Research on adaptive thermal control system of space optical remote sensor

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Abstract: The traditional thermal control system of the space optical remote sensor is mainly based on passive thermal control and supplemented by active thermal control of electric heater. But with the development of the remote sensor in the direction of multi-task and multi-function, the thermal control system needs to meet the requirements of low thermal control resource consumption under the condition of multi heat source and large heat load, and high adaptability under the condition of multi attitude complex orbit. The traditional thermal control system can not satisfy these new requirements. In this paper, a new adaptive thermal control system is studied. A geostationary orbit camera as an example is taken to compare the design scheme of the traditional thermal control system and the new thermal control system. The simulation results show that the new thermal control has the advantages of more optimized system resources and stronger temperature adaptability under complex tasks, which provides a new idea for the subsequent thermal control design of complex large space optical remote sensor.

1. Introduction

Satellite thermal control technology is an important part of aerospace technology, which controls the heat exchange process of internal and external environment of satellite to make its thermal equilibrium temperature within the required range\textsuperscript{[1-2]}. Space optical remote sensor is the main payload of remote sensing satellite. The thermal control accuracy and stability of optical and mechanical body directly affect the imaging performance of remote sensor.

With the development of remote sensing application technology, the function mode and resolution of space optical remote sensor are increasing in recent years.\textsuperscript{[3]} Traditional thermal control technology and thermal control system construction ideas are limited by cycle, cost, adaptability, resources and other aspects, which can not satisfy the needs of space optical remote sensor.

In order to solve the above problems, the adaptive thermal control technology system based on intelligent thermal control technology of space optical remote sensor is studied in this paper. Taking a geostationary orbit camera as an example, the resource and adaptability of the two thermal control systems are compared.
2. Research on adaptive thermal control system

2.1 Construction of adaptive thermal control system

It should research from four levels: heat collection, heat transfer, heat emission and active temperature control. Solve the underlying technical problems of intelligent adaptive thermal control system, carry out key technology and process research, and realize the engineering of thermal control products. In the follow-up model development process, the appropriate thermal control technology can be selected according to the characteristics of space environment, on orbit mission, structural layout and so on, which are used to construct the intelligent adaptive thermal control system suitable for the model.

(1) Heat collection
Adaptive cold plate technology, thermal switch technology and controllable phase change energy storage technology can be used to collect and store heat. Take the thermal switch technology as an example. It can control the heat by changing the thermal resistance of the heat conduction channel. When the two surfaces of the thermal switch do not contact each other, it is called the open state. The thermal resistance of the thermal switch in the open state depends on the thermophysical properties of the gap. The state of contact is called closed state and the thermal resistance of the thermal switch in the closed state depends on the surface contact state. Two different states produce different thermal resistance, so as to achieve different levels of heat transfer and temperature.

(2) Heat transfer
Variable thermal conductivity heat pipe technology, phase change heat pipe technology, loop heat pipe technology, mechanically pumped two phase loop technology can be used to control the heat transfer. Take the variable thermal conductivity heat pipe technology as an example. It can realize the function of unidirectional heat conduction by setting a gas storage chamber (non-condensable gas) at the condensing end or evaporation end to adjust the length of the condensing section of the heat pipe, so as to reduce the active temperature control power.

(3) Heat dissipation
Deployable radiation surface technology, intelligent coating technology and electrostatic adsorption technology can be used to control the heat emission capacity. Take the intelligent thermal control coating with variable emissivity as an example. It can adjust the emissivity actively / passively according to the needs, so as to improve the adaptive function of the remote sensor thermal control system. According to the principle of emissivity change, the variable emissivity intelligent thermal control coating can be divided into thermochromic intelligent thermal control coating and electrochromic intelligent thermal control coating. China, the United States, Japan, Canada and other aerospace powers are actively carrying out relevant research. But in engineering application, there are some problems such as small range of emissivity change, high phase transition temperature, high solar absorptivity, lack of research on space adaptability and poor engineering application. In the follow-up research, we should combine the working temperature region of the remote sensor to carry out the research on the devices with specific temperature region and low solar absorptivity, and carry out the verification of space environment adaptability such as anti ultraviolet radiation and anti atomic oxygen.

(4) Active temperature control
Electric heating technology is the main method to achieve precise temperature control. Intelligent electric heating technology and intelligent temperature control algorithm based on thermal characteristics are two important development directions of intelligent active temperature control technology. On the one hand, the intelligent electric heating technology based on PTC material can replace the temperature control equipment by using its own characteristics. On the other hand, the control accuracy and stability of the optical and mechanical body and detector are improved by several orders of magnitude. Conventional temperature measurement and control methods can not meet the requirements of such high precision and high stability. More active temperature control loops need to be arranged, and the temperature control algorithm based on the thermal characteristics of the controlled object should be studied to improve the temperature control accuracy.
2.2 Application cases

2.2.1 The overview of camera

An infrared camera works on the GEO orbit and uses a cryogenic optical system. The cryocoolers provide cooling capacity for low temperature optical system, calibration assembly and detector. A lot of waste heat will be produced when the refrigerators work, which needs to be discharged in time to ensure the efficient and stable operation of the refrigerator.

| Refrigerator name              | Power (W) | Temperature control requirements (℃) |
|-------------------------------|-----------|--------------------------------------|
| Optical system refrigerator   | 80        | -40℃ ~ 0℃                             |
| Calibration assembly refrigerator | 50        | -40℃ ~ 0℃                             |
| Detector refrigerator         | 100       | -40℃ ~ 0℃                             |

2.2.2 Heat dissipation scheme of camera refrigerators

(1) Traditional thermal control system

a) Layout design of heat radiation surface and selection of thermal control coating: The north and south sides of the GEO orbit remote sensor are exposed to the solar in turn, but they will not be exposed at the same time. Besides, the heat flow is relatively stable in an orbit cycle. Therefore, the coupling mode of the north and south heat dissipation surfaces is generally selected for heat dissipation. Optical solar reflector (OSR) with less degradation of solar absorptivity is selected as the thermal control coating of the heat radiation surface.

b) Design of thermal path: A single refrigerator consists of two heat sources, the compressor and the hot end. Three refrigerators have six heat sources in total. Therefore, considering the simple structure layout, the heat is first concentrated on the heat collector, and then transferred to the North-South heat dissipation surfaces through the U-shaped large heat pipe connecting the heat dissipation surfaces. The cooling path is shown in Fig.1.

c) Active temperature control power design: The active temperature control power is arranged on the radiation surface to ensure that the compressor and hot end are maintained above the safe temperature range when the refrigerator is not started under heating decontamination condition.

(2) Adaptive thermal control system based on intelligent thermal control technology

The traditional scheme adopts the coupling of North and South heat dissipation surfaces which has two disadvantages. On the one hand, due to the high temperature of the radiating surface on the irradiated side, the radiating surface on the non irradiated side should not only dissipate the heat from the internal heat source in time, but also dissipate the additional heat brought by the radiating surface on the other side, thus reducing the heat dissipation efficiency. On the other hand, when the
refrigerators are not working, a large amount of active temperature control power is needed to ensure that the refrigerator temperature is not lower than the safe temperature. This leads to a huge amount of satellite resources. Intelligent thermal control technology can effectively solve the above two problems.

a) Layout design of heat radiation surface and selection of thermal control coating: The north and south heat radiation surfaces are coupled for heat dissipation. In order to solve the problem of high active temperature control power, electrochromic intelligent thermal control coating is used on the heat radiation surface. When the internal heat source doesn’t work, the effective emission of the heat radiation surface can be reduced, which can greatly reduce the active temperature control power. Research institutions at home and abroad have conducted extensive research, and the emissivity can change from 0.46 to 0.75.[4]

b) Design of thermal path: In order to solve the problem of low heat dissipation efficiency of heat radiation surface, mechanically pumped two phase loop is used to transfer heat from heat collector to heat dissipation surface. Thus heat dissipation path can be controlled according to temperature. The heat dissipation path from the internal heat source to the heat collector can remain unchanged.

Fig.2 shows the schematic diagram of heat dissipation system coupled the south and north radiation surface based on mechanically pumped two phase loop. The system consist of a pump, an accumulator, a cold plate, two heat radiation surfaces, liquid pipe, two phase pipe, two temperature-sensing valves, and a differential transmitter and an absolute pressure sensor. In the system the pump is selected to transport the working fluid in the loop; the accumulator is used to control the working temperature of the system; the cold plate is used to absorb heat from the heat collector; the heat radiation surfaces are used to dissipate heat of the system. The working fluid that in the cold plate will change from liquid to two phase state. The two phase mixture will flow into the two branches of south and north radiation surfaces, where it is condensed to the cold liquid. Finally, the cold liquid flows into the pump.

In the real application, there is a large difference of external heat flux between the south and north heat radiation surfaces, so the temperatures from the two surfaces are different. Once the fluid with high temperature enters into the pump, and cavitation phenomen on at the vanes and bearings of the pump will occur, which will affect the lifetime and the reliability of the pump. In order to assure the pump to run safely and steadily, control strategy of the system is needed. In this section, the control strategy of the system is introduced by taking the north radiation surface for example and the control strategy of system for south radiation surface is the same.

The pump should meet the following condition as follows,

\[(T_1 - T_2) \geq \Delta T\]  

where \(T_1\) is the temperature of accumulator; \(T_2\) is the temperature at the inlet of pump; \(\Delta T\) is the minimum degree of supercooling for the pump, and it is in the range of 5~10°C. There is a relation between \(T_2\) and \(T_3\) and \(T_4\),

\[T_2 = \frac{m_1 \cdot T_3 + m_2 \cdot T_4}{m_1 + m_2} \]  

where \(m_1\) and \(m_2\) are the flow rates of two branches.

If the difference between \(T_1\) and \(T_3\) is less than \(\Delta T\), and Eq. (1) is not satisfied. The valve opening should turn down, and thus the flowrate of \(m_1\) will decrease. The adjusting process will stop until Eq. (1) is satisfied. When the difference between \(T_1\) and \(T_3\) is larger than \(\Delta T\), and the opening valve will turn up, and the flowrate of \(m_1\) in the branch of north radiator will increase to the maximum value.

c) Active temperature control power design: The active temperature control heating circuit is arranged on the cooling surface to ensure that the refrigerator is not lower than the safe temperature, and the measures are the same as the traditional scheme.
2.2.3 Scheme comparison

The thermal analysis model is established by using the thermal analysis software UG NX. The demand of thermal control resources under the above two schemes is calculated, and the analysis results are shown in the Tab.2.

![Diagram of heat dissipation system](image)

**Fig.2 The schematic diagram of heat dissipation system**

| Cooling surface requirements                                                                 | Active temperature control power |
|---------------------------------------------------------------------------------------------|----------------------------------|
| Traditional thermal control system: The north and south sides are 2.9 m² each, and the total is 5.8 m² | 775W                             |
| Adaptive thermal control system: The north and south sides are 2.3 m² each, and the total is 4.6 m² | 195W                             |

From the analysis results, it can be seen that the adaptive thermal control system based on intelligent thermal control technology can control the direction of internal heat through the mechanically pumped two phase loop under high temperature conditions, so it can autonomously select the heat dissipation surface with good heat dissipation conditions for heat dissipation and close the invalid heat dissipation surface. The heat dissipation surface area can be reduced by about 20%, which saves the weight of the satellite. Under low temperature condition, the infrared emissivity of the cooling surface can be reduced by electrochromic intelligent thermal control coating, which can reduce the heat dissipation capacity of the cooling surface and achieve the effect of heat preservation. The active temperature control heating power can be reduced by about 75%.

3. Conclusion and Prospect

In the future, the development of multi task and multi-functional remote sensing technology will put forward new requirements for thermal control technology. It is imperative to build a new thermal control system based on thermal management design and intelligent thermal control technology. In order to break through the limitation of passive thermal control for remote sensors in China, intelligent adaptive thermal control technology should be developed. The research on the universality of remote sensor thermal control design should be promoted in order to realize the generality of the thermal control system and products for the remote sensors with the same structure under different missions or orbits. The secondary design can only check the occupancy of thermal control resources, which can improve the efficiency of remote sensor thermal control development.

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