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Original research article

Thermal design and analysis of the high resolution MWIR/LWIR aerial camera

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ABSTRACT

The thermal control technology of high resolution MWIR/LWIR aerial camera is studied. Thermal design and thermal analysis of the camera are completed according to thermal control indexes of infrared aerial camera. Firstly the architecture of the aerial camera and the external working environment are introduced, the camera heat exchange model is established, and the boundary conditions of radiation, conduction, convection and aerodynamic heat are analyzed, and then the thermal design of the camera is described in detail. Finally the thermal analysis of aerial camera is done, and a heat balance test has been done for the camera. The results show that: In the specified environment, after two hours work the temperature range of optical system is 18.5 °C to 22.2 °C, the temperature range of lens set is 19.1 °C to 20.3 °C, the temperature range of detector module is 19.7 °C to 31.9 °C, meet the thermal control indexes, at the same time, under extreme operating conditions, the thermal control system can meet the start-up requirements, the thermal design is feasible and reasonable. This research method and technical route have the guidance and reference significance for the thermal control design of other infrared aerial cameras.

1. Introduction

The aerial camera is an optical instruments loaded on the plane to shoot ground targets, the image quality is the most important performance index. The temperature will change greatly in the external environment when it works. The structural and optical error caused by temperature change will result in serious damage to the images quality. In addition, the heat generated by some devices in the camera will also have an impact on the image quality. Therefore, in the complicated and variable environment, it must make reasonable thermal control design for the aerial camera to ensure that the system can work properly and obtain high quality images.

Some foreign aerial cameras adopt the temperature control module to realize the active thermal control, but its volume and weight are large, so it is not applicable to all aerial cameras [1]; The heat transfer model and thermal resistance network model of the aerial camera's lens and window component were established by Fan in China, and the maximum heat leakage rate in extreme working conditions was analyzed and calculated [2]. Li conducted a research on thermal control design of transmission optical remote sensor [3]. However, most of the research on the thermal design of the aerial camera take example by thermal control experience of space cameras [4–8], and the domestic research literature is relatively few.

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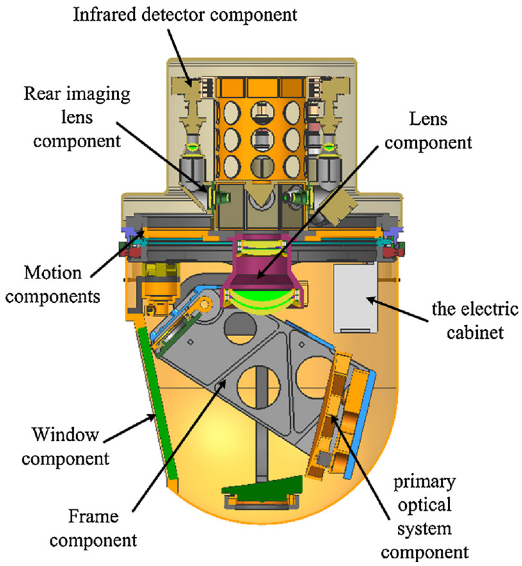

Fig. 1. The structure and composition of the infrared aerial camera.

2. Composition of the aerial camera

The infrared aerial camera is mounted on the belly of the aircraft and the camera is connected to the aircraft through the shock absorber. The upper part of the camera is installed in a pod of an aircraft, the lower part contacts with the outside air. The overall dimension of the system is: 530 mm × 530 mm × 860 mm. The system has two detection spectra: MWIR and LWIR.

The structure and composition of the infrared aerial camera is shown in Fig. 1, the system includes the frame component, window component, the primary optical system component, the lens component, the rear imaging lens components, the motion component, the infrared detector components and the electric cabinet, etc. The camera adopts the off-axis optical system, and the primary optical system include the primary mirror, the secondary mirror, the third mirror and the main frame.

3. Thermal environment of the aerial camera

The camera works mainly in the troposphere of the atmosphere. Its typical external environmental condition is not very stable. The factors that affect the camera temperature mainly include the external flight environment and the heat source inside the camera. The typical working condition of camera is: flight height 10 km, flight speed 800 km/h, and physical properties of 10 km atmosphere are shown in Table 1.

The aerial camera has two modes: preparation mode and working mode. The main heat sources of the camera include: azimuth motor and pitch motor, six infrared detector components and electric cabinet.

The heat exchange between the camera and the external environment when flying at high altitude mainly includes [9]: the conduction heat transfer with plane Φ_1, the convective heat transfer with the atmosphere Φ_2, the aerodynamic heat produced by the high-speed flight Φ_3, the earthlight radiation Φ_4, the earth infrared radiation Φ_5, atmospheric radiation Φ_6 and aerial camera external radiation Φ_7, etc.

Therefore, the dynamic heat balance equation of the infrared aerial camera shell is:

$$\Phi_3 + \Phi_4 + \Phi_5 + \Phi_6 - \Phi_1 - \Phi_2 - \Phi_7 = \rho C\frac{\partial T}{\partial t}$$

Where, ρ: density of the shell material, C: heat capacity of the shell material. In the process of thermal analysis, transient calculation is needed.

Table 1
Physical characteristics of aerosphere at 10 km altitude.

Name	Value
Atmospheric temperature	223.15 K
Atmospheric pressure	26436.3Pa
Atmospheric density	0.4127 kg/m^3
Dynamic viscosity	1.457×10^{-5} kg/ ms
Thermal conductivity	$0.02005 W\cdot m^{-1}\cdot K^{-1}$

3.1. Radiation

The infrared aerial camera is sheltered by the aircraft, so it avoided the direct radiation of the sun. In addition to ignore the plane radiation to the camera, the radiation heat flux which the camera receives mainly include: the earthlight, the earth infrared radiation and the atmospheric radiation.

Earthlight [10] refers to Earth's reflection of sunlight. With the sunlight entering earth's atmosphere, some is absorbed and some is reflected, the percentage of reflected energy is called earthlight. In thermal design, the global average reflectance $a = 0.35$ and the mean value of sun irradiance $S_0 = 1367W/m^2$, so the average radiation density of earthlight:

$$\Phi_4 = aS_0 = 0.35 \times 1367W/m^2 = 478.45W/m^2$$

When sunlight enters the earth's atmosphere, the absorbed energy is converted to the heat of the system, and then Then it radiates into space with infrared wavelengths, which is called the Earth infrared radiation. In the calculation we take the earth surface as a black body for approximate treatment, therefore, it is derived that the Earth infrared radiation is equal to the average irradiance of the received shortwave solar radiation.

$$\Phi_5 = \frac{(1-a)}{4}\mathrm{S}_0 = 222.14W/m^2$$

Atmospheric radiation is the process by which the atmosphere absorbs long-wave radiation from the ground and radiates outwards. It is the result of atmospheric absorption, emission and scattering, which is usually stable. For the atmosphere at an altitude of 10 km, the radiation value $\Phi_6 = 25W/m^2$. Therefore, the radiation heat flux density of the aerial camera is approximately:

$$\Phi = \Phi_4 + \Phi_5 + \Phi_6 = 725.59W/m^2$$

3.2. Conduction

The conduction heat transfer of the infrared aerial camera is mainly the conduction among the internal components. Because the camera is connected to the plane through heat insulation pads, the conduction heat transfer between them can be ignored. The calculation formula of conduction heat transfer is:

$$\Phi = \frac{\Delta T \bullet A \bullet \lambda}{\delta}$$

Where, ΔT: the temperature difference between two surfaces; λ: the thermal conductivity of the material, A : the heat transfer area, δ: the heat transfer thickness. The conduction heat transfer is mainly related to the material, contact area and material thickness.

There is a thermal contact resistance between two contacted objects. This is due to the microscopic irregularities of the two solid bonding surfaces, which result in the fact that the two surfaces are not in full contact, but rather there is an air-filled void layer, so it brings additional thermal resistance. The resistance value is related to material properties, contact surface roughness, contact pressure and media type. The thermal contact resistance is controlled by contact thermal resistance coefficient K, which is related to contact state. In the simulation, a certain value can be given according to experience to realize the heat conduction, and the value range is generally 50–1000 $W{\cdot}m^{-2}{\cdot}K^{-1}$.

3.3. Convection

The convective heat transfer model between the shell of the camera and the atmosphere can be simplified as the fluid sweep single pipe model, a general formula for the convective heat flux density as follows:

$$q_c = h \bullet \Delta T$$

Where, h: the convection heat transfer coefficient; ΔT: the temperature difference between the surface and the atmosphere. The convection heat transfer is described by the convection heat transfer coefficient.

For the fluid sweep single pipe model, it can be obtained from the references by Churchill and Bernstein, they proposed the applicable formula for $\mathrm{Re} \bullet \mathrm{Pr} > 0.2$ [11]:

$$Nu = 0.3 + \frac{0.62\,\mathrm{Re}^{1/2}\,\mathrm{Pr}^{1/3}}{[1 + (0.4/\mathrm{Pr})^{2/3}]^{1/4}}[1 + (\frac{\mathrm{Re}}{282000})^{5/8}]^{4/5}$$

Where, $\mathrm{Re} = 3.1473 \times 10^6$ Pr: Planck constant. For air, $Pr = 0.7$.

$$h = \frac{Nu \bullet \lambda}{l}$$

Where, l: the characteristic length is the outer diameter of the pipe, $l = 0.5m$, the convective heat transfer coefficient of the shell : $h = 134.7$ w $/(\mathrm{m}^2 \bullet \mathrm{K})$.

3.4. Aerodynamic heat

Aerodynamic heat happens when the high speed airflow flow past an object. The strong friction between the air and object in the boundary layer convert kinetic energy lost in the airflow into heat energy. The flight speed is high ($Ma = 0.74$), so the aerodynamic heat cannot be ignored.

The surface heat flux can be calculated by the approximate estimation formulas gave by Anderson [12]. The calculation is described as follow:

$$q_w = \rho_\infty^N \bullet u_\infty^M C$$

Where, q_w: surface heat flux (W/cm^2), ρ_∞: free flow density (Kg/m^3), u_∞:free flow speed (m/s);

Laminar plate: $M = 3.2$, $N = 0.5$,

$$C = 2.53 \times 10^{-9}(\cos\phi)^{0.5}(\sin\phi)X^{-0.5}(1 - \frac{h_w}{h_0})$$

Where, h_w: the wall enthalpy, h_0: the total enthalpy, X: distance along the object plane.

Turbulence plate: $M = 3.37$, $N = 0.8$,

$$C = 3.89 \times 10^{-8}(\cos\phi)^{1.78}(\sin\phi)^{1.6}X_T^{-0.2}(\frac{T_w}{556})^{-0.25}(1 - 1.11\frac{h_w}{h_0})$$

Where, ϕ: the local angle to the free flow (°), X_T: Distance along the object plane in turbulent boundary layer (m).

According to the flight environment and flight speed of the aerial camera, the Reynolds number is calculated: $\mathrm{Re} = 3.1473 \times 10^6 > 5 \times 10^5$.

For the local Angle of free flow $\phi = 12^o$, the surface heat flux density produced by aerodynamic heat can be obtained by calculation:

$$q_w = 27.31W/m^2$$

4. The thermal design of the aerial camera

In the thermal design of aerial camera, the optical and structural materials should be reasonably selected to reduce the thermal stress caused by temperature change. The combination of passive thermal control and active thermal control is adopted, and mature thermal control technology are adopted as much as possible. The implementation of thermal control should avoid blocking the optical path [13].

The thermal control index:

a) the primary optical system (20 ± 4) ℃;
b) the lens component (20 ± 4) ℃;
c) the electric cabinet for 10 ~ 45 ℃;
d) the detector components for 10 ~ 35 ℃.

The thermal control measures used in aerial camera: coating insulation layer, matching structure and optical material, installing insulation pad, applying thermal control coatings and arranging phase change materials, at the same time, the active thermal control measure of pasting polyimide heating sheet is used for temperature compensation. The thermal time constant of the system is increased through reasonable heat conduction layout design and heat insulation structure design, the problem of temperature difference is improved, and the active heat control power consumption is reduced.

4.1. The thermal design of the prime optical system and the camera shell

In order to reduce the influence of the external environment on the internal components of the camera, the surface inside the camera shell is affixed to multi-layer insulation. The material is microporous polyurethane with a thickness of 10 mm. The surface of the main frame is blackened and its surface emissivity is not less than 0.9 to ensure uniform internal temperature of the camera. The Primary mirror, the secondary mirror and the third mirror are made of SiC which is high thermal conductivity material. All the support structure components material used 4J32. The linear expansion coefficient of the material is consistent with the optical components, which can reduce the thermal stress caused by the temperature changes.

All structures in addition to the mounting surface should be done surface blackening treatment, at the same time, active heating zone is set on the main frame of the camera and each reflector component to improve the temperature level.

4.2. The thermal design of the lens component

The thermal control measures for the lens group are usually to paste the heating sheet on the outside of the lens barrel. So the heat transfer of the lens needs to pass through the lens barrel, and the material of the lens barrel is TC4. Therefore, the heat transfer

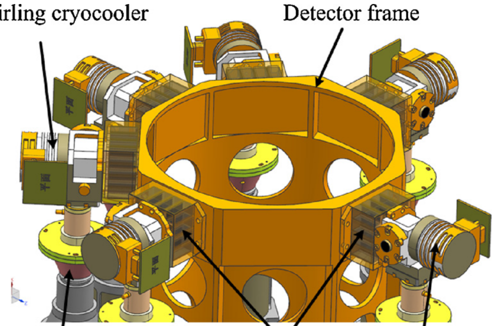

Fig. 2. The thermal design of the detector component.

efficiency is low. The lens component is the sensitive component in optical system, in order to enhance the capacity of the temperature control of the lens component, this paper adopts the thermoelectric unit which set inside the lens component as thermal control measure [14]. It use the Peltier Effect to heat and cool the lens. According to the calculation of heating and cooling capacity, each lens is arranged 36 thermoelectric units around which are divided into three layers.

4.3. The thermal design of the infrared detector components

As the key parts of infrared imaging system, Infrared Focal Plane Array detector (IRFPA) represents development direction of infrared imaging technology. High temperature will increase the thermal noise which affect the signal-to-noise ratio (SNR), and result in imaging quality decreased, or even unable to image. So the infrared detector integrates the Stirling cryocooler to reduce the temperature of the focal plane. When the detector works, the focal plane is cooled to 100 K by Stirling cryocooler, and the power consumption is no more than 15 W. Due to the number of detectors and the heat generated by the Stirling cryocooler, the detector must take thermal control measures.

The infrared detector module dissipates heat through its own heat dissipation surface and phase change component. The surface of the Stirling cryocooler shell should be treated with blackening as a radiating surface to dissipate the heat generated by the probe. It install polyimide insulation pad between the detector and the back-end imaging lens component to reduce the temperature effect on the imaging lens.

In this paper, the connection parts between the detector and the frame is used as a phase change component. The surface of the component is blackened, as shown in Fig. 2. The amount of the phase-change material is calculated by heat generation. Heat conducting grease is filled between the phase change component and the detector. The phase-change component is mainly composed of phase-change materials, encapsulated containers and heat conduction enhancers. The phase change material choose octadecane for its high latent heat and stability. In addition, the heating sheet is set on the infrared detector to compensate the temperature when the infrared detector is not working.

5. The thermal analysis of the camera

Thermal analysis is very important in the whole thermal control design. The rationality of the thermal control scheme can be verified by thermal analysis. According to the results, the thermal control scheme can be continuously adjusted and optimized to achieve the best design scheme. The analysis work can shorten the design cycle and save the development cost greatly. The finite element model of the infrared aerial camera is shown in Fig. 3. The finite element model is simplified. The number of elements is 14874, the number of nodes is 11,871 and the number of thermal coupling is 73. The infrared aerial camera has working mode and preparation mode.

(1) Working mode

The state that the aircraft turns on the camera at the specified position is called working mode. In order to eliminate the influence of vibration, all the fans inside the camera should stop working in working mode. The specific operating mode: the initial temperature is 20℃, the flight altitude is 10 km and the flight speed is 0.74Ma.

The thermal boundary conditions were input according to the analysis results. Finally, the instantaneous thermal simulation was carried out using the NX10.0 thermal analysis module.

Analysis results are shown in Figs. 4 and 5, after working 2 h, the maximum temperature of the camera is 44.2 ℃, the minimum temperature of the camera is -49.1 ℃, the maximum temperature of the infrared detector module is 31.9 ℃, the maximum temperature of electric cabinet is 32.6 ℃, and the maximum difference in temperature of the optical system is 3.6 ℃.

The temperature change of the primary optical system and the lens component is shown in Figs. 6 and 7, after working 2 h, the

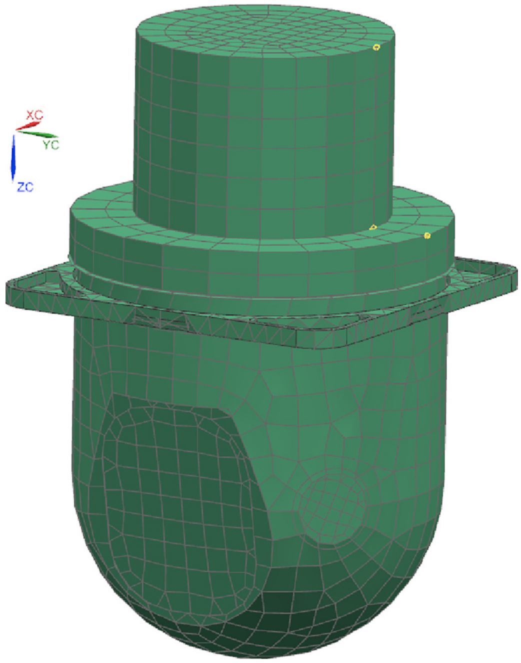

Fig. 3. Finite element model of infrared aerial camera.

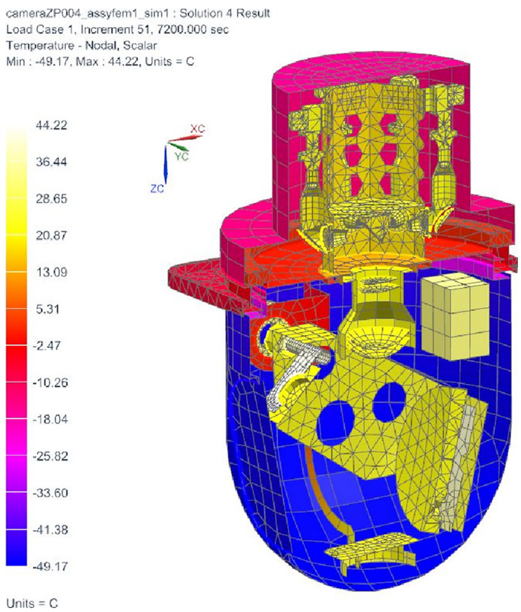

Fig. 4. Temperature distribution of camera at t = 2 h with active thermal control.

maximum temperature difference of the optical system keeps within 1.8 ℃, and the maximum temperature difference of lens component keeps within 1.0 ℃.

the temperature of infrared detector in the process of 2 h continuous work keeps at about 31.9 ℃, we can see that the thermal control measures prevent the temperature of infrared component rising fast effectively. From the analysis results, it can be seen that the temperatures of all components meet the thermal control index, and the thermal control scheme is reasonable and feasible.

(2) Preparation mode

The state that the camera is intended to execute a mission till it is ready is called preparation mode. In two cases: under low temperature working condition, the initial temperature of the camera is - 40 ℃; Under the high temperature working condition, the

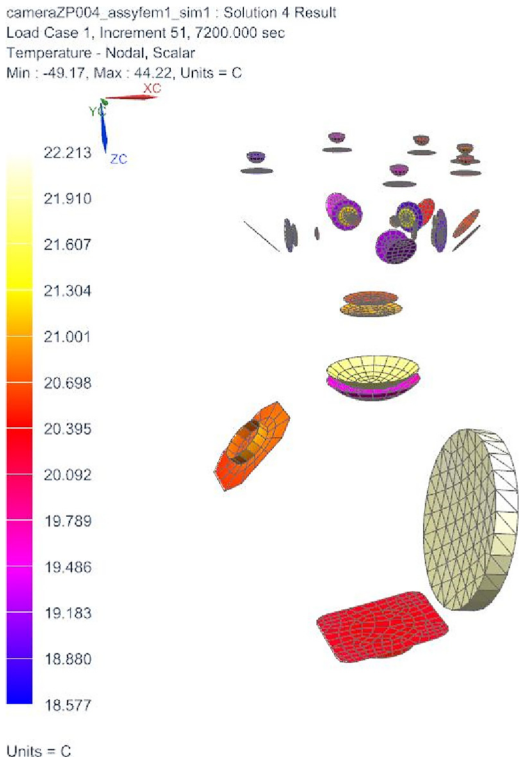

Fig. 5. Temperature distribution of optical system at t = 2 h with active thermal control.

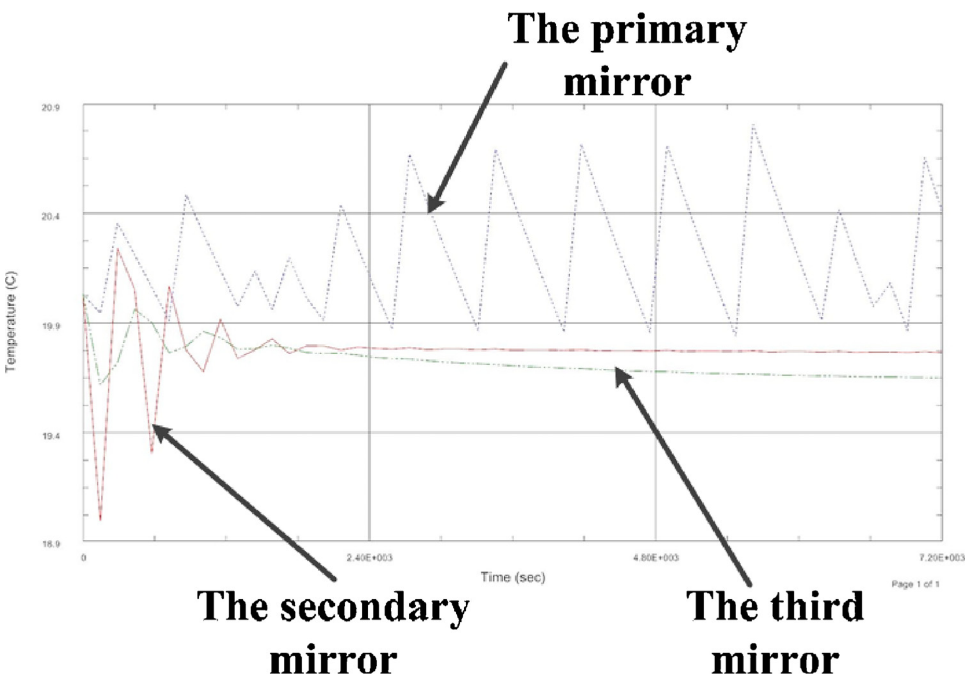

Fig. 6. Relationship between temperature of prime optical system and time in simulation.

initial temperature of camera is 50 °C; The camera is required to meet the working requirements in 40 min. The fan inside the camera works normally in preparation mode.

Working condition of low temperature analysis: the initial temperature of the camera is -40 °C, the flight altitude is 10 km and the flight speed is 0.74Ma. The thermal boundary conditions are input according to the analysis results. The temperature change curve of

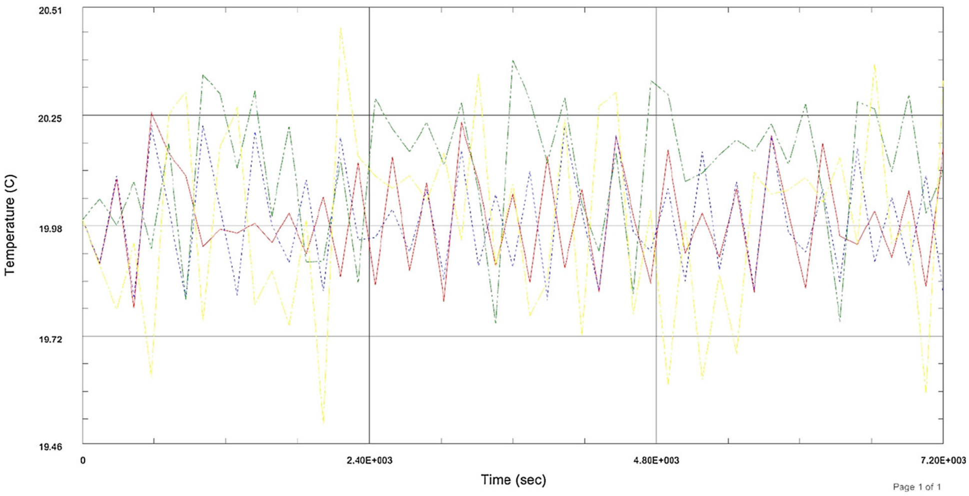

Fig. 7. Relationship between temperature of lens component and time in simulation.

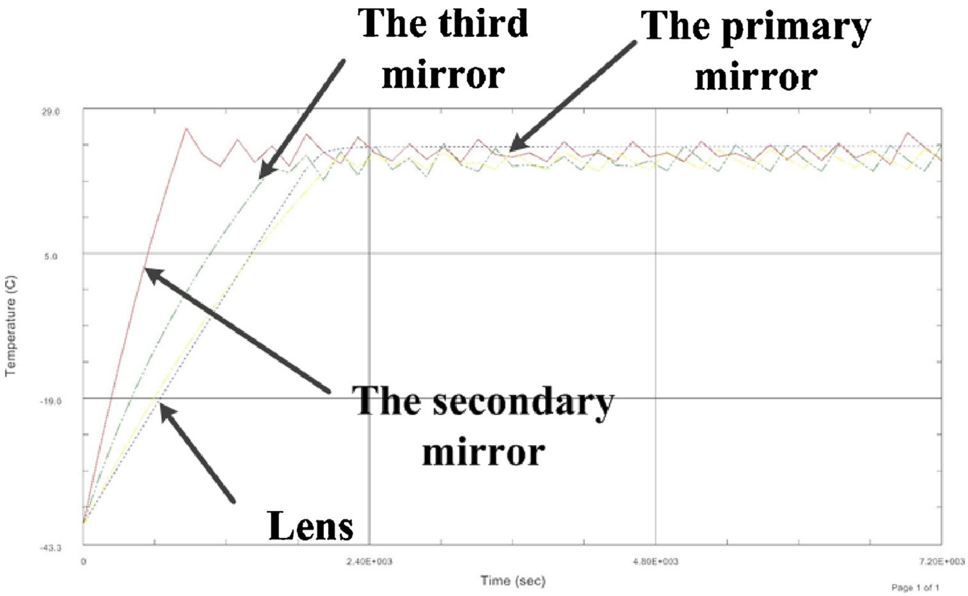

Fig. 8. Temperature curves of the optical system at the low temperature condition.

the optical system (including the primary mirror, the secondary mirror, the third mirror and lens) at low temperature is shown in Fig. 8.

Working condition of high temperature analysis: the initial temperature of the camera is 50 °C, the flight altitude is 10 km and the flight speed is 0.74Ma. The thermal boundary conditions are input according to the analysis results. The temperature change curve of the optical system (including the primary mirror, the secondary mirror, the third mirror and lens) at high temperature is shown in Fig. 9.

The analysis results show that the thermal control system can guarantee the temperature of the camera meet the requirement under low temperature and high temperature conditions.

6. Thermal balance test of the camera

The thermal test of aerial camera is relatively complex and difficult, and the methods of various thermal tests need to be explored in the test process. Due to the constraints of existing laboratories, it is impossible to simulate the outer boundary conditions such as convection heat transfer, but the effect of thermal design can be verified by thermal balance test which proceed in low temperature and low pressure environment.

In the thermal balance testing, the camera is placed in the chamber which can simulate flight environment. In the test, all the

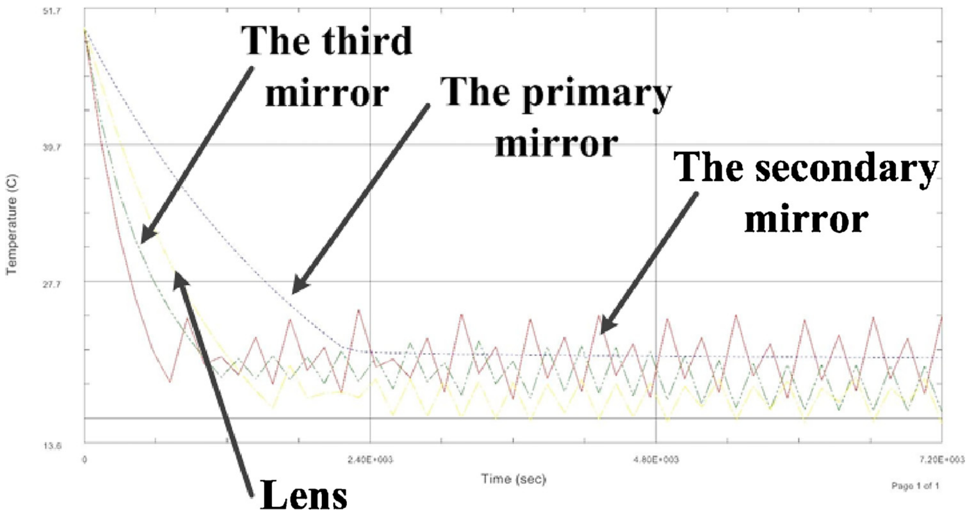

Fig. 9. Temperature curves of the optical system at the high temperature condition.

Table 2
The temperature of the main components after working 2 h.

		target temperature	calculation temperature	experimental temperature	Error (°C)
TPOS	MINT	20	18.9	18.5	−1.5
	MAXT	20	20.8	22.4	+2.4
TLC	MINT	20	19.6	19.0	−1.0
	MAXT	20	20.4	21.9	+1.9
TEC	MINT	10	19.1	19.3	/
	MAXT	45	32.6	37.9	/
TDC	MINT	10	19.7	19.2	/
	MAXT	35	31.9	31.6	/

MAXT: the maximum temperature.
MINT: the minimum temperature.
TPOS: the temperature of primary optical system.
TLC: the temperature of lens component.
TEC: the temperature of electric cabinet.
TDC: the temperature of detector components.

reference points' temperature is obtained in working mode during the whole process. The camera's initial temperature is 20 °C, the thermal control system is working, it continued for 2 h. This test is mainly to verify the camera's stability when the system is working. The temperature of the main components after working 2 h is shown in Table 2, the experimental results show that thermal control scheme meets design requirements.

7. Conclusions

In this paper, according to the camera thermal environment, the structure characteristics and the working mode, the thermal control system is designed in detail using the combination of passive thermal control and active thermal control method based on infrared aerial camera, and the heat transfer model and finite element model is established. The thermal analysis results meet the thermal control indexes. At the same time, under extreme conditions the thermal control system can satisfy the startup requirement of the camera, it validate the correctness and effectiveness of the thermal control design.

In this paper, mature thermal control technology is adopted to solve the temperature control problem of off-axis optical system effectively through reasonable layout and optimized design. The design method and conclusion of this paper have guiding and reference significance for the thermal control design of other off-axis infrared aerial cameras.

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