An Adaptive Fuzzy Temperature Controller for Electroheat Systems

Chih-Hu Wang, Chun-Hung Lin, and Bore-Kuen Lee

Department of Electrical Engineering, Chung–Hua University,
Hsinchu 300, Taiwan, R.O.C.
TEL: 03-5185428, E–Mail: mikewang@chu.edu.tw, bklee@chu.edu.tw

Abstract

In this paper, we construct a simple and cheap temperature controller for a commercial electroheat system. It is hard to build an analytical model to describe the behavior of the considered electroheat system due to heat convection in the chamber due to a fan for heat mixing, heat leakage to the environment, variation of the environment temperature, and uncertain heating dynamics such as varying resistance of the heater coil. Here, by considering the operations of the heater in transient and steady-state phases, a simple adaptive fuzzy control scheme is proposed to adjust the duty cycle of the heater for tracking of temperature setting values. Experimental results show good transient and steady-state responses of the fuzzy temperature control system.

Keywords: adaptive fuzzy control, temperature controller

1. Introduction

Temperature control has been widely studied for various thermal systems [2]-[6]. The most ordinary model of thermal systems is established by the general energy balance equation [1] with which the entire heated chamber is considered as a lumped unit and the distribution of the heat is uniform. Hence, this model has been applied to many temperature analyses as a result of its simplicity. But this model does not have a good fit for a large chamber, because the distribution of heat is radiating to the space.

In [2][3], temperature control is applied to a plastic extrusion process in which the entire chamber in the heated barrel is also considered as a lumped unit and different temperature control strategies are used to reduce the variation of the temperature. Temperature control of the heated barrel with electric heaters and water coolers was proposed in [2] which used the discrete-time variable structure system (VSS) temperature control and designed an adaptive law to change the pulse width modulation (PWM) actuating signals for solid state relays (SSRs). Meanwhile, the disadvantage of the Euler approximation using zero-order hold is improved. To improve the conventional PID temperature control, a fuzzy temperature control is introduced in [3] which utilizes two inputs (error, error change) to infer the fuzzy rules and produce an output (duty cycle) to actuate the SSRs. The transient control and the steady-state control are separated in their control method in order to simplify the control method. The advantage of the fuzzy control is that we don't need to measure the parameters of the model. Hence, many complex systems can be controlled without knowing the exact mathematical model of the plant.

In this paper, we implement a cheap but efficient temperature controller for a commercial electroheat system as shown in Figure 1. As a commercial product, instead of being an industrial equipment as studied in [2] and [3], this electroheat system has a bad environment from control point of view. In the presence of heat convection in the chamber, irregular heat leakage to the environment, variation of the environment temperature, and uncertain and time-varying heating dynamics, it is not easy to analytically design a temperature controller based on a physical model. With operating experiences of the electroheat system in the transient and steady-state phases, an adaptive fuzzy temperature controller is implemented to adjust the duty cycle of the heater for temperature tracking. This adaptive fuzzy temperature controller is built in a cheap 8051-based microprocessor system. Several experiments are conducted to show the satisfactory efficiency and accuracy of the control system.

2. Description of the System

2.1 The Electroheat System

In this section, we shall introduce the instrumental settings in our experiment. The electroheat system, RB-6240, produced by Cook Power Co., Ltd. is of iron construction throughout. The purpose of the electroheat system is to bake bread and cake at home. It contains two heaters (one in the top and the other in the bottom), a fan, and a lamp. The configuration of RB-6240 is shown in Figure 1. The fan is used to stir the air in the chamber to make the temperature distribution more uniform. However, since the chamber is not perfectly sealed, cool air is also drawn into the chamber from the environment. Injection of cool air by the fan leads to undesired heat convection which is a significant disturbance for temperature control.

There is a transparent glass in the front side of the electroheat system for observation purpose. This provides a way of severe heat leakage to the environment. The rate of heat leakage also depends on the environment temperature which can vary with the weather in a domestic environment. Lastly, the resistance of the heater do vary with the temperature of the chamber so that the rate of supplied heat energy is not constant. It is also observed the heater is a nonlinear component in that the maximum temperature driven by the heater is saturated at about $250°C$.

In the presence of the previously mentioned uncertainties, temperature of the chamber in the electroheat system RB-6240 will be controlled by an adaptive fuzzy temperature controller which is implemented by an 8051-based microprocessor system.

2.2 The Temperature Controller

The temperature controller contains two principal parts: the analog part and the digital part. The analog part consists of a power supply, a temperature sensor (PT-100), an instrumentation amplifier (IA), a solid state relay (SSR), and two heaters. The digital part includes the microcontroller AT89C51 produced by Atmel Corporation, the analog-to-digital converter (ADC) ADS774 produced by Texas Instruments Inc., the Field-Programmable Gate Array (FPGA) EPM 7032SLC44 produced by Altera Inc., a liquid-crystal display (LCD), eight light emitting diodes (LEDs), and a 4*4 keypad. The block diagram of our temperature controller is shown in Figure 2.

The feedback signal V_o of the temperature sensor is read by the microcontroller AT89C51 via the ADC using Port 0 and Port 2. We use the Timer 0 to produce the PWM signal for actuating the solid state relay (SSR). The keypad is used to provide the temperature setting value T_r.

Temperature Sensor The input signal of the analog part is from a platinum sensor which changes its resistance according to temperature variation. In our experiment, a platinum sensor PT-100 is used to detect the present temperature. It is a long stick which is installed at the bottom of the electroheat system shown in Figure 1. The operation curve of temperature vs. resistance of the platinum sensor PT-100 is shown in Figure 3. Obviously, we can observe that the curve is linear especially in the temperature range (less than $600°C$) in our experiment. Therefore, its high linearity is very useful as a good temperature sensor.

Instrumentation Amplifier The instrumentation amplifier (IA) is a very popular voltage amplifier used in many kinds of the meters for signal measurement and conditioning. This IA together the platinum sensor PT-100 form a Wheatstone resistive bridge sensor for temperature. A resistor in the IA is calibrated so that the output voltage V_o of the instrumentation amplifier is set to zero at $0°C$. The analog signal V_o is then converted into binary data using the ADC ADS744. The reading of the binary data output of the ADS774 is calibrated so that the binary output N is in the range $0 \leq N \leq 4000$ corresponding to $0°C \leq T \leq 400°C$. The relationship between the reading N of the ADC and the temperature T is given by $N = 10T$.

It is worth noting that the current, passing through the platinum sensor PT-100, should be well confined since electric power consumption in the platinum sensor is transformed into heat energy. This heat energy contributes an additional temperature increment which is a measurement error. Therefore, due to thermal noise, the signal-to-niose ratio (SNR) of the measured signal is not good. To solve this problem, temperature measurement and heater actuation are operated at different sampling rates. Temperature measurement is operated at a higher sampling rate so that an average of a segment of temperature measurement is provided to calculate a heater actuation signal, which is operated at a lower sampling rate. Since the heating dynamics has a slow time response, this window-average method can improve the SNR of temperature measurement.

3. Model of Heat Transfer and Operating Experience

In this section, the characteristics of heat transfer will be studied from a lumped parameter perspective. The general energy balance equation [1] is given by

$$\begin{aligned} & Rate\ of\ accumulation\ of\ energy \\ = & Rate\ of\ energy\ input - Rate\ of\ energy\ output \end{aligned} \quad (1)$$

For the considered electroheat system shown in Figure 1, we have

$$Rate\ of\ accumulation\ of\ energy = \rho c V \frac{dT(t)}{dt} \quad (2)$$

$$Rate\ of\ energy\ input = \omega(t) \quad (3)$$

$$Rate\ of\ energy\ output = hA\left[T(t) - T_\infty\right] + f(t) \quad (4)$$

where ρ and c are the density and the specific heat of the air contained in the chamber, respectively, and V the volume of the chamber. Assume the entire chamber is considered a lumped unit with temperature $T(t)$. Let constant h be the heat transfer coefficient, T_∞ the temperature of the environment, and A the external area surrounded by the temperature T_∞. The term $f(t)$ accounts for the drawn heat power by using the fan, heat leakage to the environment, the effect of convection, and other uncertain terms.

We now turn to discuss the energy input rate $\omega(t)$ for heating process. In our experiment, two heaters are supplied with a AC voltage $V_{ac}(t)$

$$V_{ac}(t) = V_m \cos(2\pi f_0 t + \phi) \tag{5}$$

where V_m is the amplitude, $f_0 = 60$ Hz is the frequency, and ϕ is the phase angle of $V(t)$, respectively. The rms value of $V(t)$ is defined as follow:

$$V_{rms} = \sqrt{\frac{1}{T_{ac}} \int_0^{T_{ac}} V_{ac}^2(t)\, dt} = \frac{V_m}{\sqrt{2}} \tag{6}$$

where T_{ac} is the period of the AC voltage $V_{ac}(t)$. Average power P_{ave} produced in a period (T_{ac}) of alternating voltage can be found as

$$P_{ave} = \frac{1}{T_{ac}} \int_0^{T_{ac}} \frac{V_{ac}^2(t)}{R} dt = \frac{1}{R} V_{rms}^2 = \frac{V_m^2}{2R} \tag{7}$$

where R, the value of electric resistance, is assumed to be constant. To improve the efficiency of the power transmission, a PWM stage is used to drive the heaters.

Remark 1 *A periodic signal can be represented by a Fourier series. The Fourier series contains two parts, one is called the DC (average) component of the series and the other is called the harmonic components. As the electroheat system can be regarded as a low pass filter, the effect of the harmonic components can be ignored. Only the DC component of the PWM signal is effective to the heater. This is why the analysis of the average power of the heater is discussed in the above.*

Let $x(t)$ be the tuning duty ratio (in percentage) of the PWM. Then the input power given by the heaters can be expressed by

$$\omega(t) = c_0 P_{ave} x(t)$$

where c_0 is a constant that transforms electric energy to heat energy. The overall heat dynamics can be rewritten by

$$\frac{dy(t)}{dt} = -my(t) + Q(c_0 P_{ave} x(t) - f(t)) \tag{8}$$

where $y(t) = T(t) - T_\infty$, $m = \frac{hA}{\rho c V}$, and $Q = \frac{1}{\rho c V}$. With the overall plant dynamics in (8), the control input is the duty cycle $x(t)$ and control output is the chamber temperature $T(t)$.

For baking purpose, the desired setting temperature T_r of the chamber is between $100°C$ to $200°C$. For this operating range, it is observed from experiments that if we set $x(t) = x^*$, then there exist T^*, δ^*, and t^* such that

$$|T(t) - T^*| \leq \delta^* \tag{9}$$

for $t \geq t^*$. The fluctuation of $T(t)$ around T^* in a confined range is due to the effect of the term $f(t)$, i.e., the drawn heat power by using the fan, heat leakage to the environment, the effect of convection, and other miscellaneous uncertain terms. The deviation amplitude δ^* can be larger then $10°C$. The corresponding value T^* also varies with the environment temperature T_∞. Furthermore, the response of the electroheat system is very slow, e.g. $t^* \simeq 10$ minutes, and a large overshoot usually occurs before entering the region in (9).

Based on the previously mentioned operating experiences, the duty ratio $x(t)$ will be adjusted by a fuzzy control law based on the zero-order Sugeno fuzzy model [7] as shown in the next section.

4. Fuzzy Temperature Controller

For the electroheat system introduced in the previous section, we shall construct a fuzzy temperature controller with its block diagram shown in Figure 4. The fuzzy system based on the zero-order Sugeno fuzzy model to adjust the duty ratio $x(t)$ will be considered.

Strategy for transient phase: Given a temperature setting value T_r, we shall first set $x(t) = 100$, i.e., use full power, to heat up the chamber. Once if the chamber temperature $T(t)$ exceeds some threshold value βT_r with $0 < \beta < 1$, we set $x(t) = x_2$, with $0 < x_2 < 100\%$. The value β must be suitably chosen in order to reduce overshoot of $T(t)$ and the value x_2 is determined to drive $T(t)$ to approach to the setting value T_r. Note that both the values β and x_2 depends on the temperature setting T_r and x_2, in addition, also depends on the environment temperature T_∞. Usually a couple of suitable pairs (β, T_r) and (x_2, T_r) can be determined through experiments. Then, for arbitrary T_r, its corresponding β and x_2 can be calculated by fuzzy interpolation. We shall carefully design the fuzzy rules such that there exists a time instant t_c with $T(t_c) = T_r$.

The values x_2 and β are calculated by inferring the following fuzzy Rules 1~3:

Stage 1:
Rule 1: IF T_r is F_1, THEN $\beta = \beta_1$ and $x_2 = c_1$.
Rule 2: IF T_r is F_2, THEN $\beta = \beta_2$ and $x_2 = c_2$.
Rule 3: IF T_r is F_3, THEN $\beta = \beta_3$ and $x_2 = c_3$.

The fuzzy sets F_1, F_2, and F_3 represent low, middle, and high temperature setting, respectively. Membership functions of these fuzzy sets are shown in Figure 5. Then by using the product reference engine, singleton fuzzier, and center average defuzzifier [?], the values of β and x_2 are given by

$$\begin{aligned} \beta &= \beta_1 F_1(T_r) + \beta_2 F_2(T_r) + \beta_3 F_3(T_r) \\ x_2 &= c_1 F_1(T_r) + c_2 F_2(T_r) + c_3 F_3(T_r) \end{aligned}$$

In this paper, for simplicity, we use the symbol $F_i(\cdot)$ to represent the membership function of the fuzzy set F_i. The calculated values of x_2 and β will be used in

Rules 4 and 5 in the following to determine the duty ratio $x(t)$ in the transient phase. For $t \leq t_c$, the duty ratio $x(t)$ are determined based on Rules 4 and 5:

Stage 2:
Rule 4: IF $T(t)$ is F_4, THEN $x(t)$ is 100.
Rule 5: IF $T(t)$ is F_5, THEN $x(t)$ is x_2.

Membership functions of these fuzzy sets are shown in Figure 6. The output of the fuzzy temperature controller is given by

$$x(t) = 100 \times F_4(T(t)) + x_2 F_5(T(t)) \qquad (10)$$

Remark 2 *Note that the value β determined from Rules 1~3 is implicitly used in the membership functions $F_4(T(t))$ and $F_5(T(t))$ and the value x_2 also appears in the THEN part of Rule 5. Therefore we have a two-stage cascade fuzzy inference engine. At the stage 1, according the temperature setting T_r, the two values β and x_2 are generated by inferencing Rules 1~3. These two values are then fed into stage 2 in order to calculate the duty ratio $x(t)$ by inferencing Rules 4~5. The cascade structure of the fuzzy inference engine not only reflect our control strategy but can also effectively reduce the number of rules.*

Strategy for steady-state phase: At the time instant t_c, the system has been brought around the desired operating point $T(t) = T_r$. We may roughly say that for $t \leq t_c$, the system is in transient phase and for $t \geq t_c$, the system is in the steady-state phase. However, due to uncertain environment temperature, the drawn heat power by using the fan, heat leakage to the environment, the effect of convection, and other miscellaneous uncertain terms, $T(t)$ will fluctuate around the set point in the steady-state phase. To reduce the fluctuation and obtain the desired steady-state tracking accuracy, after $t = t_c$, the duty ratio $x(t)$ will be adjusted by an adaptive scheme.

For $t > t_c$, the value x_2 in the THEN part of Rule 5 is update according to the following adaptive law

$$x_2(t+1) = \begin{cases} x_2(t), & \text{if } |e(t)| \leq \delta_d \\ x_2(t) - k_c\, sgn(e(t)), & \text{if } |e(t)| > \delta_d \end{cases} \qquad (11)$$

where $e(t) = T_r - T(t)$ is the temperature tracking error, δ_d the desired accuracy, and k_c the adaptation gain. Therefore the fuzzy interpolation of the duty ratio $x(t)$ in the steady-state phase is given by

$$x(t) = 100 \times F_4(T(t)) + x_2(t) F_5(T(t)) \qquad (12)$$

Note that as the step response of the open-loop electroheat system has a slow transient response and a large overshoot, the bandwidth of the system is not wide and the phase margin can be poor. Therefore, the adaptation gain k_c should be small and on the contrary, the sampling time of the digital temperature control system should not be small. In this study, the control sampling time for generating the actuation signal $x(t)$ is 3 minutes, the adaptation gain k_c is equal to one, and the desired accuracy δ_d is $1°C$.

5. Experimental Results

In this section, we shall demonstrate the experimental results of the fuzzy temperature control method. The temperature settings $50°C$, $100°C$, and $200°C$ are tested to obtain feasible fuzzy control parameters β_i and c_i in Rules 1~3 in advance. The testing results are summarized in the following table.

Table 1. Parameters in Rules 1~3

Rule 1		Rule 2		Rule 3	
$50°C$		$100°C$		$200°C$	
β_1	c_1	β_2	c_2	β_3	c_3
0	3%	0.2	20%	0.6	73%

In the following, we proceed to check the tracking capability of the proposed adaptive fuzzy temperature controller with respect to the temperature settings to $100°C$, $150°C$, and $200°C$. For the temperature setting $T_r = 100°C$, the experimental result is shown in Figure 7 which shows an overshoot about $3°C$ and an average steady-state tracking error about $1°C$. Next, tracking performance for the temperature setting $T_r = 200°C$ is illustrated in Figure 8. In this figure, we can observe that the overshoot is about $5°C$ and the average steady-state error is about $1°C$. For the above two cases, overshoot of the temperature response is lessened by the suitably chosen parameters β_i and c_i in fuzzy Rules 1~3. On the other hand, fluctuation of chamber temperature $T(t)$ in the steady state is effectively reduced by the adaptive tuning law so that good tracking performance is attained.

Now we test the temperature setting $T_r = 150°C$ which is not considered in the training of the fuzzy control system. Therefore, in this case, the duty ratio $x(t)$ is generated by fuzzy interpolation using the fuzzy sets F_1, F_2, and F_3 which correspond to the temperature settings $50°C$, $100°C$, and $200°C$, respectively. The experimental result is shown in Figure 9. From this figure, we can see that the overshoot is about $6°C$, and the average steady-state error is about $1.5°C$. The transient and steady-state responses are still satisfactory.

6. Conclusions

In this study, we implement a simple fuzzy temperature controller by using some cheap and standard ICs. Because the real electroheat system is a complex process, it can not be satisfactorily controlled by using conventional control methods. Therefore, we take advantage of the fuzzy control to avoid the complex mathematical modeling of the plant and utilize operation experiences

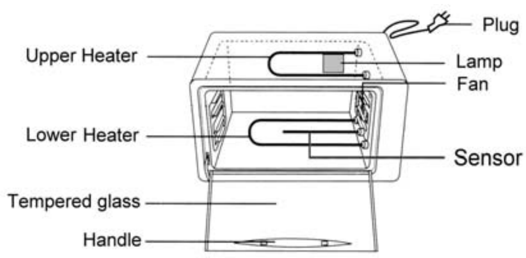

Figure 1: Configuration of the heater RB-6240

to construct the fuzzy controller. From the experimental results, good transient and steady-state responses are obtained.

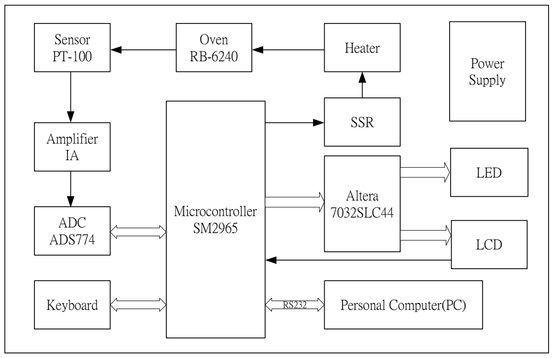

Figure 2: Block diagram of the temperature controller

References

[1] B. A. Ogunnaike and W. H. Ray, *Process Dynamics, Modeling, and Control,* Oxford, 1994.

[2] Wu-Chung Su and Ching-Chih Tsai, "Discrete-time VSS temperature control for a plastic extrusion process with water cooling systems," *IEEE Transactions on Control Systems Technology*, Vol.9, No.4, pp. 618 -623, July 2001.

[3] Jiann-Joug Lin, *Applications of Fuzzy Control on Thermal Systems*, Master Thesis, Chung Hua University, Hsinchu, Taiwan, 1995.

[4] D. Sankowski, J. Kucharski, and W. Lobodzinski, "Autotuning temperature control using identification by multifrequency binary sequences," *IEE Proc. Control Theory Appl.*, Vol.144, No.3, pp. 1-3, May 1977.

[5] Un-Chul Moon and Kwang Y. Lee, "Temperature control of glass melting furnace with fuzzy logic and conventional PI control," *Proceedings of the American Control Conference, Chicago*, Illinois, June 2000.

[6] Z. Bil, B. S. Butkiewicz, "Furnace temperature control with fuzzy microcontroller," *SMCia/99,1999 IEEE Midnight-Sun Workshop on Soft Computing Methods in Industrial Applications*, Kuusamo, Finland, pp. 16-18, June1999.

[7] J.-S. R. Jang, C.-T. Sun, and E. Mizutani, *Neuro-Fuzzy and Soft Computing: A Computational Approach to Learning and Machine Intelligence*, Prentice Hall, Upper Saddle River, New Jersey, 1997.

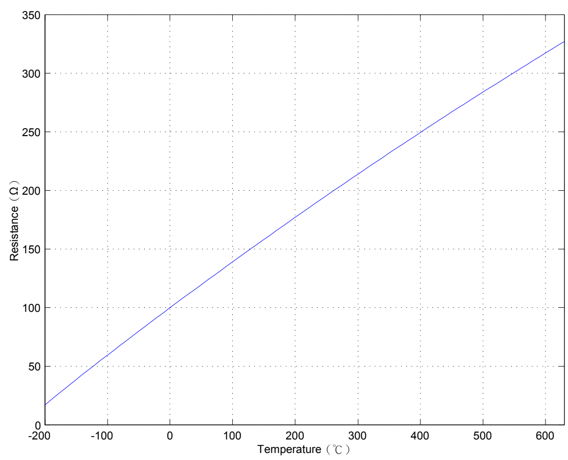

Figure 3: Operation curve (temperature vs. resistance) of the platinum sensor PT-100.

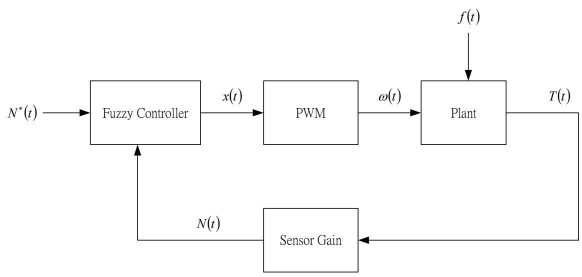

Figure 4: Block diagram of the fuzzy control system.

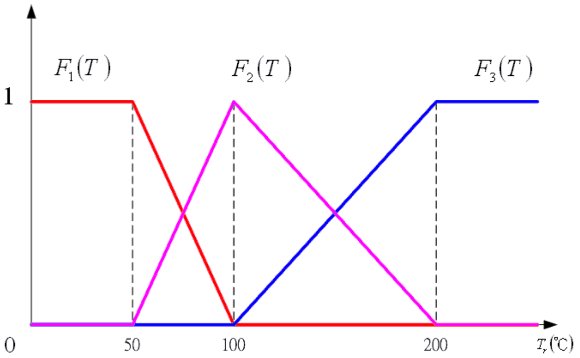

Figure 5: Membership functions of fuzzy sets F_1, F_2, and F_3.

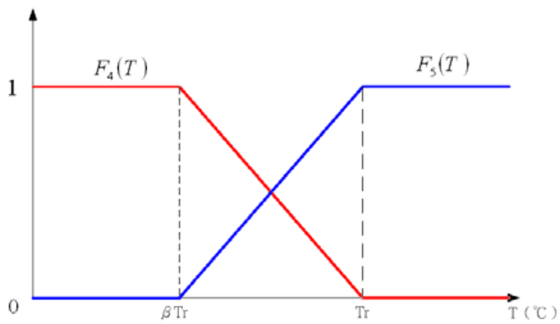

Figure 6: Membership functions of fuzzy sets F_4 and F_5.

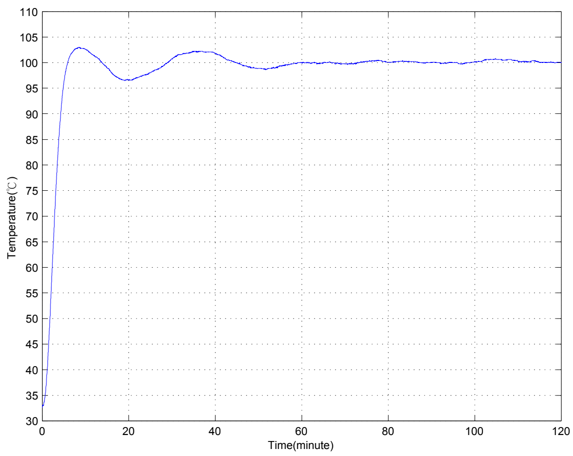

Figure 7: Control for low temperature ($T_r = 100°C$).

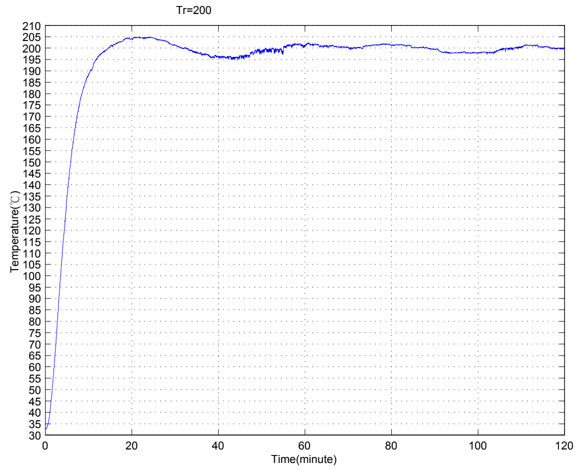

Figure 8: Control for high temperature ($T_r = 200°C$).

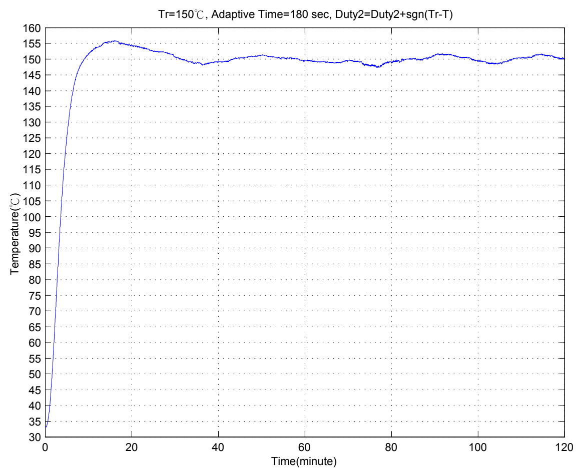

Figure 9: Control for middle temperature ($T_r = 150°C$).