Thermal design and optimization of the stratospheric airship equipment module

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Abstract. Stratospheric airship is a special air vehicle which suspended in the stratosphere for a long period of time, it can be used for military and civil investigation, observation, communication and other purposes to the Earth's surface. Because its altitude is about 20 km, its thermal environment is different from normal aircrafts or spacecrafts. On the one hand, the solar heat flux during daytime and the heat source of the equipment require a good heat dissipation design of the airship; on the other hand, the radiation and convective heat exchange at night require a good thermal insulation design of the airship. The key thermal design of the airship is how to balance daytime heat dissipation and nighttime insulation. In this paper, the convective and radiative heat transfer model of a certain stratospheric airship is established based on the CFD simulation method, and the daytime and nighttime operating modes are analyzed. Three thermal design optimization schemes including compartmentalization, cooling holes, and fans are proposed and evaluated by simulation methods. The calculation results show that the thermal design margin in different operating modes of the airship can be effectively improved by controlling the fan operating, which provides a reference for future development of corresponding models.

1. Introduction
The stratosphere is a layer of the atmosphere from the top of the troposphere to 50 km above sea level, and its mass accounts for about 1/4 of the total mass of the atmosphere. There is almost no condensation of water vapor in the stratosphere, no atmospheric convection, no rain, no snow and other meteorological conditions, and the air temperature is relatively stable [1]. Stratospheric airships are important floating platforms for real-time monitoring, early warning, missile defense, counter-terrorism, communications and other missions, it can be combined with satellites, aircraft and ground equipment to form an integrated air, space and ground command, control, communication, computer, intelligence, surveillance and reconnaissance system. It can play a stronger, faster and more convenient support role for joint force operations, and has been included in the U.S. Army’s development plans of "operational rapid response" and "joint warfare". Near-space airships were also introduced in the simulation exercise [2]. Compared with Earth-orbiting spacecraft, stratospheric airships are characterized by a more complex thermal environment. The atmosphere, which is less than 1/14 density of the ground, also brings a weak convective heat transfer besides the solar irradiation, terrestrial infrared radiation, terrestrial albedo and heat dissipation to the cosmic space background [3]. Liu et al. applied the nodal network method to
analyze the effect of the solar cell on the thermal characteristics of the stratospheric airship, and obtained the effect of different bedding cell areas on the helium "superheat" effect inside the airship [4]. Yao et al. established a thermodynamic control model of the airship during ascent, and analyzed the thermodynamic and dynamic heat transfer processes of the internal gases of the airship during ascent and their influence on the buoyancy forces and flight control [5]. Guo et al. established a thermodynamic, kinetic, and kinematic model of the airship and gave the optimal trajectory of the airship's ascent in different scenarios by using a nonlinear solver with flight time as the optimization goal [6]; Shi et al. established a static and thermodynamic model of the airship, and based on the Runge-Kutta method, they gave the effects of sunshine time, season and other parameters on the outer membrane, primary and secondary helium temperatures, and evaluated their influence on the airship's flight control at fixed points [7]. In summary, the convective heat exchange between the atmosphere and the air inside the airship causes the temperature change inside the airship, which further affects the trajectory and motion control of the airship. It is one of the important issues that must be considered in the structure and thermal control design of the airship, but the current research mainly focuses on the control of the airship, and there is little research on the heat dissipation and insulation of the equipment inside the pod. In this paper, a simulation model of a certain type of airship equipment pod is established. The calculation results show that it is difficult to realize the temperature control of high and low temperature conditions only by passive means. On this basis, three optimization schemes are proposed and compared by using the simulation method, which provides a reference for the design of airship pod in the future.

2. Stratospheric thermal environment

2.1 Convective environment

The main thermal characteristics of the stratosphere include: the temperature gradually changes from isothermal distribution to counter-temperature distribution with increasing height, the temperature at the bottom is about -55 °C, and increases significantly with altitude above 20 km; the airflow is dominated by horizontal motion, with very weak vertical motion, and the wind speed is low at about 20 km [8], and when the airship has no active power, it can be considered to be dominated by natural convection, which can be corrected according to the empirical correlation formula for natural convective heat exchange at low pressure as follows [9].

\[ h = h_0 \times \left( \frac{P}{P_0} \right)^c \]  

Where, \( h \) is the natural convective heat transfer coefficient at the corrected low pressure, \( W/(m^2 \cdot ^\circ C) \); \( h_0 \) is the natural convective heat transfer coefficient analyzed by the dimensionless number method, \( W/(m^2 \cdot ^\circ C) \); \( P \) is the current pressure, Pa; and \( P_0 \) is the sea level atmospheric pressure, 101325 Pa; \( C \) is a constant, 1/2 for laminar flow and 2/3 for turbulent flow. Because the natural convective heat transfer coefficient at atmospheric pressure is generally around 10~20 W/(m^2 \cdot ^\circ C), it can be obtained that the natural convective heat transfer coefficient around 20 km is around 1~5 W/(m^2 \cdot ^\circ C). Although the heat transfer coefficient of convection is only about 20% compared to atmospheric pressure, natural convection may also bring about very considerable heat leakage, considering the stratospheric temperature of about -55 °C.

2.2 The radiation environment

The main radiative heat flow in the environment of the stratospheric airship is shown in Figure 1 [10]. In the figure: \( Q_s \) is the solar irradiation heat flow (W), about a solar constant (1367 W); \( Q_e \) is the Earth infrared radiation heat flow, W, which can simplify the Earth to an absolute black body about 250 K; \( Q_a \) is the Earth albedo heat flow, W, take the global average reflectivity around 0.3 to 0.35; \( Q_r \) is the dissipative heat flow from the stratospheric airship to the cosmic space background. That is to say, there will be a big difference between the daytime and nighttime heat flow of the stratospheric airship, and the
use of Maximum Power Point Tracking Solar Controller (MPPT) and other devices that generate heat in the daytime poses a challenge to the thermal design of the airship pod.

![Figure 1. Orbital thermal environment](image1)

### 3. Stratospheric airship thermal design

#### 3.1 Modelling

Figure 2 shows the internal design of a stratospheric airship pod, in which the lower deck mainly contains two lithium batteries. The batteries are controlled by independent thermostatic circuits. The upper deck contains 12 equipment including DC, MPPT and others. Four MPPTs’ heat consumption is 100W in the daytime and has no heat source at night, so the heat consumption of the upper cabin is 578W in the daytime and 178W in the nighttime.

For the modeling of flow and heat transfer, the gas in the stratosphere still satisfies the continuity equation, the conservation of momentum equation, and the conservation of energy equation.

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = S_m
\]

\[
\frac{\partial}{\partial t}(\rho \mathbf{v}) + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) = -\nabla p + \nabla \cdot \left( \rho \mathbf{g} \right) + \rho \mathbf{f}
\]

\[
\frac{\partial}{\partial t}(\rho E) + \nabla \cdot (\rho E \mathbf{v}) = \nabla \cdot \left( k_{\text{eff}} \nabla T - \sum \beta_i j_i + \beta_{\text{eff}} \mathbf{v} \right) + S_h
\]

By selecting a suitable turbulence equation, the computational domain space can be discretized and solved. In this paper, based on the structured grid, IcePak is used to establish the flow heat transfer model inside and outside of the pod, where the devices are modeled according to an empty box structure to simulate their heat capacity, and Figure 3 shows the computational grid.

![Figure 2. Airship pod design](image2)

![Figure 3. Computational domain grid](image3)

#### 3.2 Thermal design

When the pod is approximately 1.3m×1.3m×1.3m, the reaching heat flow of external solar irradiation is approximately 3.2 kw (irradiated from an oblique 45°).

Calculated according to the total set of parameters, the wall temperature is set to \(T\) and the daytime heat balance equation is:

\[
S \times [(T - 218) \times 1 + 5.67 \times 10^{-8} \times \epsilon \times (T^4 - 218^4)] = 578 + 3200 \times \alpha
\]

The nighttime heat balance equation is satisfied:
Where, $S$ is the surface area; $\varepsilon$ is the emissivity of the material; and $\alpha$ is the solar absorption ratio. When the absorption ratio, emissivity is 0.1, the minimum convective heat transfer coefficient (daytime) and the maximum convective heat transfer coefficient are $1\text{W/(m}^2\text{°C)}$ and $5\text{W/(m}^2\text{°C)}$ (considering extreme conditions), the calculated temperature will exceed $30^\circ\text{C}$ and $-50^\circ\text{C}$, the temperature control requirements cannot be satisfied. The external disturbance (solar radiation during the day and heat dissipation at night) should be blocked by the outer wall surface insulation material as much as possible. In this paper, 0.01m-thick foamed polyurethane is selected for thermal insulation, and a single layer of aluminized film is pasted on the surface to reduce the effects of solar irradiation.

### 3.3 Calculation results and analysis

Calculation conditions for working conditions of high and low temperature are shown in Table 1.

| Table 1. Calculation of working conditions |
|-------------------------------------------|
| External illumination | High-temperature conditions | Low-temperature conditions |
| 1414W/m², 45° oblique exposure | 0W |
| Internal heat source | MPPT 100W×4 | MPPT 0W |
| Other equipment work with a constant heat flow | |
| Upper mounting plate heating | no start | 150W |
| Outside air temperature/°C | -55 | -65 |
| Battery temperature/°C | 10 | -10 |
| Flight altitude/m | 19000 |

Figure 4 and 5 show the temperature distribution in the most extreme working conditions in the daytime. Figure 6 and 7 show the temperature distribution in the most extreme working conditions in the nighttime (with 150W internal heating). Figure 8 shows the temperature distribution of each individual device for the transient analysis.

Figure 4. Temperature distribution of equipment in extreme high-temperature conditions

Figure 5. Temperature distribution of cross sections in extreme high-temperature conditions
Figure 6. Temperature distribution of equipment in extreme high-temperature conditions

Figure 7. Temperature distribution of cross sections in extreme high-temperature conditions

Figure 8. Transient analysis of each individual device temperature

As shown in the figure: due to the big difference between day and night heat flow, the equipment inside the pod has only about 2°C margin in high temperature and about 20°C margin in low temperature, which makes it difficult to meet the heat control requirements. At the same time, since the stratospheric airship pod generally uses lighter materials, it will reach the equilibrium temperature in 4 hours during the day and night, and it is difficult to optimize the temperature distribution of the pod during the day and night by means of heat capacity.

4. Stratospheric airship thermal design optimization solutions

4.1 Compartment design

The MPPT compartment solution is to set up a separate mounting plate for MPPT, which is directly convective with the outside world for heat exchange and temperature control through the heating circuit at night (other devices have a more stable heat consumption and can be controlled through insulation). Since MPPT and the main cabin are relatively independent, they can be modeled separately. The mounting plate size is 660 mm (Height) x 340 mm (Width), 2 MPPTs are installed top and bottom, and the extreme high-temperature conditions are set for external sun irradiation, heat flow 1414 W/m², MPPT power 100 W, external temperature -55°C; extreme low-temperature conditions are set for external no sun irradiation, MPPT power 0, external temperature -65°C, heating power 75 W. The results are shown in Figure 9 and Figure 10, which shows that the high temperature margin of this scheme is about 10°C and the low temperature margin is about 8°C. It is not much improved than the existing scheme.

Figure 9. Extreme high-temperature conditions

Figure 10. Extreme low-temperature conditions

4.2 Vent design
As there is solar radiation outside the pod, reducing the thickness of the bulkhead will also lead to solar radiation penetration, which in turn will increase the cabin temperature. Therefore, taking the ventilation holes solution can reduce the temperature range inside the pod. With 4 ventilation slots of 1m×0.2m in the top of the cabin (circular arrangement), the hot air in the cabin can naturally convectively overflow from the slots, which is easy to dissipate the heat in the cabin. But the rainproof structure during airship ascent and descent should be considered. As shown in Figure 11 to 14, we can see that the ventilation holes can lower the temperature of the equipment cabin by 5~10°C in both high and low temperature conditions, but they cannot reduce the temperature difference between day and night in the cabin.

4.3 Fan design
Fans are one of the most common devices used to dissipate heat in electronic equipment, and introducing fans into stratospheric airship pods can optimize the thermal design of the pods. Fans will efficiently remove waste heat from the equipment in the daytime, and in nighttime shutting down the fans will reduce the heat leakage of the equipment. In this paper, the Papst 5112 all-metal fan is selected for cooling, and the curve of the fan at low pressure is corrected by IcePak. The calculations show that the fan can effectively reduce the cabin temperature by working in daytime, and even reduce the working temperature by 10-20°C for MPPT and other high heat flow equipment.
However, the following issues still need to be considered for the design of the fan cooling method.

1. At present, the temperature of industrial cooling fans is generally above -40 °C, which is higher than the stratospheric temperature of -55 °C. The temperature adaptability of fan blades, bearings, lubrication, etc. should be considered.

2. In order to reduce the impact of fan openings on nighttime insulation, check valves could be designed on the cabin, but due to the low air density in the stratosphere, the opening angle of ground-based check valves during daytime will be much smaller than the ground-based design value, and the check valves used in the stratosphere need to be redesigned.

3. Protection from stratospheric rain and snow during the ascent and descent of the airship needs to be considered.

5. Concluding remarks
For the thermal control problem that stratospheric airship pod needs to dissipate heat in the daytime and keep it warm at night, this paper establishes a flow and heat transfer model of an airship pod using CFD simulation, and compares three heat transfer optimization schemes. The analysis results show that: through the compartment scheme, the equipment with large fluctuations in heat source can be controlled separately to reduce its influence on other equipment, but it has little influence on its high and low operating temperature. The cooling vent scheme, which will reduce the daytime and nighttime temperatures in the cabin, can not reduce the difference between daytime and nighttime temperatures, and will require consideration of rain and snow protection when airship go through the stratosphere. By adding the fan scheme, the daytime temperature of the airship pod can be reduced with little effect on the nighttime temperature, and the temperature difference between day and night can be reduced effectively, but the problems of rain and snow prevention, check valve design and temperature adaptation of the fan need to be considered. The findings of this paper can be used for the thermal design and optimization of stratospheric aircraft pods, and provide a reference for the development of corresponding models.

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