Study on PID temperature control performance of a novel PTC material with room temperature Curie point

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Abstract: Positive Temperature Coefficient (PTC) material is a kind of thermo-sensitive material, using PTC resistors to replace the ordinary resistive materials as heating elements may become a new means of precise temperature control for electronic devices. In this paper, a novel PTC material with Curie temperature of 34°C was prepared and the new thermal control method of combining PTC material with Proportional-Integral-Derivative (PID) control algorithm was proposed. The experimental system and mathematical model of PID temperature control by using PTC material were established. Based on this, the PID temperature control performance of PTC material was investigated with a comparison of ordinary resistance heater experimentally and theoretically. The results show that using PTC material for PID temperature control can effectively reduce overshoot; while the parameters of PID controller are within certain ranges, temperature control effects of PTC material are superior to ordinary heater, the temperature overshoot is reduced and the temperature control accuracy is increased. Furthermore, preparing PTC material with larger resistance-temperature coefficient may likely contribute to improve its PID temperature control effect. The research results specify possible directions for PID temperature control by using PTC materials in order to achieve precise thermal

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22 control of electronic devices.

23

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25 thermal control

26

27 Nomenclature

A	cross-sectional area of material (cm^2)	i	time(s)
A_1	upper surface area of aluminum block (cm^2)	k	time(s)
		K_P	proportional coefficient
A_2	side surface area of aluminum block (cm^2)	L	thickness of material (cm)
		m	mass of aluminum block (kg)
B	characteristic parameter of PTC material (K^{-1})	R	resistance of PTC material (Ω)
		R_C	resistance of PTC heater at Curie temperature(Ω)
c_P	specific heat capacity of aluminum block ($\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$)	R_t	resistance of PTC heater at terminate
$e(k)$	temperature difference between set temperature and transient temperature ($^{\circ}\text{C}$)		temperature(Ω)
		T	transient temperature of aluminum block ($^{\circ}\text{C}$)
h_1	average heat transfer coefficient of the upper surface ($\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$)	T_C	Curie temperature ($^{\circ}\text{C}$)
		T_D	differential time constant(s)
h_2	average heat transfer coefficient of the side surface ($\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$)	T_I	integration time constant(s)
		T_s	sampling time(s)

T_t	terminate temperature (°C)		the PTC material (K ⁻¹)
T_∞	ambient temperature (°C)	ρ	resistivity of PTC material (Ω·cm)
U	output of PID controller (V)	β	characteristic parameter of PTC
<i>Greek letters</i>			material
α_T	resistance-temperature coefficient of		

1

2 1. Introduction

3 Thermal control systems are of great importance to maintain the temperatures of electronic devices
4 within acceptable ranges in order to guarantee the stable operation of the electronic devices. Any
5 electronic equipment will occur malfunction or failure under the condition of non-uniform thermal
6 stress over a long period of time, and 55% of all the electronic equipment failures are caused by
7 temperature [1, 2]. Furthermore, with the development of electronic technology, thermal control
8 accuracy and stability requirements of some sophisticated equipments are also increasing [3-5]. This
9 requires that the temperature control quality of thermal control systems should be further improved.
10 Active electric heating method is one of the common means to achieve high-precision temperature
11 control for thermal control systems [6]. It is widely used in thermal control systems of spacecraft load
12 components, atomic clocks, optic devices and other precision instruments [7-10].

13 Positive temperature coefficient (PTC) material is a kind of thermo-sensitive material. Their
14 resistivity remains relatively unchanged when the temperature of the materials is in certain range, but
15 begins to rise rapidly when the temperature is above the temperature named the Curie temperature.
16 Studies have shown that using PTC material as a heating element to conduct active thermal control has
17 the ability to achieve adaptive temperature control as well as to improve temperature control accuracy

[11-13]. The rationale of this temperature control method is that the resistivity of PTC material will increase sharply with temperature while the temperature exceeds the Curie point, leading to a sharp decline in heating power. However, the existing commercial PTC materials are mainly used in high temperature ranges. For the fact that electronic devices usually operate at room temperature, a series of novel PTC materials with room temperature Curie point were prepared [14], which laid the foundation for precise thermal control of electronic devices. However, when using PTC materials for adaptive temperature control, this method is limited to the Curie temperature of the material, and it cannot be precisely controlled to the desired temperature point; when combining PTC materials with switch control method for precise temperature control, although this method is simple in structure and easy to implement, it has shortcomings of large temperature fluctuation, low temperature control accuracy and low energy efficiency [15, 16].

In order to further enhance the temperature control quality of PTC material, the new thermal control method of combining PTC material with Proportional-Integral-Derivative (PID) control strategy is proposed in this paper. PID control is widely used in various industrial controls because of its simple structure, easy implementation, and strong robustness. So far, PID control technology is still the basis of industrial process control. According to the survey data, among a variety of control techniques at present, PID control technology and its optimized control technology are accounted for more than 90%, and the ordinary PID control technology is also accounted for 84.5% [17]. Ordinary PID temperature control uses the temperature deviation for proportional, integral and differential calculation, then feed back to ordinary resistance heater to adjust the heating power in order to achieve precise temperature control. For ordinary PID temperature control method, the choice of its proportional, integral and differential parameters depends on experience. It has defects of large overshoot, low steady-state

accuracy if the parameters are inappropriately selected [18, 19]. It is often unfavorable for the precise thermal control process of electronic devices. In addition, since the characteristic of PTC resistor is different from the ordinary resistor, it is difficult to directly apply PID controller to the PTC material for precise temperature control.

According to these situations, in this paper, a novel PTC material with Curie temperature of 34°C was prepared for the heating element, combined with PID temperature control strategy, the experimental system and mathematical model were presented. Based on the experimental system, the PID temperature control characteristic of PTC material was investigated and its comparison with an ordinary resistance heater was conducted. Furthermore, the PID temperature control method which suited for the PTC material and the effect of material parameter on PID temperature control process were investigated by simulation analysis.

2. Experimental system and theoretical modeling

2.1 Characteristic of the novel PTC material

According to reference [14], a novel PTC material was recently prepared. The logarithmic resistivity-temperature curve of the material was measured and the results are shown in Fig. 1. As shown in Fig. 1, the resistivity of the material remained constant in low-temperature region, but suddenly began to increase sharply when the temperature exceeded its Curie temperature ($T_C=34^\circ\text{C}$). When the temperature continued to rise up to another point, which is named as terminate temperature ($T_T=37^\circ\text{C}$), the resistivity increased slowly. The resistance-temperature coefficient of the PTC material, which expresses the relative change of resistance when temperature changes per unit, is defined

as: $\alpha_T = \frac{1}{R} \cdot \frac{dR}{dT} = \ln 10 \cdot \frac{d \lg \rho}{dT}$. So the resistance-temperature coefficient of the material can be

obtained as about 2.06 K^{-1} .

When the temperature was higher than Curie temperature and lower than terminate temperature of the PTC material, the resistivity increased exponentially with the temperature, which can be expressed as:

$$\rho = 10^{BT+\beta} \quad (1)$$

where β is a parameter related to the initial resistivity of the PTC material, B is the gradient of the logarithmic resistivity-temperature curve, which is proportional to resistance-temperature coefficient

$$\alpha_T \left(B = \frac{1}{\ln 10} \cdot \alpha_T \approx 0.9 \right).$$

So the resistance of the PTC material can be expressed as:

$$R = \rho \cdot \frac{L}{A} = 10^{BT+\beta} \cdot \frac{L}{A} = 10^{BT+\beta+\lg \frac{L}{A}} \quad (2)$$

where L is the thickness of the material, A is the cross-sectional area of the material.

The resistance of PTC material was measured as 56.4Ω when temperature was 34°C . So in the temperature ranges of $34\sim 37^\circ\text{C}$, the resistance of PTC material can be derived as:

$$R = 10^{BT+\beta+\lg \frac{L}{A}} = 10^{0.9 \cdot T - 28.84855} \Omega \quad (3)$$

2.2 PID temperature control experimental system

The PID temperature control experimental platform of PTC material and ordinary resistor was established. Schematic of the experimental system is shown in Fig. 2. It mainly consists of a controlled element, temperature sensors, a temperature acquisition module, a PID controller, a digital output module and the heating elements.

The novel PTC material and constantan wire were used as the heating elements respectively, and the resistance of constantan wire was the same as that of PTC material at Curie temperature. The PTC

material was polished with the size of $22\text{mm} \times 28\text{mm} \times 2\text{mm}$ and then it was processed and sealed to be a heating element, as shown in Fig. 3(a) and Fig. 3(b). The constantan wire was intertwined on a thin copper sheet to form an ordinary resistance heater. Two aluminum blocks with the same size of $22\text{mm} \times 28\text{mm} \times 20\text{mm}$ were used to simulate the controlled electronic components. The heating elements were placed in the middle of the two aluminum blocks and the contacting surfaces were painted with silicone grease to reduce the impact of thermal contact resistance. The whole component was placed on a substrate which had a good heat insulation performance. The temperature of the aluminum block was measured by platinum resistance thermometer and the uncertainty of the thermometer is less than $\pm 0.002\text{K}$. NI-9217 (National Instruments Corporation) was used for the temperature acquisition module. It has 24 bits acquisition accuracy and the uncertainty caused by NI-9217 is less than 1%. PID controller was implemented in PC by software and NI-9474 (National Instruments Corporation) was used for digital output module.

The experimental component, together with the substrate, was placed in a container full of air. And the container was placed in a thermostat water bath for a better control of the ambient temperature. Platinum resistance thermometer was fixed to the bottom side of the aluminum block to measure the surface temperature. The experiment began while the temperature of aluminum block reached equilibrium with ambient temperature, then PID control process got started by adjusting the set temperature, three parameters (proportional, integral and differential coefficient) of the controller and the sampling time in PC. The digital output of the controller was realized through Pulse Width Modem (PWM) voltage converter module, which was aimed at controlling the heating time per sampling cycle to precisely adjust the heating power of the heater in order to control the temperature of aluminum block. An external DC power supply was used to enhance the load capacity of the output module and

the supply voltage was kept constant. The pictures of the experimental system and temperature control interface are shown in Fig. 4.

Since high-precision electronic devices have strict requirements for its temperature stability, the temperature control accuracy refers to temperature control stability in this paper. The temperature stability of the platinum resistance thermometer could be acquired by calibrating ice water mixture, as shown in Fig. 5. It was observed that while the temperature of ice water mixture became stable after 2200s, the temperature stability of the platinum resistance thermometer was about $\pm 0.001\text{K}$.

2.3 PID temperature control model by using PTC material

The theoretical model of PID temperature control by using the PTC material was established and schematic of the model is shown in Fig. 6. PTC material was placed in the middle of the same two aluminum blocks with close contact in order to reduce the impact of thermal contact resistance. Heat was insulated between the aluminum blocks and the substrate. Since two aluminum blocks were symmetric, the left one was selected for analysis. The size of the aluminum block was $28\text{mm}\times 22\text{mm}\times 20\text{mm}$ and had no internal heat source. According to reference [20], in process control systems, most of the heat transfer processes does not include heat radiation. Besides, the surface emissivity and temperature of the aluminum block were low. In order to simplify calculation, heat radiation process was not taken into account. Therefore, natural convection heat transfer existed between the surfaces of the aluminum block and the environment except the bottom and the right sides. Since the thickness of the PTC material was extremely thin and the mass was very small, its own heat storage and the heat exchange with external environment were negligible. So the heat generated by the PTC material was all transmitted to the aluminum block by heat conduction.

The lumped temperature model could be used here [13, 14]. Therefore, the energy conservation equation is obtained:

$$mc_p \frac{dT}{dt} + h_1 A_1 (T - T_\infty) + h_2 A_2 (T - T_\infty) = \frac{U^2}{R(T)} \quad (4)$$

where m is the mass of the aluminum block, c_p is the specific heat capacity of the aluminum block, h_1 and h_2 are average heat transfer coefficient of the side and the upper surface, A_1 and A_2 are areas of the side and the upper surface, T is transient temperature, T_∞ is ambient temperature, U is the output of PID controller, $R(T)$ is resistance of the PTC material.

The basic equation of digital PID controller is expressed as:

$$U(k) = K_p \left[e(k) + \frac{1}{T_I} \sum_{i=0}^k e(i) T_s + T_D \frac{e(k) - e(k-1)}{T_s} \right] \quad (5)$$

where K_p is proportional coefficient, T_I is integration time constant, T_D is differential time constant, T_s is sampling time, $e(k)$ is temperature difference between set temperature and transient temperature at time k , $U(k)$ is output of the controller at time k .

According to Eq. (5), and transformed Eq. (4) into a discrete equation, then Eq. (4) can be expressed as:

$$mc_p \frac{T(k) - T(k-1)}{T_s} + h_1 A_1 (T(k) - T_\infty) + h_2 A_2 (T(k) - T_\infty) = \frac{K_p^2 \left[e(k) + \frac{1}{T_I} \sum_{i=0}^k e(i) T_s + T_D \frac{e(k) - e(k-1)}{T_s} \right]^2}{R(T(k))} \quad (6)$$

where $T(k)$ is temperature of the aluminum block at time k . $R(T(k))$ is the resistance of PTC material when temperature is $T(k)$.

According to Eq. (3), and an assumption was made that the resistance of PTC heater didn't change with temperature when it was below Curie temperature or above terminate temperature, then $R(T(k))$ can be expressed as:

$$R(T(k)) = \begin{cases} 10^{0.9T_C - 28.84855} = R_C & (T(k) \leq T_C) \\ 10^{0.9T(k) - 28.84855} & (T_C \leq T(k) \leq T_t) \\ 10^{0.9T_t - 28.84855} = R_t & (T(k) \geq T_t) \end{cases} \quad (7)$$

where T_C is the Curie temperature of PTC material and T_t is the terminate temperature of PTC material. R_C is the resistance of the PTC heater when temperature is below Curie point. R_t is the resistance of the PTC heater when temperature is above terminate temperature.

Assuming that the initial temperature of aluminum block was the same as ambient temperature, the convection heat transfer coefficient $h1$ and $h2$ could be calculated according to reference [14]. Then the transient temperatures of the aluminum block at different times could be calculated by specifying set temperature, ambient temperature and the three (K_p , T_i , T_D) parameters of PID controller.

3. Experimental results and analysis

3.1 PID temperature control characteristic of the PTC material

The PID temperature control characteristic of PTC material was firstly investigated by experimental study. In order to discuss the impact of PTC material on PID temperature control process, the set temperature shouldn't be lower than the Curie temperature of the material. Thus, the experiment was firstly conducted while the set temperature was 35°C and 36°C, respectively, and the ambient temperature was 30°C. Three parameters of PID controller ($K_p/T_i/T_D$) were 1/6s/3s and sampling time was 0.1s. The temperature curves of aluminum block are shown in Fig. 7.

According to Fig.7, it was observed that both the temperature rising processes became very slow after the Curie temperature of PTC material. The target temperature even couldn't be reached when the set temperature was 36°C. This phenomenon can be interpreted that when the temperature of PTC material exceeded its Curie temperature, the resistance increased rapidly as the temperature increased,

leading to the decrease of heating power sharply. While temperature continued rising, the resistance of PTC material became larger, which would result in a very low heating power even if the output duty ratio of PID controller was 100%. The heating power was unable to maintain the heat dissipation of aluminum block to the environment. Therefore, the aluminum block couldn't reach the set temperature of 36°C. Additionally, it also can be seen in Fig.7 that both the temperature rising curves experienced a process which the slope decreased first and then begun to increase near the Curie point of the PTC material. This phenomenon occurred probably due to the influence of heat capacity of the PTC material.

As can be seen from the above results, in order to better investigate PID temperature performance of the PTC material, it is more appropriate to choose the set temperature as 34°C in the following experiments.

3.2 PID temperature control comparison between PTC material and ordinary resistor

In order to further study PID temperature control quality of the PTC material, an ordinary resistor which used the constantan wire was selected for comparison and the resistance of constantan wire was the same as that of PTC resistor at Curie temperature. The experiment was conducted while the set temperature was 34°C and ambient temperature was 29°C. The sampling time was 0.1s. The results are shown in Fig.8, Fig. 9 and Fig. 10 under conditions of different parameters of PID controller ($K_P/T_I/T_D$). According to the above three figures, together with other experimental results at different conditions, the temperature overshoots and temperature control accuracies by using different heating elements under different situations could be sorted out, as shown in Table 1.

It can be seen in Fig.8 that the overshoot of temperature curve while using PTC material was 0.13°C,

it was significantly less than that of ordinary resistor which was 0.72°C . However, the temperature control accuracy of PTC material was $\pm 0.08^{\circ}\text{C}$, which was lower than the control accuracy of ordinary resistor $\pm 0.03^{\circ}\text{C}$, and the steady temperature regulating process of PTC material became extremely slow compared with that of ordinary resistor. This is because the heating power of PID controller output decreased significantly due to the rapid resistance increase of PTC material after Curie temperature. So the temperature overshoot of PTC material was reduced. Meanwhile, under this condition, proportional coefficient K_p of PID controller was small. The proportional adjustment effect of deviation was weak, which might also lead to a sluggish temperature regulating process. Thus, the difference between two temperature curves became more obvious after Curie point.

It can be observed in Fig.9 that the overshoot of temperature curve while using PTC material was also significantly less than that of ordinary resistor, and the temperature control accuracy of PTC material was lower than that of ordinary resistor. In addition, integral windup occurred in temperature rising process when using ordinary resistor for temperature control and the steady temperature regulating process of PTC material was obviously faster than that in Fig.8. This is because the proportional coefficient K_p was large and the integration time constant T_i was small at this condition, the integral effect of PID controller was proportional to K_p and inversely proportional to T_i according to Eq. (5), so it would lead to a strong integral effect. Furthermore, the PTC characteristics could affect the temperature deviation to alter the integral process of PID control, which may be the reason why the temperature control accuracy of PTC material became deteriorated.

As it illustrated in Fig.10, the temperature overshoot of ordinary resistor was about 0.02°C , and the temperature control process of PTC resistor basically had no overshoot. The temperature control accuracy of PTC resistor was $\pm 0.001^{\circ}\text{C}$, it was higher than that of ordinary resistor which was about

$\pm 0.005^{\circ}\text{C}$. Since the temperature stability of thermometer was $\pm 0.001^{\circ}\text{C}$, it completely eliminated the steady-state error. Thus, the temperature control quality of PTC material was better than ordinary resistor in this situation.

According to Table.1, while PID parameters were 100/120s/0.3s, both of the processes had a steady-state error which couldn't be eliminated, although the overshoot of PTC material was smaller than that of ordinary resistor. It is because the proportional coefficient K_p was too large that would make the control process instable. When PID parameters were 10/1200s/3s, the target temperature could hardly be reached for both of the control processes. It is because the integration time constant T_i was too large that could greatly weaken the integral effect. The control process became sluggish and ineffective.

As far as it can be seen from Table.1 and the above Figures: PTC material could reduce temperature overshoot compared with ordinary resistor in every circumstance when using PID strategy for temperature control. However, the temperature regulating process of PTC material would become sluggish after Curie temperature. When PID parameters were in certain ranges, temperature control accuracies of PTC material were higher than that of ordinary resistor. While in other conditions, temperature control accuracies of PTC material became deteriorated compared with ordinary resistor, which meant the PID parameters were inappropriate for the PTC material.

4. Simulation results and analysis

4.1 Verification of the model

Based on the theoretical model, the transient temperatures of aluminum block by using PTC material for PID control were calculated under the same circumstance as that in experiment. The comparison

between the calculated and experimental temperature curves is shown in Fig. 11.

It can be observed in Fig.11 that the tendency of calculated transient temperature curve was generally consistent with that of experimental curve. The temperature rising of calculated curve was slightly faster than that of experimental curve at the beginning. This may be interpreted as follows: Since the thermal contact resistance actually existed between the PTC material and the aluminum blocks in experiment, when the temperature of aluminum block reached the Curie temperature of PTC material, the actual resistance of PTC material was larger than the calculated resistance at Curie point. So the heating power in experiment was smaller than that in calculation. Moreover, when the output of PID controller changed in the experiment, the temperature of aluminum block did not change immediately with the change of heating power. There was a certain time lag. It also can be seen that the temperature control accuracy of calculated curve was $\pm 0.008^{\circ}\text{C}$ and it was slightly higher than that of experimental curve which was $\pm 0.012^{\circ}\text{C}$. This may be caused by the measurement error in the experiment.

The calculation curve agreed well with the experimental results, which indicated that the PID temperature control model of the PTC material was reasonable. Since the resistance of ordinary resistor was constant, the PID temperature control curve of the ordinary resistor could also be calculated accurately.

4.2 Simulation analysis of the model

In order to further investigate PID temperature control performance of the PTC material, the theoretical model was used for simulation analysis. The numerical simulation was conducted under different PID parameters and the other conditions were the same as that in experiment. The temperature overshoots and temperature control accuracies by using different heating elements under different

situations could be acquired and some of the results are shown in Table.2.

According to Table.2, it can be observed that the value of proportional coefficient which suited for the PTC material used in this paper was from 5 to 10. The proportional effect was introduced by PID controller to reduce temperature deviation and accelerate regulating process. When the proportional effect was weak, the PID regulating process would become sluggish. As for PTC material, the temperature regulating process after Curie point would become slower compared with the ordinary resistor; when the proportional effect was too strong, the PID regulating process of both materials would become instable. The integral effect was introduced by PID controller to eliminate steady-state error in order to increase the control accuracy. According to Eq. (5), the integral effect was proportional to proportional coefficient K_P , and inversely proportional to integration time constant T_I . When K_P remained constant, a small T_I would also make the temperature control process instable and a large T_I would lead to a weak control effect which couldn't reduce the steady-state error of temperature control. While using PTC material for PID temperature control, the temperature rising process after Curie point was slower than that of ordinary resistor, which indicated the temperature deviation $e(k)$ differed from that of ordinary resistor at different times. The parameters that suited for the two kinds of materials were different. When the value of integration time constant T_I was from 15 to 30, the temperature control accuracy of PTC material was superior to that of ordinary heater. The differential effect was introduced by PID controller to improve the dynamic characteristics of the control process. It was capable to suppress the temperature deviation changes so as to shorten the transition time and reduce overshoot. According to Eq. (5), the differential effect was proportional to proportional coefficient K_P and differential time constant T_D . When K_P remained constant, either a large or small T_D could lead to the deterioration of dynamic characteristics. The suitable T_D was approximately from 0.1 to 10

according to Table.2.

Furthermore, when $K_P/T_I/T_D$ was chosen in suitable ranges, the numerical simulation was conducted with different B values of the PTC material. The obtained results are shown in Fig. 12.

It could be found in Fig. 12 that with the increase of B value of PTC material, the overshoot of PID temperature control process decreased. This is because when parameter B of the PTC material was larger, the resistance increased faster after Curie temperature, which would result in the larger decrease of heating power. Since B was proportional to the resistance-temperature coefficient of the PTC material, it suggested that the PID temperature control performance would be better when the resistance-temperature coefficient of the material was larger. Therefore, preparing PTC material with larger resistance-temperature coefficient might likely contribute to enhance its PID temperature control effect.

5. Conclusions

In this paper, the method of using the novel PTC material to replace ordinary resistor as a heating element for PID temperature control of electronic devices was proposed. Compared with the ordinary resistor, the PID temperature control performance of the novel PTC material was investigated experimentally and theoretically. In addition, the appropriate PID parameters for the PTC material and the effect of PTC material parameter on the PID temperature control process were discussed. The obtained conclusions are as follows:

- (1) Combining PTC material with PID control strategy provides a new effective method for high-precision thermal control of electronic devices.
- (2) Using PTC material for PID temperature control can effectively reduce overshoot of the process.

(3) When the parameters of PID algorithm are within certain ranges, the temperature control quality of the PTC material is superior to that of ordinary resistor, the temperature overshoot is reduced and temperature control accuracy is improved.

(4) Preparing PTC material with larger resistance-temperature coefficient holds promise to improve its PID temperature control effect.

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Figure captions

Fig.1. The logarithmic resistivity-temperature curve of the novel PTC material

Fig.2. Schematic of the experimental system

Fig.3. PTC material and PTC heater

Fig.4. The pictures of the experimental system and temperature control interface

Fig.5. The temperature stability of the platinum resistance thermometer

Fig.6. Schematic of the theoretical model

Fig.7. Temperature curves when ambient temperature is 30°C, set temperature is 35°C and 36°C

Fig.8. Temperature curves when ambient temperature is 29°C, set temperature is 34°C, $K_P/T_I/T_D$ is

1/6s/3s

Fig.9. Temperature curves when ambient temperature is 29°C, set temperature is 34°C, $K_P/T_I/T_D$ is

10/3s/3s

Fig.10. Temperature curves when ambient temperature is 29°C, set temperature is 34°C, $K_P/T_I/T_D$ is

10/30s/3s

Fig.11. Comparison between the calculated curve and the experimental curve

Fig.12. PID temperature control simulation with different B values of the PTC material

Fig.1. The logarithmic resistivity-temperature curve of the novel PTC material

Fig.2. Schematic of the experimental system

(a)

(b)

Fig.3. PTC material and PTC heater

(a)

(b)

Fig.4. The pictures of the experimental system and temperature control interface

Fig.5. The temperature stability of the platinum resistance thermometer

Fig.6. Schematic of the theoretical model

Fig.7. Temperature curves when ambient temperature is 30°C, set temperature is 35°C and 36°C

Fig.8. Temperature curves when ambient temperature is 29°C, set temperature is 34°C,

$$K_p/T_I/T_D \text{ is } 1/6\text{s}/3\text{s}$$

Fig.9. Temperature curves when ambient temperature is 29°C, set temperature is 34°C,

$$K_p/T_I/T_D \text{ is } 10/3\text{s}/3\text{s}$$

Fig.10. Temperature curves when ambient temperature is 29°C, set temperature is 34°C,

$$K_P/T_I/T_D \text{ is } 10/30\text{s}/3\text{s}$$

Fig.11. Comparison between the calculated curve and the experimental curve

Fig.12. PID temperature control simulation with different B values of the PTC material

Table captions

Table.1. The temperature overshoots and temperature control accuracies by using different heating elements under different PID parameters in experiment

Table.2. The simulation results of temperature overshoots and temperature control accuracies by using different heating elements under different situations

Table.1. The temperature overshoots and temperature control accuracies by using different heating elements under different PID parameters in experiment

PID parameters	Temperature overshoot(°C)		Temperature control accuracy(°C)	
$K_P/T_I(s)/T_D(s)$	PTC	Ordinary	PTC	Ordinary
1/6/3	0.13	0.72	±0.08	±0.03
10/3/3	0.06	0.71	±0.03	±0.006
10/30/3	0.002	0.03	±0.001	±0.005
100/120/0.3	0.024	0.07	0.024	0.07
10/1200/3	—	—	—	—
8/15/6	0.01	0.31	±0.002	±0.004

Table.2. The simulation results of temperature overshoots and temperature control accuracies by using
different heating elements under different situations

PID parameters	Temperature overshoot(°C)		Temperature control accuracy(°C)	
$K_P/T_I(s)/T_D(s)$	PTC	Ordinary	PTC	Ordinary
5/15 /0.1	0.35	0.86	±0.014	±0.02
8/30/10	0.05	0.30	±0.005	±0.008
10/30/0.1	0.03	0.25	±0.002	±0.006
5/20/1	0.22	0.64	±0.018	±0.025
10/15/5	0.14	0.51	±0.001	±0.004