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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 control of electronic devices.

1. Introduction

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

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

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Nomenclature

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

Greek letters

α_T	resistance-temperature coefficient of the PTC material (K^{-1})
ρ	resistivity of PTC material (Ω cm)
β	characteristic parameter of PTC material

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 Ref. [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 °C). When the temperature continued to rise up to another point, which is named as terminate temperature (T_t = 37 °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:

$$\rho = 10^{BT+\beta} \tag{1}$$

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

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

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

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

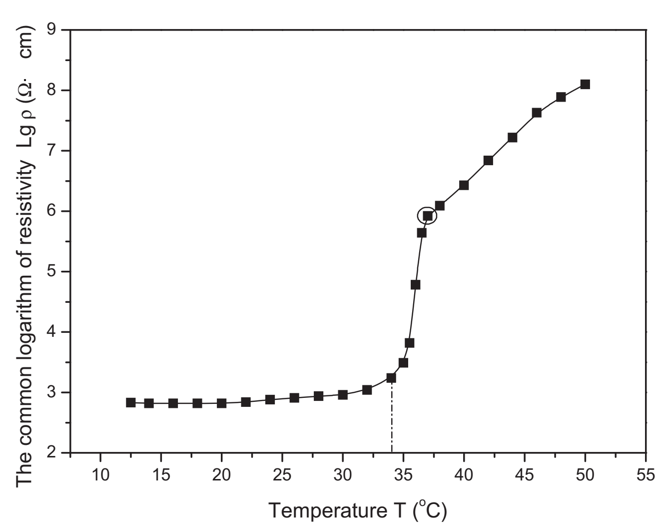

Fig. 1. The logarithmic resistivity–temperature curve of the novel PTC material.