Research on Intelligent Temperature Control Technology for Spacecraft with Instantaneous High Power Load

JinWang¹, MengmengGong², ShanglongZhu¹, QunZhang¹, Yi Chen¹, DefuLi¹, WanDeng¹ and FengQi¹

¹ Beijing Institute of Aerospace Systems Engineering, Beijing,10076, China
² China Academy of Launch Vehicle Technology, Beijing,10076, China
*Corresponding author’s e-mail: wj820buaa@163.com

Abstract. Thermoelectric modules are widely studied by domestic and foreign experts and scholars because of their light weight, small size, absence of mechanical moving parts, and the ability to switch between cooling and heating and adjust the cooling/heating capacity by current. Based on the advantages of thermoelectric modules, this paper proposes an innovative thermoelectric module-based intelligent temperature control device for instantaneous high-power payloads of spacecrafts, which can realize the rapid heat dissipation of high power payloads and adjust the current of thermoelectric modules through intelligent temperature control strategies to precisely regulate the payload temperature. The results show that the thermal control device can efficiently control the heat of the instantaneous high power load during the orbit, and the precision temperature control of the thermoelectric cooling work during the load operation is achieved with the temperature control accuracy of ±0.5°C.

1. Introduction

Research in thermoelectric cooling has been going on since the discovery of the thermoelectric effect in the 1820s. Many researchers have tried to improve the overall efficiency of thermoelectric modules, and some explored the application and optimization of thermoelectric modules. Based on the superiority of thermoelectric module with small size and no mechanical parts, a lot of application studies have been carried out in China and abroad [1-6]. L. Shen et al. [1] proposed a radiant air conditioner based on thermoelectric cooling by replacing the original water pipe with a thermoelectric module to provide cooling (heat) to the radiant plate. When the operating current of the thermoelectric cooling sheet is 1.2 A, the temperature of the cold plate can reach 20°C and the maximum COP can reach 1.77. F. Volklein et al. [2] applied thermoelectric cooling to microelectronic circuits, using SiCr/Si3N4 as the material of the thermoelectric sheet, and the cooling capacity can reach several MW and the cooling temperature difference can reach 30 K-50 K. Shanghai Institute of Technology Physics, Chinese Academy of Sciences The infrared detector temperature control system was designed and implemented for the need of operating at low temperatures for the on-board infrared detector, and a closed-loop feedback control method was used in the design [2]. A combination of phase change materials and thermoelectric cooling is used and an intelligent temperature control composite material that integrates structural temperature control functions [3] proposed by Beihang University.

The intelligent control strategy has the characteristics of strong self-adaptability, good robustness, and its learning ability as well as control ability can be continuously enhanced, etc. It can automatically measure the controlled quantity of the controlled object and find out the deviation from...
the expected value, as well as collect the information of the input environment, and then reason based on the collected input information and existing knowledge to obtain the output control of the controlled object, while making the deviation as small as possible or eliminating it. Generally used artificial intelligence control methods include neural networks, fuzzy logic, machine learning, evolutionary computation, and genetic algorithms. Fuzzy control\cite{7} is a rule-based control, which directly adopts language-based control rules and starts from the control experience of field operators or the knowledge of relevant experts, and requires no establishment of an accurate mathematical model of the controlled object in the design, thus making the control mechanism and strategy easy to accept and understand, simple to design, easy to apply, and the robustness of the fuzzy control system and the ability to resist disturbances and parameter changes is strong. Fuzzy control is especially suitable for the control of nonlinear, time-varying and purely hysteresis systems.

2. Thermal Control Device Principle of Combining Thermoelectric Cooling and Space Radiator

2.1 Thermal Control Device Principle of Operation

For the instantaneous operating characteristics of instantaneous high power load, combined with the advantages of thermoelectric cooling, a fuzzy incremental control based on the combination of thermoelectric cooling and space emitter thermal control scheme is proposed, through the intelligent controller to adjust the TEC thermoelectric cooling current size, to achieve intelligent temperature control. Figure 1 shows the working-principle diagram of the thermal control device. During the operation of the instantaneous high power load, the instantaneous high power load releases heat and the space radiator realizes heat dissipation. When the temperature of the instantaneous high power load is higher than the set value, the thermoelectric module realizes cooling near the instantaneous high power load end and heat dissipation near the space radiator end through the external power supply to realize the active heat transfer.

2.2 Mathematical Model of Thermal Control Device

The heat of the instantaneous high power load is transferred to the thermoelectric device by heat conduction. According to the conservation of energy, the dynamic equation of the instantaneous high power load temperature is

\[
C_z \frac{dT_z}{d\tau} = Q_z - \frac{1}{R_t}(T_z - T_{sl})
\]

where \(C_z\) is the heat capacity of the instantaneous high-power load; \(Q_z\) is the thermal power consumption of the instantaneous high-power load; \(T_z\) is the average temperature of the instantaneous high-power load, \(R_t\) is the thermal resistance between the laser and the top of the thermoelectric device and can be expressed as
where \( h_z \) is the contact heat transfer coefficient between the instantaneous high-power load and the top of the thermoelectric device.

The temperature dynamic equation of the top of the thermoelectric device is

\[
R_{d_1} \frac{dT_{d_1}}{d\tau} = \frac{1}{R_1} (T_z - T_{d_1}) - Q_{rd\_cold}
\]

(3)

where \( R_{d_1} \) is the heat capacity of the top plate of the thermoelectric device, \( T_{d_1} \) is the average temperature of the top of the thermoelectric device, \( Q_{rd\_cold} \) is the cooling capacity of the thermoelectric device and can be expressed as

\[
Q_{rd\_cold} = \eta \left[ \alpha IT_{d_1} + \frac{1}{2} I^2 R_e - K(T_{d_2} - T_{d_1}) \right]
\]

(4)

where \( \eta \) is the number of electric couple pairs, \( \alpha \) is the equivalent Seebeck coefficient for the whole device, \( I \) is the input current, \( R_e \) is the equivalent resistance, \( K \) is the equivalent thermal conductance, and \( T_{d_2} \) is the average temperature at the bottom of the thermoelectric device.

The temperature dynamic equation of the bottom end of the thermoelectric device is

\[
R_{d_2} \frac{dT_{d_2}}{d\tau} = Q_{rd\_hot} - \frac{1}{R_1} (T_{d_2} - T_{d_1})
\]

(5)

where \( R_{d_2} \) is the thermal capacity of the bottom of the thermoelectric device, \( R_2 \) is the thermal resistance between the bottom of the thermoelectric device and the radiator, \( T_k \) is the average temperature of the radiator, \( Q_{rd\_hot} \) is the thermoelectric device heat production and can be expressed as

\[
Q_{rd\_hot} = Q_{rd\_cold} + W_e = \eta \left[ \alpha IT_{d_2} + \frac{1}{2} I^2 R_e - K(T_{d_2} - T_{d_1}) \right]
\]

(6)

where \( R_2 \) can be expressed as

\[
R_2 = \frac{1}{h_{rf}}
\]

(7)

where \( h_{rf} \) is the contact heat transfer coefficient between the bottom plate of the thermoelectric device and the radiator.

The temperature dynamic equation of the space radiator is

\[
C_s \frac{dT_s}{d\tau} = R_3 (T_{d_2} - T_s) + Q_w - Q_m
\]

(8)

where \( C_s \) is the heat capacity of the space radiator, \( Q_w \) is the heat flow outside the space, \( Q_m \) is the external radiation heat of the space radiator and can be expressed as

\[
Q_m = \varepsilon \delta A_r T_r^4
\]

where \( A_r \) is the radiation area of the radiator, \( \varepsilon \) and \( \delta \) are the equivalent emissivity of the external surface of the radiator and the Stephen Boltzmann constant, respectively.

### 3. Control Model of Thermal Control Device

The essence of the fuzzy control strategy is to adjust the driving voltage of the thermoelectric device
and thus the driving current through the fuzzy control algorithm according to the error between the given value of the temperature control target and the actual measured value, in order to achieve the control of the heating surface temperature within the safe working range. The specific fuzzy control schematic is shown in Figure 2.

Figure 2. The specific fuzzy control schematic

In the designed fuzzy controller applied to the thermal control system, the instantaneous high power load temperature $T_z$ is chosen as the reference value and the thermoelectric device drive voltage $u$ as the control output value. The theoretical domains of both $e$ and $\Delta e$ are {-6,-4,-2,0,2,4,6} and the theoretical domains of $U$ are {-15,-10,-5,0,5,10,15}, respectively corresponding to: NB (negative large), NM (negative medium), NS (negative small), ZO (zero), PS (positive small), PM (positive medium) and PB (positive large). The subordinate functions of the fuzzy subsets of $e$ and $U$ are selected as Gaussian functions and the subordinate functions of the fuzzy subsets $\Delta e$ are selected as trigonometric functions. After input fuzzification, the operation to determine the fuzzy set uses the excitation strength of the fuzzy rule, which can be expressed as

$$\mu_{ji} = \min[\mu(i), \mu(j)]$$

(9)

The fuzzy rules consist of a series of "IF-THEN" fuzzy conditional sentences, which are a series of control rules represented by the fuzzy language variables $E$, $EC$ and $U$. All the rules are shown in Table 1. When the deviation is small, the control output is to prevent overshoot and system stability. According to empirical analysis, the fuzzy control rules for thermal control systems follow the following theories:

- when the amount of error change is small, for the temperature error is positive, it is necessary to reduce the thermoelectric device drive voltage, that is, the negative control variable increment, on the contrary, when the temperature error is negative, it is necessary to increase the thermoelectric device drive voltage, the output is positive.
- Whether the amount of error change is positive or negative, a large temperature error change requires a large thermoelectric device drive voltage output, and conversely a small drive voltage output is appropriate for a small error change.
- When the error increment is positive, an increase in the error variation will enhance the tendency for the thermoelectric device drive voltage output to decrease, while when the error increment is negative, an increase in the error variation means that there is a tendency to moderate the increase in the thermoelectric device drive voltage output.
- The decrease of error variation tend to moderate the driving voltage output of the thermoelectric device when the error increment is positive, and the decrease of error variation has a tendency to enhance the driving voltage output of the thermoelectric device when the error increment is negative.
The Mamdani algorithm is used to find the fuzzy subset of the output of the fuzzy control, and the center of gravity method is used to defuzzify the controller output, which can be expressed as

$$u = \int u_{t(i)} \mu_{f(i)} \, du \int \mu_{f(i)}$$  \hspace{1cm} (10)

where $u_{t(i)}$ is the theoretical domain of the fuzzy output value, $\mu_{f(i)}$ is the affiliation degree of the fuzzy output value.

### Table 1. Fuzzy control rules.

| E  | NB | NM | NS | ZO | PS | PM | PB |
|----|----|----|----|----|----|----|----|
| NB | PB | PB | PB | PB | PM | ZO | ZO |
| NM | PB | PB | PB | PB | PM | ZO | ZO |
| NS | PM | PM | PM | PM | ZO | NS | NS |
| ZO | PM | PM | PS | ZO | NS | NM | NM |
| PS | PS | PS | ZO | NM | NM | NM | NM |
| PM | ZO | ZO | NM | NB | NB | NB | NB |
| PB | ZO | ZO | NM | NB | NB | NB | NB |

### 4. Simulation Analysis

#### 4.1 The instantaneous High Power Load Operation Mode

According to the task requirements, the instantaneous high power load operation includes two modes of reduced power operation and intermittent continuous operation. In this paper, we focus on the analysis of the control effect of the thermoelectric device under the two different modes of operation of the instantaneous high power load. Figure 3 and Figure 4 show the variation curves of power consumption with time for the two modes of operation respectively.

**Figure 3. The variation curves of power consumption with time for step mode**

**Figure 4. The variation curves of power consumption with time for pulse mode**

#### 4.2 Control effect of switching operation mode for instantaneous high power load

The temperature variation curves of the instantaneous high power load under the system open-loop, PID control and fuzzy control under the instantaneous high power load switching operating mode and the temperature control curves of the thermoelectric device using PID and fuzzy are given in Figure 5~Figure 6, respectively, and the temperature data under the three operating conditions are given in Table 2. The following observations are obtained as per the figures:

- Under the system open loop, the system temperature continues to rise up to 50.2°C when the instantaneous high power load power consumption of 100W is working for 500s, and the temperature decreases up to 49.8°C at the end of the work after switching the working mode. And when using PID control as well as fuzzy control, the instantaneous high power load temperature...
can be well regulated, the temperature change range under fuzzy control is 30°C~31.75°C, and the temperature change range under PID control is 30°C~31.25°C.

- Fuzzy control under the system disturbance is small, the maximum overshoot is 1.25 °C, and the adjustment time is faster, but because of the power consumption, heat dissipation is slow, there is a large amount of heat accumulation situation, resulting in the thermoelectric device needs to constantly adjust the regulation voltage to achieve sufficient cooling capacity to meet the load temperature control needs, so in the 100W power consumption working 500s working conditions, the system has not reached steady state, the load temperature range in 30°C~31.25°C, which is smaller than 30°C~31.75°C under PID control. After 500s load mode switching, the fuzzy control responds faster than the PID control and reaches steady state sooner with a steady state value of 30.42°C, which is less than the steady state value achieved by the PID control.

### Table 2. The temperature data of three conditions.

| Conditions | Temperature at the end of the first stage(°C) | Temperature at the end of the second stage(°C) | First stage steady state error | Second stage steady state error |
|------------|--------------------------------------------|--------------------------------------------|-------------------------------|-------------------------------|
| Open loop  | 51.6                                       | 49.1                                       | -                             | -                             |
| PID        | 31.82                                      | 30.69                                      | -                             | 0.69                          |
| Fuzzy      | 31.29                                      | 30.42                                      | -                             | 0.42                          |

### 4.3 The instantaneous High Power Load Switching Operating Mode Control Effect

Figure 7~Figure 8 gives the temperature change curves of instantaneous high power load according to the working time sequence working under system open loop, PID control, fuzzy control of instantaneous high power load and temperature control curve of thermoelectric device using PID and fuzzy respectively, from the figure it can be seen that.

- In the initial 0 ~ 5800s, the instantaneous high power load is not working, the temperature has been reduced, the reduction is very small, within 2 °C; system open loop, in the instantaneous high power load work, the load temperature increases, up to 50.2 °C, and with the switch mode of work periodically increase and decrease; PID control as well as fuzzy control can be good control of the instantaneous high power load temperature variation range under both PID control and fuzzy control is 28.50°C~32.75°C.

- From Figure 8, it can be seen that the fuzzy control under the instantaneous high power load in the first two working cycles, the system perturbation is small, the maximum overshoot is 1.25 °C, and the regulation time is short, the time to reach steady state when the load is not working is short, the third working cycle, the maximum overshoot of fuzzy control is the same as PID control, the steady state error is increased compared to PID control, the steady state value is 30.15 °C, but the regulation response is fast and the time to reach steady state is shorter.
5. Conclusion

Instantaneous high power loads with intermittent operation, high instantaneous power density and high requirements for temperature control accuracy pose new challenges to the thermal control system. To solve the temperature control problem of the instantaneous high-power load in orbit, this paper proposes an innovative thermal control device combining thermoelectric cooling and space radiator to realize the active heat dissipation of the instantaneous high-power load in orbit; an active controller with fuzzy incremental control strategy is employed to solve the precise temperature control problem of the instantaneous high-power load; the node network method is employed to establish the in-orbit dynamic model of the thermal control device and the controller through. Finally, the in-orbit dynamic model and the controller model of the thermal control device to perform simulation and analysis and thereby to verify the feasibility and effectiveness of the temperature control technology. The results show that the thermal control scheme can efficiently control the heat of the instantaneous high-power load in orbit, and the precision temperature control can be achieved by thermoelectric cooling during the load operation with a temperature control accuracy of ±0.5 ℃.

References

[1] Haomang Hu, Tianshu Ge, Yanjun Dai, Ruzhu Wang. (2016). Up to date development of thermoelectric refrigeration technology: from material to application. J. Chinese Journal of Refrigeration Technology, 36:42-52.
[2] Xiaoqun Wang, Shanyi Du. (2006). Application of thermoelectric refrigeration technology in aerospace field. J. Erospace China, 10:22-24.
[3] Limei Shen, Huanxin Chen, Fu Xiao, et al. (2014). The step-change cooling performance of miniature thermoelectric module for pulse laser. J. Energy Conversion and Management, 80: 39-45.
[4] Dongliang Zhao, Gang Tan. (2014). Experimental evaluation of a prototype thermoelectric system integrated with PCM (phase change material) for space cooling. J. Energy, 68, 658-666.
[5] Wei He, Jinzhi Zhou, Jingxin Hou, et al. (2013). Theoretical and experimental investigation on a thermoelectric cooling and heating system driven by solar. J. Applied Energy, 107: 89-97.
[6] Jianglan Li, Yunbo Shi, Pengfei Zhao, et al. (2014). High precision thermostat system with TEC for laser diode. J. Infrared and Laser engineering, 43(6): 1745-1749.
[7] Lingshuang Yuan, Yunze Li, Meng Liu, et al. (2006). Fuzzy control research on the active thermal control system for planet spacecraft. J. Journal of Astronautics, 27(1):81-84.