Research on High Temperature Protection Technology of Infrared Temperature Measuring Equipment in Space Environment

Liu ZeYuan, Shang Yonghong, Su Xinming, Wen Jing, Lin Boying
Beijing Institute of Spacecraft Environment Engineering, YouYi Road, Beijing, China
zeyuannuaa@163.com

Abstract. With the increasing complexity of spacecraft structure and thermal design, it is more difficult to implement surface temperature measurement technology, and the temperature measurement area tends to diverse. Therefore, there is an increasing demand for the application of non-contact temperature measurement technology in spacecraft thermal test. This paper takes the application of infrared temperature measuring equipment in vacuum and high temperature environment as the research object, designs the thermal protection scheme and device of the equipment, and simulates and analyses the thermal protection of infrared temperature measuring equipment based on node network method. Through physical test, the device can effectively realize the thermal protection of equipment in vacuum and high temperature environment, and ensure that the equipment is in the normal working temperature range and its temperature measurement algorithm model is not affected, the accuracy of temperature measurement is better than ±2℃, which meets the use requirements in spacecraft thermal test.

1. Introduction
The vacuum thermal test is one of the most complex test items in the process of spacecraft development. Its temperature data is the key technical parameter in the test process, which is used to provide effective data support for spacecraft thermal design and thermal analysis\[1-2\]. The measurement methods of temperature data are mainly divided into contact type and non-contact type. Contact type temperature measurement mainly includes thermocouple, platinum resistance and thermistor, which is easy to realize and widely used in the existing spacecraft thermal test. With the improvement of the complexity of spacecraft structure and thermal design, the surface structure is more complex, the implementation of temperature sensor technology is more difficult, and the temperature measurement requirements are no longer limited to a certain measurement point. In view of the limitations of conventional non-contact temperature measurement methods, it is required to use non-contact temperature measurement methods to achieve the above temperature measurement requirements\[3-4\].

At present, the commonly used non-contact temperature measurement methods mainly include infrared radiation temperature measurement and optical interference temperature measurement. Between them, infrared radiation temperature measurement has strong anti-interference ability, high technical maturity and good reliability, which can be used as an effective technical means of non-contact temperature measurement in spacecraft thermal test.

Infrared thermal imager has been widely used in the field of non-contact temperature measurement because of its fast response, wide range of temperature measurement and high sensitivity. However, at
present, the infrared thermal imager is mostly designed according to industrial standards, and its working temperature range is -10℃~50℃, which is difficult to meet the application requirements of vacuum, high or low temperature in space environment simulation equipment (SESE) for spacecraft thermal test. Firstly, the low temperature protection can be easily realized by the active thermal protection technology, which is based on the temperature control of film heater. In order to solve the high temperature protection, this paper takes it as the research object, designs the thermal protection scheme and device, and carries out the thermal simulation analysis based on the thermal radiation theory. Through the physical test verification, the high temperature protection device can realize the thermal protection of infrared thermal imager at a maximum temperature of 100℃. It can eliminate the influence of external temperature change on the thermal model and working temperature range of the equipment, and its temperature measurement accuracy is better than ± 2℃, which meets the requirements of non-contact temperature measurement technology in spacecraft thermal test.

2. Analysis of space environment impact factors
The infrared thermal imager is mainly composed of optical system, infrared detector system, electronic processing system and display system. Its working principle is to receive the infrared radiation energy on the surface of the measured object, and convert the radiance into electrical signal, so as to realize the measurement of the temperature of the measured object. The effective radiation received by the infrared detector mainly includes four parts: the self-radiation of the measured object, the environmental reflection radiation, the atmospheric radiation and the self-radiation of the thermal imager. The infrared thermal imager detector generally works in two bands of 3-5μm (short wave) or 8-14μm (long wave). The infrared thermal imager detector studied in this paper works in the long wave band. The monochromatic radiance (wavelength λ) received by the infrared thermal imager is shown in (1).

$$E_{\lambda} = A_{0}d^{2}(\tau_{\lambda\alpha}E_{\lambda}(T_{0}) + \tau_{\lambda\alpha}(1-\alpha_{\lambda})E_{\lambda}(T_{a}) + \epsilon_{\lambda\alpha}E_{\lambda}(T_{a}))$$

In (1), $T_{0}$ is the actual temperature of the measured object, $T_{a}$ is the ambient temperature, $T_{r}$ is the atmospheric temperature, $A_{0}$ is the visible area of the measured object corresponding to the minimum spatial resolution of the thermal imager, $d$ is the distance from the detector to the measured object, $\tau_{\lambda\alpha}$ is the spectral transmittance of the atmosphere, $\epsilon_{\lambda\alpha}$ is the surface emissivity of the measured object, $\alpha_{\lambda}$ is the surface absorption of the measured object, $\epsilon_{\lambda\alpha}$ is the atmospheric emissivity, $E_{\lambda}$ is the monochromatic of the black body Radiation capacity density. It can be seen from (1) that the influence factors of the temperature measurement of infrared thermal imager mainly include atmospheric spectral transmittance, ambient temperature, atmospheric temperature and measuring distance [5-6].

When the infrared thermal imager is applied in the internal of SESE, the internal environment is in the state of high vacuum, and the measurement distance is in the range of 0.4m~5m. Therefore, the influence factors of its atmospheric spectral transmittance, atmospheric temperature and measurement distance for the thermal imager can be basically ignored. At the same time, the components of thermal imager are designed to withstand vacuum, and their performance is not affected by the vacuum environment. However, in the process of spacecraft thermal test, the ambient temperature in the SESE will be in the temperature range of 180℃~100℃, and the above temperature changes will have a certain degree of impact on the ambient temperature parameters of the thermal imager receiving radiation and its body temperature. The impact of the ambient temperature parameters on the infrared thermal imager can be corrected by the temperature measurement software algorithm, but the container ambient temperature change is bigger than the normal working temperature range of 10℃~50℃ of the thermal imager, and it results in the disorder of the temperature model of the thermal imager body. This will affect the accuracy of the temperature measurement of the thermal imager. Therefore, in order to ensure the normal use of the thermal imager in the space environment, especially in the vacuum and high temperature environment, it is necessary to analyze and design the high temperature protection.
3. The high temperature protection design and simulation analysis

3.1 The high temperature protection design

The maximum temperature of BZ class SESE is 100℃. In the view of vacuum background inside the SESE, if air-cooled or water-cooled cooling devices are used to protect the thermal imager equipment from high temperature, the technical implementation is difficult. In case of gas or liquid leakage, it is easy to affect the tested product safety.

In this paper, from the perspective of practicability and reliability, a passive thermal protection method combining shield and heat flow baffle is adopted. In which, the baffle is mainly used to effectively block the infrared heat flow generated by the infrared heating cage in the container. The shield is used to realize the secondary shielding of the radiation heat flow, and it also plays a role in strengthening the reliability of the thermal imager structure[9].

The thermal imager and its thermal protection device constitute an integral module, which includes the thermal imager, thermal control accessories (film heater, multilayer aluminum coating film), shield, baffle and module support. The design principle of the module is shown in Figure.1. The shield is designed as a 100mm×124mm×184mm three-dimensional box type, and the shield is made of aluminum. In order to reduce the absorption of infrared heat flow by the shield, the shield surface is polished, and the emissivity after treatment is about 0.13. The shutter is designed as a semi cylindrical device with a diameter of 300 mm and a length of 200 mm. The shutter structure is made of stainless steel plate, and a single-layer aluminum coating with an emissivity of about 0.026 is pasted on its surface to improve the reflectivity of infrared thermal radiation.

3.2 The establishment of simulation model

In order to verify the effectiveness of thermal protection design of thermal imager, thermal desktop (TD) is used to simulate the thermal imager module[7-8]. The core principle of TD software is to use the Sinda program of thermal network model based on node network method, which can establish the thermal balance equation for each node i and realize the solution of temperature. The thermal balance equation is shown in equation (2).

\[ \frac{dT_i}{dt} = \sum G_{ij}(T_i - T_j) + \sum GR_{ij}(T_i^4 - T_j^4) + Q_i \]  

in (2), The \(T\) is the temperature of node \(i\). The \(mc_p\) is the heat capacity of node \(i\). The \(Q\) is the internal and external heat source power of node \(i\). The \(G_{ij}\) is the linear heat conduction between node \(i\) and node \(j\). The \(GR_{ij}\) is the nonlinear heat conduction between node \(i\) and node \(j\), which is also radiation heat transfer. The TD software can be built into AutoCAD software to realize the functions of thermal analysis model, model coefficient calculation, result display, batch calculation and reliability analysis.

In this paper, the TD software is used to model the heat source (infrared cage) on the inner wall of SESE and the thermal imager module. The thermal analysis model is shown in Figure 2. The model
consists of infrared cage, baffle and shield from the outside to the inside. The SESE is a horizontal cylinder with a diameter of 0.78m and a length of 0.8m. The cylinder surface and the inner end face are equipped with heat sink and infrared cage, and the outer end face is free of cold plate and infrared cage. The thermal imager module is installed on the outer end face of the SESE, and its front lens is facing the inner part of the SESE, which is within the thermal radiation range of the infrared cage.

During the thermal simulation analysis, the thermal nodes are established for the infrared thermal imager body and shield. The location of the thermal node is shown in Figure 3, in which camera.2 and camera.7 are the temperature monitoring points at the front and rear ends of the thermal imager body respectively, and Al.1 and Al.6 are the temperature monitoring points at the front and rear ends of the shield respectively. The surface material of the thermal imager is iron and its emissivity is 0.85. The internal heat source power is 4W, and the heat source is set at the front end. The emissivity of the shield is 0.13, and the thermal conductivity value between thermal imager and shield is 1.2W/K which is calculated by the thermal resistance formula. There is a heat leakage path between the shield and the external environment through the module support and the bottom guide rail of SESE. In the analysis, it is simplified as the thermal conductivity between the two ends of the thermal imager and the environmental node, the thermal conductivity value is 0.06 W/K. The emissivity of the inner surface of the infrared cage is 0.88, and the temperature value of the environmental node is 20℃, which is a constant temperature boundary.

3.3 The simulation without baffle structure
If the baffle structure is not considered in the thermal analysis model simulation, under the condition of high vacuum and the highest temperature of the infrared cage is 100℃, the starting temperature of the thermal imager shield is 20 ℃, and the surface temperature distribution simulation of the shield after 30min is shown in Figure 4.

It can be seen in the Figure 4 that the shield of thermal imager rapidly rises to 50℃ in 30 minutes, which is higher than the maximum allowable working temperature of the thermal imager, under the condition of no baffle. Therefore, it cannot meet the high temperature protection of the thermal imager.

3.4 The simulation with baffle structure
If the baffle structure is considered, the setting conditions are the same as that of no baffle. The temperature change curve of the thermal analysis model nodes, and the thermal balance steady state temperature distribution of the thermal imager module are shown in Figure 5 and Figure 6.
Figure 5. The temperature curve of thermal analysis model nodes on the thermal imager module with baffle.

Figure 6. The temperature distribution of thermal balance steady state of the thermal imager module with baffle.

It can be seen in Figure 5 and Figure 6 that when the temperature of the infrared cage is 100°C, the thermal analysis node Al.1 at the front end of the shield will reach 50°C in about 5 hours, the thermal analysis node Camera.2 at the front end of the body of the thermal imager will reach 50°C in about 8 hours. The thermal balance steady state of the thermal imager and the shield can be reached after about 40 hours, and the body temperature of the thermal imager is between 67.1°C and 80°C. It can be seen from the data analysis that if the baffle design was considered, the temperature rise time of the thermal imager body from 20°C to 50°C is more than 8 hours, which is much longer than the temperature rise time of the non-baffle design scheme, and it can meet the requirements of high temperature working condition time of spacecraft component level thermal test.

4. Test verification and result analysis

4.1 The test method

In order to verify the feasibility of the design of high temperature protection device for infrared temperature measurement equipment, this paper designs and carries out performance verification tests. Under the environmental conditions of vacuum and high temperature of SESE, the temperature model of thermal protection device and the temperature measurement data of infrared temperature measurement equipment are tested and analyzed [10].

Figure 7. The test site

In order to realize the analysis of the temperature model of the high temperature thermal protection device of the thermal imager, thermocouple temperature measuring points T5, T6, T7 and T8 are respectively arranged on the upper surface of the front end of the baffle, the upper side of the front end of the shield, the upper surface of the rear end of the baffle and the upper side of the rear end of the shield. The arrangement points are as shown in Figure 8. In combination with the body temperature sensor T9 for the low temperature protection of the thermal imager and the temperature sensor T10 built in the thermal imager body. The key temperature point of thermal protection analysis model is extracted.
The cube copper box is used as the temperature measurement sample of the thermal imager. Black paint is coated on every surface of the copper box. The surface emissivity is about 0.88. The black body has its own independent temperature control function, and the maximum temperature control value is 150℃. During the test, take a surface of the copper box as the temperature measurement target area, and take an optical target point of the surface as the benchmark, paste T-type thermocouple T1~T4 at four positions around it, which as shown in Figure 9. The temperature values of T1~T4 measured by the thermocouple are taken as the standard temperature, and compare it with the temperature value of P1~P4 measured by the thermal imager. Furthermore, the analysis of the temperature measurement accuracy of the thermal imager is realized.

4.2 The data analysis

Under the condition that the vacuum degree of SESE is lower than 5×10^{-3}pa, and the infrared cage of the SESE is controlled to the maximum temperature value of about 100℃. The time of heating period takes 2 hours, and the holding period of the infrared cage is 1 hour. During the high temperature holding stage, the temperature curve of T5~T8 which sets on the thermal protection device are shown in Figure 11.

It can be seen from Figure 11 that at the end of high temperature condition, the upper surface of front end of baffle and shield are in the inner part of infrared cage, ant its temperature values are 58.6℃ and 38.5℃ respectively. The upper surface of rear end of shutter shield are outside the infrared cage, and its temperature values are 24.6℃ and 18.5℃ respectively. In addition, the body temperature T9 and the internal temperature T10 of the thermal imager are 34.2℃ and 36.6℃ respectively at the end of high temperature condition. Based on the above data:

1) The temperature points at the rear end of baffle and shield are lower than those at the front end.
2) The temperature at the front end of the shield is 38.5 ℃. It is lower than the temperature at the front end of the baffle which is 58.6℃, and also lower than the temperature value of thermal analysis node A1.1, which is 40℃ in the high temperature thermal simulation analysis.
3) The body temperature of the thermal imager is 34.2 ℃, which is also lower than the thermal imager body thermal analysis node camera.2 at 36.7 ℃ in the high temperature thermal simulation analysis.
In addition, in the high temperature maintaining stage, the temperature measurement error of the infrared thermal image is shown in Figure 12. It can be seen from Figure 12 that the temperature measurement accuracy of the thermal image device can still be within ±2℃ under the environmental conditions, which further explains the effectiveness of the design of the high temperature protection device of the thermal image device. The design of the high temperature protection device ensures that the temperature model of the thermal image device itself is within the design range, which will not affect the temperature correction of the thermal image device, and meets the requirements of normal use conditions and working time under vacuum and high temperature environment.

5. Conclusion
In this paper, the high temperature protection technology of infrared temperature measuring equipment under space environment is studied. The thermal analysis model is established to simulate the thermal protection design, and the high temperature thermal protection schemes and devices are designed. The physical test results show that the device can ensure the equipment is working properly in the vacuum and high temperature environment, which is up to 100℃. The thermal image temperature measurement accuracy is better than ±2℃ and can work normally for at least 8 hours, which effectively realizes the application of infrared temperature measurement equipment in the space environment for the spacecraft component level thermal test.

References
[1] ZHANG J CH, XIE J H, WANG Y R, et al. The application and the development trend of the measurement and control system in the spacecraft vacuum thermal test[J]. Spacecraft Environment Engineering
[2] XU F, LUO J, PENG F. Application of infrared temperature measurement technology in liquid rocket engine test[J]. Journal of Rocket Propulsion
[3] SHI D P, WU CH, LI Z J, et al. Analysis of the influence of infrared temperature measurement based on reflected temperature compensation and incidence temperature compensation[J]. Infrared and Laser Engineering
[4] QUAN Y M, XU H, KE ZH Y. Research on some influence factors in high temperature measurement of metal with thermal infrared imager[J]. Physics Procedia
[5] SH J L, ZH Y C, X T T. The study on the measurement accuracy of non-steady state temperature field under different emissivity using infrared thermal image[J]. Infrared Physics & Technology
[6] J S. Thermal science and analysis[J]. Journal of Thermal Analysis and Calorimetry
[7] ZHANG Y C, CHEN Y M, FU X B, et al. A method for reducing the influence of measuring distance on infrared imager temperature measurement accuracy[J]. Applied Thermal Engineering
[8] YANG ZH ZHANG SH, CH, YANG L. Calculation of Infrared Temperature Measurement on Non-Lambertian Objects [J]. SPECTROSCOPY AND SPECTRAL ANALYSIS
[9] YANG Q, XIE W H, PENG Z J, et al. New concepts and trends in development of thermal protection design and analysis technology[J]. Acta Aeronautica ET Astronautica Sinica
[10] LIU ZH H. Analysis of the Standards and Methods of Thermal Vacuum Test[J]. Electronic Product Reliability and Environmental Testing Engineering.