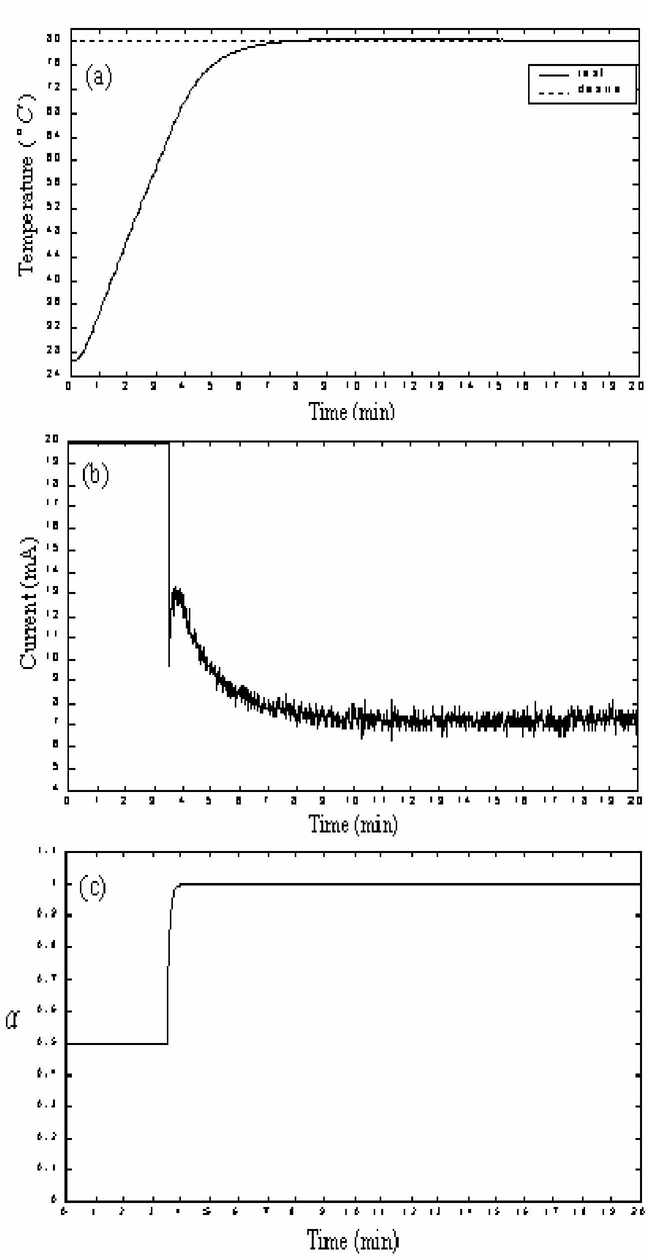

Fig. 8 (a) Temperature $80^{\circ}C$ step response, (b) the heater input current and (c) the adjusting parameter of an iron cylinder with Fuzzy-PID control.

It can be concluded from these experiments that the temperature step response has final steady-state error within $0.2^{\circ}C$ with small even no overshoot for both auto-tuning PID and Fuzzy-PID control algorithms. It has satisfied the requirement of industrial application. Since, the Fuzzy-PID control scheme has varying PID gains, it has better transient response performance for hollow aluminum rectangular block with quickly response speed. However, the auto-tuning PID controller has smaller overshoot.

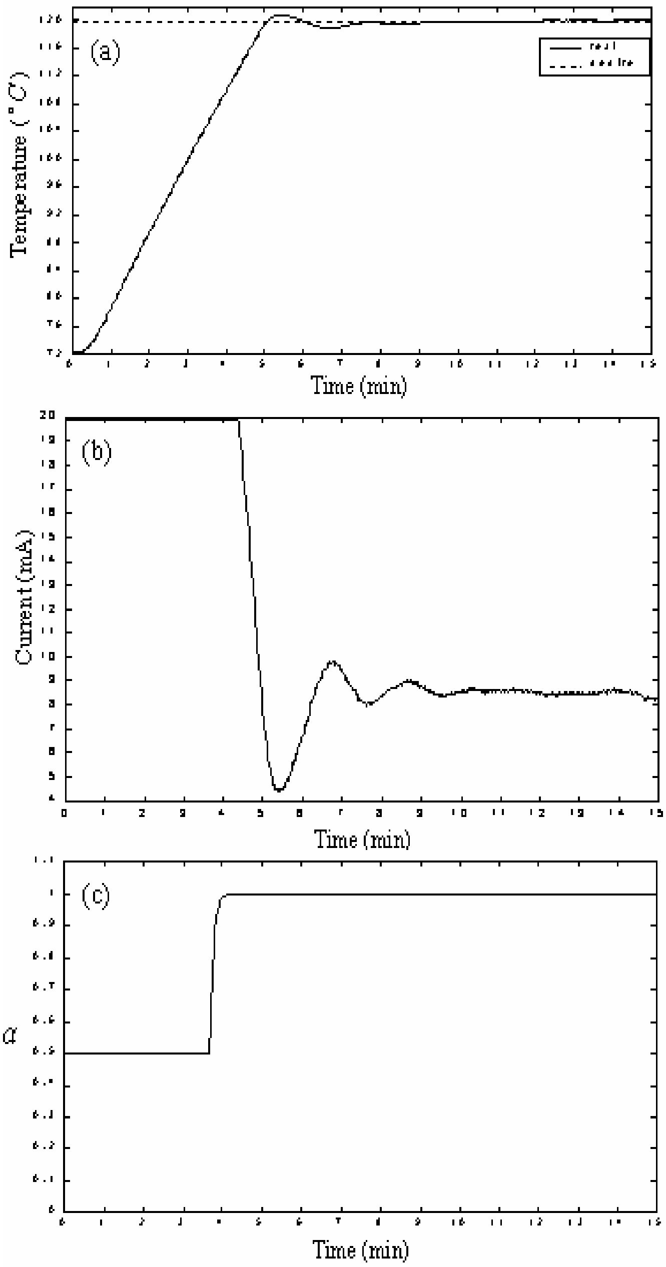

Fig. 9 (a) Temperature $120^{\circ}C$ step response, (b) the heater input current and (c) the adjusting parameter of an iron cylinder with Fuzzy-PID control.

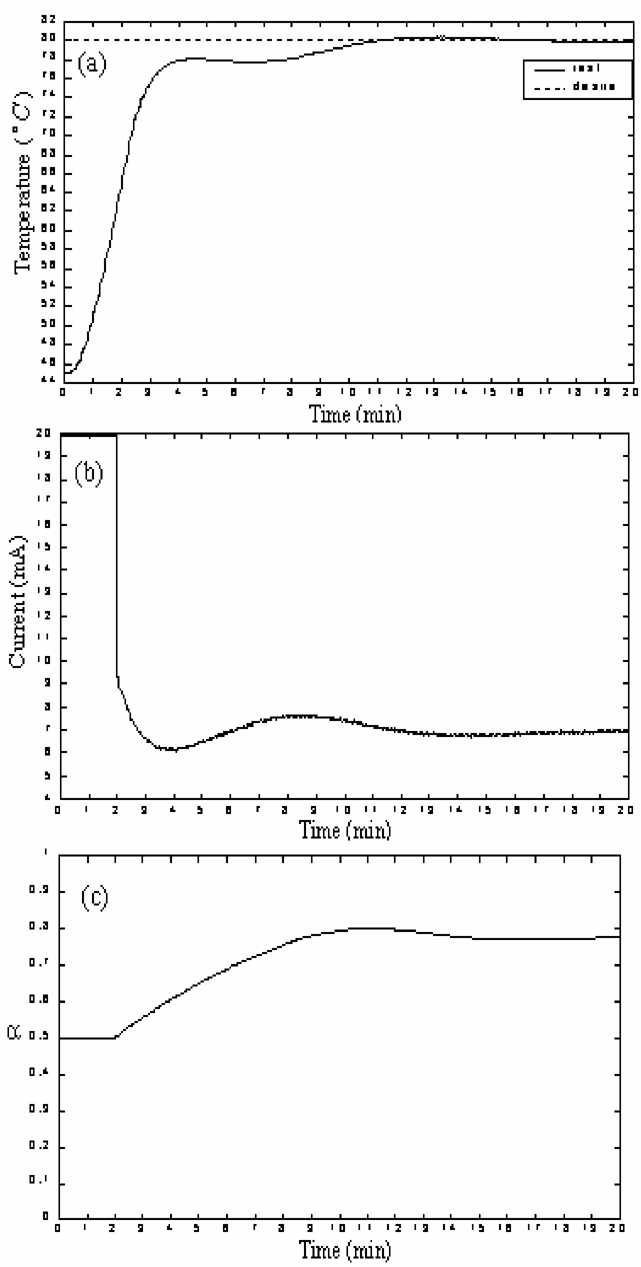

Fig. 10 (a) Temperature $80^\circ C$ step response, (b) the heater input current and (c) the adjusting parameter of an aluminum rectangular block with Fuzzy-PID control.

6 Conclusion

The heater input only temperature control system has time-delay and un-symmetric control behavior. It is difficult to establish reasonable dynamic model for model-based control design. Two PID gains auto-tuning control algorithms are proposed for the heater input only temperature control system. They can auto-search or auto-adjust the PID control gains based on the auto-tuning process or a fuzzy strategy instead of the trial-and-error process of designing a traditional PID controller. It has effectively eliminated the time-consuming work and obtained a good dynamic response. The steady-state error always converges into $0.2\ ^\circ C$ with very smaller overshoot even without overshoot. They have satisfied the industrial application requirements.

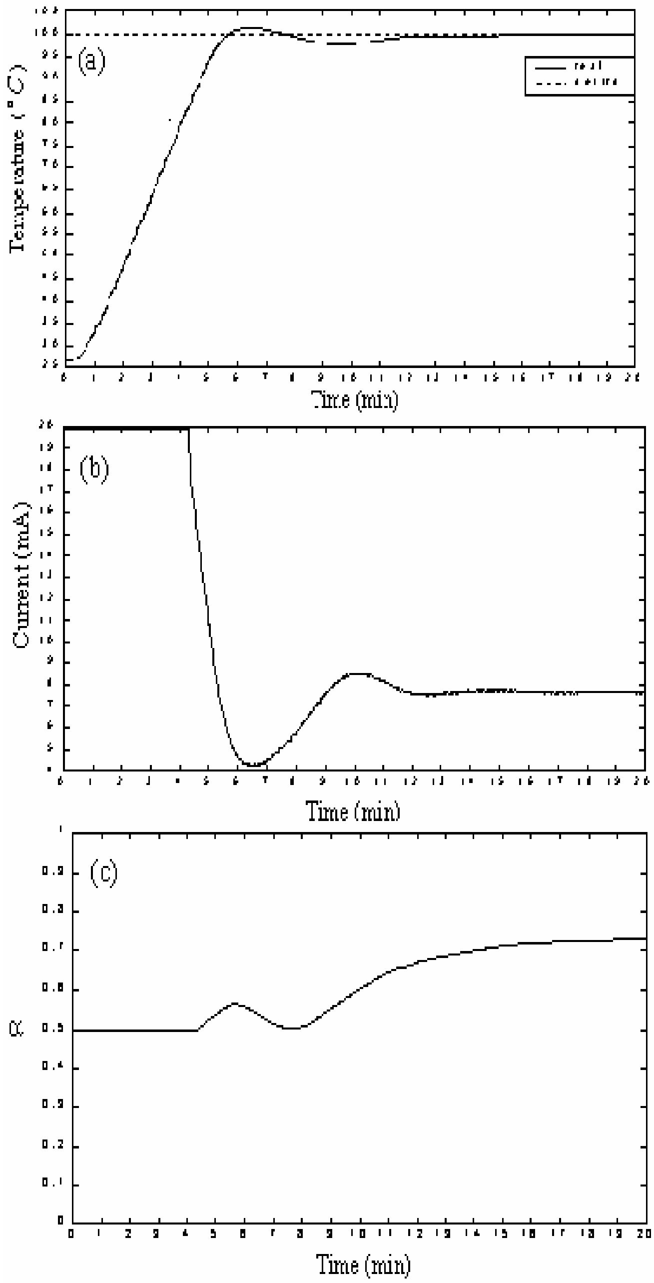

Fig. 11 (a) Temperature $120\ ^\circ C$ step response, (b) the heater input current and (c) the adjusting parameter of an aluminum rectangular block with Fuzzy-PID control.

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