Thermal design and simulation of monitoring payload on manned spacecraft

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Abstract. Discharge monitor is a kind of primary payload monitor loaded on the manned spacecraft in the Low Earth Orbit, which is designed for monitoring the secondary discharge problem on the solar array. The issue of integrated electronic device heat dissipation is the key for normal operation supporting. In this study, the integral payload is simulated by finite element method, through structure modeling, based on the theory of heat conduction and heat radiation. In the result, under the measures of adjusting the layout of the electronic devices, coating the circuit board with copper, and black anodization for the case, the payload could definitely meet the needs of the heat dissipation in the extreme conditions, survive safely and functionally in the orbit, at least from the angle of thermal design.

1. Introduction

When a large-scale spacecraft orbits in the Low Earth Orbit, the high-voltage solar array would be attacked by the plasma in the ionosphere, which would cripple the spacecraft’s reliability of on-orbit performance, raising the problems like high-voltage solar array current leakage and the electrostatic discharge. Aiming at the aforementioned problems which flexible solar array might be confronted with, types of measures for secondary discharge restraint have been taken, and the validation has been confirmed. The working mode of the solar array discharging monitor is: setting the flexible solar array in the ionosphere, to check if there occurs discharging beyond 1ms, so as to validate the effectiveness of the plasma protection design for the solar array circuit components from sustainable secondary discharge.

Downsizing & highly-integrating is the fundamental aim for on-site payload development, but the structure design with highly integrated layout of the electronic components would definitely result in the increasing heat flux. According to the data reported, excessively high temperature would lead to electronics malfunction [1, 2]. As the experiments and researches illuminated, each 10°C that a semiconductor is warming, 50% that the system reliability is dropping [3, 4]. For the validation of payload performing reliability as well as the normal working condition for surrounding devices, strict and well-considered thermal design lays the primary foundation for function realization.

It is under this background and necessity that the work in this paper is undertaken. Through structure modeling, finite element analysis, suggestion of electronic devices layout is taken to promote the payload design.
2. Thermal design input of the discharge monitor

The purpose of thermal design is to organize the components’ cooling channels and heat dissipation measures of the case rationally, based on the surrounding thermal environment and the case’s structure layout, so as to validate the components junction temperature to meet the level I derating requirements, with a certain allowance.

The discharging monitor is installed on the heat dissipation face on the instrument panel in the resource module, with 2.5° deviation from quadrant III to quadrant II, at 2750mm distant from the back frame. The temperature range is from -40°C to +40°C; The thermal interface is located on the resource module bulk-head, the allocation arrangement is illustrated in Figure 1.

![Figure 1. Schematic diagram of the allocation arrangement and installation.](image)

Based on the thermal test condition corresponding to the discharging monitor, the working temperature range is from 40°C to 45°C, while restoring temperature range at -40°C to +55°C. According to the provisions of GJB/Z35-93, the highest junction temperature of most level I derating integral electronic components is 85°C.

3. Integral thermal design of the discharging monitor

3.1. Input of the case structure

Dimension of the case: 220×120×160mm³, weighing 4kg, with heat capacity of 4280 J/K, surface emissivity ≥85%, Al (2A12-H112 GB/T 3880-1997), heat conductivity of 138W/(m·°C), dimension of the mounting surface is 26400mm², with flatness of 0.1, roughness of 3.2.

Three circuits boards are included: a) Board 1, in charge of the compensation and discharging current monitoring and primary transformation for the power; b) Board 2 is the power board, in charge of the secondary convention of the power; c) Board 3 is in charge of the signal acquisition control and data processing.

![Figure 2. The case structure.](image)
The case is constructed by 6 panels, with 3 circuit boards in it. The exterior and internal view is shown in Figure 2.

3.2. The thermal design of the discharging monitor
The functional modules employ the vertical pull-out drawers onto the mounting surface, which could transfer the heat directly through the side wall, so as to further enhance the heat dissipation throughout the mounting surface.

Given the absence of the convective heat transfer in the vacuum environment, heat transfer capability is relatively weaker; as a result, conductivity plays the dominant role in the heat transfer, which carry the heat directly to the wall surface, and reject it through radiation.

3.2.1. Heat dissipation of the high power components. In order to be benefit for the components’ heat dissipation, and validate the distribution equilibrium of the heat power consumption on the PCB, which is for preventing the over concentrated heat consumption in a certain area, the high-power-consumption components are allocated in the periphery of the PCB, while low-power-consumption components are allocated in the central area [5-7]. The layout of the PCBs is illustrated as Figure 3, in which only those whose heat consumption ≥0.25W are shown.

![Figure 3. Circuit board layout.](image-url)
3.2.2. Design of the PCBs and the case. The electrical chassis is set to be orbiting for 2 years, with working time of 11680h. All the faces are black anodized except for the mounting surface, in this way, to benefit the thermal radiation.

The maximum heat power consumption is 10W, with totally metallic texture, the PCBs conjunct with the case by frame supporting shell, and there’s no need for thermal conductive filler through the validation of accounting.

The power board, control board and measuring board are all made from 6 layers, with over 2 layers of copper coating; considering the large dimension and high power of the board, the components of AME270461Z and AFL12028SZ are moved to the measuring board so as to improve the heat dissipation.

4. Results of simulation and discussion

4.1. Meshing and boundary condition setting

Set the structure design as the input for modeling, and the finite modeling is shown in Figure 4 after meshing. Here, configuration was simplified by ignoring the influence of Φ<10mm holes, so as to regarded the case as an entity.

![Figure 4](image)

**Figure 4.** Infinite modeling of the payload monitor.

Thermal analysis should consider the extreme temperatures which would appear under high/low temperature conditions [8, 9]; The ambient temperature is also set as the boundary condition.

4.2. Theory of computation

When the electronic devices are working, heat is dissipated through 3 ways: heat conduction, heat convection and heat radiation. However, for the payload on the satellite, heat convection is inexistence, so the heat conduction and heat radiation should take the priority under considered.

The basic theory of the thermal conduction is Fourier’s law, which should be stated as the heat quantity going through certain layer of cross section per unit time, the calculation formula [10] is:

\[
\Phi = -\lambda A \frac{dt}{dx} \quad (1)
\]

\[
\Phi = \frac{dT}{dx} \quad (2)
\]

Where, \(\Phi\) refers to the heat flux goes through a certain cross section per unit time, W; \(\lambda\) refers to the material coefficient of thermal conductivity, which represents the material’s performance of conductivity, W/(m·K); \(A\) refers to the area of cross section, m²; \(T\) refers to the impetus of the heat transfer; \(\frac{\Delta T}{A\lambda}\) is the thermal resistance.
The radiation obeys the law of Maxwell-Boltzmann, the calculation formula [10] is:

\[ E_b = \sigma A (T_1^4 - T_2^4) = C_0 A \left[ \left( \frac{T_1}{100} \right)^4 - \left( \frac{T_2}{100} \right)^4 \right] \] (3)

\[ E = \varepsilon \sigma A (T_1^4 - T_2^4) \] (4)

Where, \( \sigma \) refers to the Boltzmann constant; \( C_0 \) refers to the blackbody radiation coefficient, \( \text{W}/(\text{m}^2 \cdot \text{K}^4) \); \( T_1 \) refers to the temperature of the emission surface, K; \( T_2 \) refers to the temperature of the absorbing surface, K; \( \varepsilon \) refers to the emissivity.

4.3. Thermal analysis under high temperature condition

The environment temperature of the exterior case is up to the maximum of 40°C, the circuit board could finally reach the thermal balance as a result of power up for a long time, the temperature distribution is illustrated as Figure 5.

![Figure 5. Temperature distribution of the case under high temperature condition.](image)

The result revealed from comprehensive analysis tells that, the maximum temperature is 67°C, which appears at 422 chips. That could meet the requirement of components’ derating temperature beneath 80°C.

4.4. Thermal analysis under low temperature condition

The environment temperature of the exterior case could reach the minimum of -40°C, the circuit board could finally reach the thermal balance as a result of power up for a long time, the temperature distribution is illustrated as Figure 6.

The result revealed from comprehensive analysis tells that, the minimum temperature could reach -40°C, which mainly appears on the exterior of the case. The minimum temperature on the control board, power board and measuring board is basically set at -35°C, which appeared at the margin of the boards. The minimum temperature of the working components is -30°C, which appear at the AD1671 on the control board, FMC-461NTF at the power board, and AFL12028SZ at the measuring board, that could meet the requirement of components’ working temperature.
5. Conclusions
Rational thermal design is an effective mean for preventing electrical components from damage. Thermal resistance should be decreased as possible when the temperature difference is determined in the intensive heat transfer. For the projects in practice, materials with superior heat conductive coefficient should be selected to manufacture the thermal generate/conductive devices, as well as the utilization of thermal conductive silicone or conducting strip, so as to reduce the contact thermal resistance; Transform the parameter of the surface emissivity, surface area and angle coefficient to strengthen or weaken, such as coating high emissivity paints or increasing the thermal radiation area, so as to realize the thermal radiation enhancement effect.

This study has conduct structural thermal design for discharging monitor. Worth to mention that, rather than designing upon the experiences, finite element analysis was introduced into this work, accordingly, temperature field could be demonstrated sufficiently and clearly. It could be read easily that whether the electronic components meet the requirements from the angle of thermal designing, thus measures could be conducted with more pertinency through the whole iteration process. In the result, qualify the thermal designing further close to the aim—unload the squeezing to platform resources as possible, of course, in the premise of functioning.

To summarize, by means of adjusting the electric components layout, coating the circuit board, black anodizing the case, the design could meet the heat dissipation requirements under extreme conditions, thus guarantees the orbiting reliability and functionalization.

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