Thermal design and analysis of payload cabin of solar UAV in near space

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Abstract. Aiming at the temperature control demand of the near space solar unmanned aerial vehicle (UAV) payload cabin, this paper establishes the thermodynamic model of the payload cabin through thermal characteristic analysis, and proposes a system design method of structural thermal control integration. The thermal design of the payload cabin is carried out by means of thermal control such as uniform temperature, heat insulation, coating and active temperature control. The design weight of the whole payload cabin is only 7kg. The results of thermal analysis show that the temperature of the equipment in the cabin meets the requirement of the target during the whole UAV mission period, which verifies the correctness of the thermal design method. Compared with the traditional active temperature control scheme, the low temperature level increases by 3°C under the same heating power. The heat dissipation of the payload cabin is mainly convective heat transfer, but with the increase of altitude, the proportion of radiation heat dissipation is gradually increased. The research results can provide reference for the thermal design of similar aircraft.

1. Introduction
Near space refers to the space area with altitude between 20 km and 100 km. It is neither in the field of aviation nor in the field of space [1]. General Rod, commander of the U.S. Air Force Space Command, first proposed the concept of near space at the 20th Pacific Space Summit in Hawaii, and stressed that near space vehicles would have the characteristics of 'long-term, low-cost, high survival and rapid response'. With the continuous improvement of understanding of the near space field, the huge military and civil value of the near space has become increasingly prominent, and has become a space field that countries are scrambling to enter.

Due to the drastic changes in the near space environment conditions, the space thermal environment at different altitudes and in different regions has significant differences. Different from aviation and aerospace, the external environmental conditions to be considered include pressure, temperature, humidity, ozone, ultraviolet and space particle radiation, etc., which is far beyond people's imagination. Thermodynamic analysis and thermal control of aircraft interior and exterior are very important problems in the field of near space vehicle design. The thermal design of the loading cabin as the platform is the key to ensure the temperature of the equipment in the aircraft at a reasonable level.
At present, Japan, Korea, Germany and the United States are the countries that have studied the thermal analysis and thermal control of aircraft. Due to the technical blockade, there is no public report on the successful thermal design methods and cases of the payload cabin of near space vehicles. In China, from the published papers [2-4], it can be seen that the research of near space thermal control technology is still in its infancy, and many engineering application problems have not been solved. However, with the continuous development of the near space vehicle technology, the flight climbing height and flight time of the aircraft are required to continue to improve, which leads to the higher requirements of the near space vehicle thermal control technology. It is urgent to put forward and apply the targeted and practical thermal control scheme.

In this paper, the thermal design of the payload cabin of a solar UAV with altitude range of 0-30km is carried out to ensure the temperature of the equipment in the cabin. In view of the harsh environmental conditions and the restrictions of weight and energy, a thermal design scheme of the structure thermal control integrated payload cabin system is put forward by analysing the thermal characteristics of the UAV in the near space environment, and is verified by thermal analysis.

2. Thermal characteristic analysis of payload cabin

2.1. Mission characteristic

Solar UAV can be left vacant for tens of days or even months from takeoff to cruise to landing. There are 16 equipment in the UAV payload cabin, the total weight is 17kg, the total heat consumption is 270W, and the working temperature is between -30~+55°C (the temperature of the equipment shell is taken when UAV is working), due to the limited resources, only two active temperature control loops are allocated to the thermal control system, totalling 100W.

The UAV is designed to fly at a maximum altitude of 27,000m. As shown in figure 1, typical mission profiles can be divided into three stages: first day climb, circular flight and landing. Gliding landing is mostly in the night, especially in the daytime. During normal flight, UAV's pitch angle is -5~8 degree, and the rolling range is small. The take-off time is 5~10 am and the climb / glide speed is 0~2m/s. The whole mission profile has a flying time of 30 days.

2.2. Physical model

The payload cabin is located in the center of UAV, and it is the core compartment of the whole UAV, which is equipped with flight control, navigation, measurement and control equipment. As an independent cabin, the entire payload cabin is located in the outer skin of the UAV; only the bottom surface is exposed as a heat dissipation surface, and contacts with the external atmospheric environment.

![Figure 1. Typical mission profile of UAV.](image1)

![Figure 2. Structure of payload cabin.](image2)

As shown in figure 2, to maximize mechanical decoupling with the UAV, the entire payload cabin is connected only to the main girder of the UAV; to maintain good aerodynamic characteristics and appearance, the outer surface of the payload cabin bottom is in conformity with the local wing, and the
inner surface needs to ensure the contact area between the equipment and the mounting surface due to the installation equipment and the contact heat exchange, so the inner surface is still level; because the solar unmanned aerial vehicle is extremely demanding on weight, in order to minimize weight loss, the bottom plate uses 0.3 mm thickness of aluminium skin aluminium honeycomb sandwich structure, the area is 0.79 m². The main bearing structural members on both sides of the load compartment are based on the additive manufacturing 3D printing independently developed by the mechanical division of the CAST. Dot matrix structure, each design weight is only 750g. The rest of the tie rods and brackets are made of ultra-light material magnesium-lithium alloy, which is nearly 500g less than the traditional aluminium alloy structural parts; the thermal insulation support structure is based on PMI foam board Hollow sandwich structure. The weight of the entire load compartment is estimated to be around 7kg.

2.3. Analysis of thermal environment characteristics

The adjacent stratosphere is 12~50km away from the ground. The flying height of the solar UAV is at the bottom of the stratosphere. According to the vertical distribution curve of the atmospheric properties of the 1976 version, as shown in figure 3, the atmospheric temperature, density and pressure vary with height. In the ground preparation stage before flight, it takes 1-2 hours, the extreme minimum temperature is -40°C, the extreme maximum temperature is 42.9 °C, and a suitable takeoff time should be selected according to the weather conditions. In the climbing stage, when the altitude is less than 11 km, the average temperature decreases about 6.5 °C/Km, 11-20 Km, the temperature is about -56.5 °C, the air speed increases with the altitude, and the air pressure increases. And the temperature decreases with the altitude rising; during the mission flight, according to the national military standard, the maximum temperature is -36.2°C, and the minimum temperature is -82.4°C.

2.4. Thermodynamic model

The thermal environment of solar UAV in near space is rather complicated. From take-off to mission, the external thermal environment is constantly changing, and the total influencing factors are the sun, the earth, cold space and the surrounding atmosphere. As shown in figure 4, the payload cabin includes direct solar radiation $Q_{\text{SUN}}$, ground (or cloud) reflected solar radiation $Q_{\text{reflect}}$, infrared radiation $Q_{\text{E-air}}$ between the earth surface (or cloud) and the payload cabin, infrared radiation $Q_{\text{rad}}$ from the payload cabin to the outside, convective heat transfer $Q_{\text{conv}}$ from the bottom of the payload cabin to the outside atmosphere, and natural heat transfer inside the payload cabin $Q_{\text{N-conv}}$ and heat source in the payload cabin, the heat consumption of the equipment $\overline{Q}$.

![Figure 3](image1.png)  
*Figure 3. 1976 vertical distribution of atmospheric physical properties[5].*

![Figure 4](image2.png)  
*Figure 4. Schematic diagram of thermal environment for near space solar UAV.*
For the entire UAV, the transient energy control equation[6] is:

\[
\frac{\partial (\rho c_p T)}{\partial t} + \text{div}(\rho c_p \mathbf{u} T) = \text{div}(k \cdot \text{grad} T) + S_f
\]  

(1)

In the equation, \(\rho\)-density, \(T\)-temperature, \(t\)-time, \(k\)-thermal conductivity, \(\text{div}\)-divergence, \(\mathbf{u}\) - velocity vector, \(\epsilon\)-constant pressure specific heat, \(\text{grad} T\)-temperature gradient, \(S_f\)-source term. The source term includes the sum of the factors affecting the thermal environment of the UAV described above.

\[
S_f = q_{\text{SUN}} + q_{\text{Reflect}} + q_{E, \text{air}} + q_{\text{Rad}} + q_{\text{Conv}} + q_{S, \text{Conv}} + q
\]  

(2)

Assuming that the outer skin is isothermal, equation (1) can be simplified as:

\[
\rho c_p \frac{\partial (T)}{\partial t} = q_{\text{SUN}} + q_{\text{Reflect}} + q_{E, \text{air}} + q_{\text{Rad}} + q_{\text{Conv}} + q_{S, \text{Conv}} + q
\]  

(3)

For the payload cabin, since the bottom only faces the atmosphere, and which is facing the ground and is not directly exposed to the sun, the steady-state energy balance equation of the payload cabin is:

\[
Q_{\text{Reflect}} + Q_{E, \text{air}} + \bar{Q} = Q_{\text{Rad}} + Q_{\text{Conv}} + Q_{N-\text{Conv}}
\]  

(4)

Among them, the atmosphere albedo heat flux of the earth[7] is:

\[
Q_{\text{Reflect}} = \alpha AS
\]  

(5)

\(A\) is the area of the bottom plate, \(S\) is the intensity of solar radiation, and \(\alpha\) is the albedo. Generally, it takes \(\alpha = 0.30 \sim 0.35\), which is closely related to the surface state, latitude and even time of the earth. The corresponding albedo at different latitudes of the earth is zonal distribution[8].

Infrared radiation heat flux of the earth is:

\[
Q_{E, \text{air}} = \epsilon_e \sigma A T_e^4
\]  

(6)

Among them, the earth's surface temperature is related to latitude, geographical location, weather and other conditions. Generally, it decreases with the increase of latitude. According to the season statistics, the average earth surface temperature is approximately 288K.

The infrared radiation heat flux from the payload cabin to the outside is:

\[
Q_{\text{Rad}} = \epsilon_e \sigma A (T_o^4 - T_e^4)
\]  

(7)

\(T_o\) — Outside surface temperature of payload cabin bottom.

\(T_e\) — External radiation source temperature, take \(T_e\) as the effective temperature of the sky.

Sky effective temperature[9] is a function of atmospheric water vapor content, cloud amount (or sunshine percentage), atmospheric temperature and surface temperature defined by absolute blackbody radiation flux according to Stephen-Boltzmann law. Because these-meteorological factors have obvious regional and temporal variations, the sky effective temperature is also a function of geographical location (space) and seasonal (time). Under the clear sky condition, the Brunt equation is used to estimate.

\[
T_e = (0.51 + 0.208(\epsilon_e)^{0.25}) \times T_u
\]  

(8)

\(e_e\) — Partial pressure of water vapor in the atmosphere.

In the stratosphere of 20 km, there is very little water vapor in the atmosphere, and the partial pressure of water vapor is considered to be zero, thus the effective temperature of the sky can be expressed as \(0.51^{0.25} T_u\).

For convective heat transfer:

\[
Q = hA(T_o - T_d)
\]  

(9)
The convective heat transfer between the bottom plate of the payload cabin and the outer atmosphere is correlated by the mean surface heat transfer coefficient of the external forced convection tube.

\[ Nu_f = 0.0266 \text{Re}^{0.08} \text{Pr}^{1/3} \]  

Experimental correlation of natural convection heat transfer in large space is used in natural convection inside the payload cabin:

\[ Nu_N = 0.11(Gr \cdot Pr)^{1/3} \]  

2.5. Brief summary

From the above analysis, we can see that:

1) The thermal environment of the solar UAV is similar to that of the satellite. We can draw lessons from the mature thermal design method of the satellite, such as temperature equalization design of heat pipe and active temperature control.

2) Compared with the satellite, due to the influence of rarefied air, the thermal environment in the near space is more complex and changes more dramatically. Natural convection and forced convection heat transfer exist in the payload cabin under sealed or unsealed conditions, so the thermal design needs to consider the corresponding insulation requirements.

3) Due to the UAV cruising day and night, the flight altitude is constantly changing, so it is necessary to analyse the influence of convective heat transfer and radiative heat transfer at different altitudes on the UAV, and to reasonably design the heat dissipation surface and heating power to adapt to the influence of thermal environment at different heights.

Thermal design should take into account the above factors, so as to put forward a reasonable and systematic thermal design scheme.

3. Thermal design

3.1. Temperature equalization design

A total of 16 equipments in the payload cabin, the maximum heat consumption is 120W, and the minimum heat consumption is 1W. In order to reduce the temperature non-uniformity between the equipment in the payload cabin, two I-shaped single-hole aluminum-ammonia channel heat pipes with a cross-section of 30 \times 11.4 were semi-embedded in the honeycomb panel, as shown in figure 5, has a length of 1.3m and 1.4m respectively, and is designed as a U-shaped structure. The thickness of the honeycomb panel is 25.6mm, and the upper surface of the heat pipe is attached to the upper surface of the honeycomb skin. To reduce weight, the fins on the lower surface of the heat pipe are cut off. The temperature difference between the devices is reduced by the uniform temperature of the heat pipes and reasonable layout of the devices.

![Figure 5. Schematic diagram of thermal design of heat sink.](image-url)
3.2. Heat insulation design

According to the standard atmospheric physical properties, the lowest temperature of the UAV cruising altitude in the vicinity of 15-27 km is -56.5°C. According to the national military marking, the extremely low temperature can reach -82.4°C, far exceeding the operating temperature limit of the equipment. Therefore, insulation design is required. Due to the existence of thin gas in the adjacent space, this paper proposes a hollow sandwich insulation structure based on PMI foam board. As shown in figure 6, the selected PMI foam density is 32kg/m³, corresponding to the environment of -100~80°C, the thermal conductivity is 0.02~0.04W/m·K[10], which increases with the increase of temperature.

![Figure 6. Hollow sandwich insulation structure based on PMI foam board.](image_url)

The PMI insulation structure serves as both a support structure and an insulation material to keep the entire payload cabin warm. The single-layer PMI has a thickness of 5 mm and the heat-insulating structure has a total thickness of 15 mm. Aluminized film is adhered to both inner and outer surfaces to further reduce heat transfer of radiation between the bulkhead and the external environment as well as the equipment inside the cabin.

3.3. Heat dissipation design

According to the evaluation of the thermal characteristics of the payload cabin, this paper only designs passive heat dissipation to meet the heat dissipation requirements of the payload cabin. The honeycomb panel is exposed in the atmosphere, and is the main channel of heat dissipation through convection and radiation. As can be seen from figure 4, when the UAV flying altitude exceeds 20 km, on the one hand, the ambient temperature begins to rise continuously, but the air density and pressure are still decreasing. From equation (9) ~ (12), the convective heat transfer is decreasing continuously. When the flying altitude is 27 km, it is known from equation (4) that, without considering radiation heat dissipation, convective heat transfer alone cannot meet the requirements of heat dissipation; if radiation heat dissipation is considered, but the aluminum alloy material which keeps the original surface of honeycomb panel, its emissivity is about 0.1, and the calculation cannot meet the load cabin dispersion. Therefore, it is designed to spray a certain area of low-absorption and high-emission thermal control coating SR107 white paint on the outer surface of the honeycomb panel with a solar absorption ratio of 0.2 and an emissivity of 0.88.

According to the calculation boundary conditions of external heat flow under extreme high temperature conditions given by CSBF[11], equation (5) ~ (8) is calculated according to the parameters of high temperature conditions corresponding to UAV flying to 27 km and 40 degrees north latitude. Assuming that the temperature of payload cabin bottom plate is 40°C, the area of white paint, which can be calculated by equation (4), is about 0.325 m², and the maximum external heat flux at the bottom plate is 168.4W.

3.4. Active temperature control design

Based on the limitation of temperature control loop and power, taking into account the bottom honeycomb panel as the main heat dissipation channel, which is the cause of strong convection heat transfer, in order to improve the ability of active temperature control and reduce the heat leakage during heat transfer, instead of the traditional method of pasting heating sheet on the heat pipe on the satellite, the heating sheet is directly pasted on the equipment. The power of the heater applied to each
device is determined based on the results of the thermal analysis. Each heater is 50W, a total of 2 channels, and the temperature control threshold is [-20,0] °C.

4. Thermal analysis verification
Through the analysis of the external environment, the high and low temperature working conditions are established. The thermal analysis modeling calculation is carried out by using NX 8.5 software. Three steady-state working conditions are calculated. The detailed analysis results are shown in table 1.

Among them, the low temperature working condition is used to evaluate the temperature control ability of the heater under the extremely low temperature in the adjacent space, and the standard condition is used to verify the temperature level of the equipment in the cabin if the heater is not used, so as to judge whether the design can achieve the purpose of saving energy.

| Condition       | Height (m) | Flight speed (m/s) | Ambient temperature (K) | Explain                                                                 |
|-----------------|------------|--------------------|--------------------------|--------------------------------------------------------------------------|
| High temperature| 27000      | 46                 | 236.8                    | Considering the external heat flux of the sun and the earth's infrared, the heater closes |
| Low temperature | 18000      | 24.3               | 190.8                    | No solar outside heat flux, heaters on                                    |
| Standard working| 18000      | 24.3               | 216.5                    | No solar outside heat flux, heaters on                                    |

The calculated temperature results of each equipment in the payload cabin are shown in table 2, all within the operating temperature range. Figure 7 shows the temperature cloud chart of the payload cabin under different conditions.

| Condition                  | High temperature | Low temperature | Standard working |
|----------------------------|------------------|-----------------|------------------|
| Temperature level °C       | 37.3~50.0        | -19.5~-5.5      | -21.1~0.0        |

From the calculation results, it can be concluded that: under high temperature conditions, the area of the heat dissipation surface is suitable to meet the heat dissipation demand; under low temperature conditions, the power of the heater is enough to ensure that the equipment does not exceed the lower limit of the working temperature; under standard operating conditions, the heater can be closed to save UAV energy.

4.1. Comparison of temperature levels in low temperature working conditions under different active temperature control modes
For the active temperature control design, compared with the traditional scheme of attaching the heating sheet to the heat pipe. As shown in figure 8, the temperature level of the device is -22.4~
10.5°C under low temperature conditions with the heaters long-passed, the minimum temperature is reduced by 3°C compared with the heating plate directly pasted on the equipments, and the overall temperature level of the equipments is much lower than the direct attachment of the heating sheet to the equipments.

![Figure 8](image)

**Figure 8.** Temperature chart of low temperature condition (heat sheet pasted on heat pipe).

4.2. *Analysis of the effects of radiative heat dissipation and convection heat dissipation at different heights*

According to the results of the thermal analysis, the radiative heat dissipation and the convection heat dissipation at the heights of 18 km and 27 km are respectively counted as shown in table 3. Combined with the thermodynamic model of the UAV payload cabin in section 2.4, the convective heat transfer accounted for a large proportion, but with the increase of the height, the convective heat transfer was significantly weakened, and the proportion of radiative heat dissipation increased gradually. Therefore, in thermal design, it is necessary to combine the specific level of heat consumption, thermal characteristics and flight altitude and other factors to determine whether it is necessary to strengthen radiation and cooling surface size.

| Height(km) | $Q_{Rad}$ (%) | $Q_{Conv}$ (%) |
|-----------|---------------|----------------|
| 18        | 15.3          | 84.7           |
| 27        | 40.4          | 59.6           |

5. **Conclusion**

Aiming at the thermal control requirements of the payload cabin of the near space solar UAV, this paper analyzes the thermal environment of the payload cabin in the near space, establishes the thermodynamic model, puts forward a thermal design method of the integrated structural thermal control system which is easy to be realized in engineering, and determines the area of the heat dissipation surface. The thermal analysis proves that the temperature of the equipment meets the requirements of the index, which shows that the thermal design method is reasonable and feasible. The main conclusions are as follows:

(1) The payload cabin of the structure integrated thermal control design, weighing only 7kg, meets the requirements of thermal control performance and saves weight on the premise of meeting the structural strength.

(2) Compared with the traditional heating sheet sticking on the heat pipe, the active temperature control method with direct heating equipment can raise the low temperature level by 3 °C at the same
heating power, and the temperature control effect is better, and is more suitable for the thermal environment in the near space.

(3) The heat dissipation of the payload cabin is mainly convective heat transfer, but as the altitude increases, the proportion of radiation heat dissipation increases. For specific thermal design, the size of the heat dissipation surface should be determined according to the heat consumption level and the flying height.

The thermal design method proposed in this paper has certain engineering application value and can be used as a reference for similar aircraft thermal design.

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