Numerical calculation and analysis of infrared radiation characteristics of stratospheric airship

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Abstract. In order to estimate the spatial distribution of infrared radiation of stratospheric airship, the geometric model of stratospheric airship was firstly constructed in this paper. Then, considering the influence of environmental radiation, the one-dimensional heat conduction differential equation of airship skin was established, the equation was solved by backward difference method, and the temperature distribution of airship skin was numerically calculated. On this basis, the spatial distribution of airship infrared radiation was further calculated. The results show that the infrared radiation intensity of the airship in the sunny face is higher than that in the shadow face, and the infrared radiation intensity of the airship in the 8~14μm is obviously higher than that in the 3-5μm.

1.Introduction
Stratospheric airships can achieve longer flight time, higher cost efficiency and lower energy consumption, so airships have attracted more and more research attention in recent years[1]. The infrared radiation characteristics of airship are studied by real time measurement, but the experimental data are relatively few due to the high cost and difficulty, and it is difficult to establish a reliable empirical model.

This paper mainly studies the infrared radiation characteristics of airship surface and obtains the infrared radiation model of airship surface by numerical calculation. To study the infrared radiation characteristics of airship surface, the key step is to calculate the temperature distribution of airship skin. According to the thermal properties of the surface material, the infrared radiation of the airship itself can be obtained. Then, combined with the influence of environmental factors on the infrared radiation characteristics of the airship skin, the infrared radiation reflected by the airship can be calculated.

2. Computational model

2.1 Airship geometry model
The shape of the airship is approximately an ellipsoid[2]. The three parameters a, b and c of the ellipsoid are the major axis, the middle axis and the short axis of the ellipsoid respectively, and b=c. From these three parameters, the equation of the ellipsoid in the spatial cartesian coordinate system
can be expressed as \( \frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1 \). Taking points \((2a-1)\) along the long axis of the ellipsoid, divide the long axis of the ellipsoid into \(2a\) equal parts, and cut the ellipsoid into \(2a\) small rings with a width of 1, as shown in figure 1. Then, each ring is evenly spaced with 8 points, and each small ring is further divided, as shown in figure 2. The ellipsoid is divided into \((2a-1) * 8\) facets.

Fig. 1 division of the long axis          Fig. 2 division of the ring

2.2 Skin material properties
The surface of modern airships is mostly laminated composite materials[3], as shown in figure 3. The coating material used as the outer surface coating is generally polyvinyl chloride coating (PVC) or polytetrafluoroethylene coating (PTFE), among which polytetrafluoroethylene is the ideal coating for the stratospheric airship, and this coating can roughly meet the various material requirements of airships. Due to the low infrared emissivity of PTFE, it is of great significance for airship stealth in infrared[4].

Fig.3 Typical laminated membrane structure

3. Airship skin radiation heat transfer factor
The energy of airship surface heat balance includes solar direct radiation \( Q_{\text{sun\text{dir}}} \), reflection of earth to solar radiation \( Q_{\text{sun\text{ref}}} \), scattering of atmosphere to solar radiation \( Q_{\text{sun\text{dis}}} \), earth radiation \( Q_{\text{ground}} \), sky radiation \( Q_{\text{skye\text{f}}} \), aerodynamic heating \( Q_{\text{outside}} \), the skins outer surface thermal radiation \( Q_{\text{self}} \) and internal heat transfer.

3.1 Skin self radiation
The radiation loss of the skin surface to the outer space can be obtained by the Stephen-Boltzmann law.

\[
Q_{\text{self}} = \varepsilon_{\text{skin}} \sigma T_{\text{skin}}^4
\]  

(1)
where $\varepsilon_{\text{skin}}$ is the emissivity of the skin outer surface, $\sigma$ is the Stephan-Boltzmann constant, $T_{\text{skin}}$ is the temperature of the skin outer surface.

### 3.2 Solar radiation

The total illumination of the solar radiation received by the skin surface includes the direct radiation $E_{\text{sundir}}$, the reflection of the earth to the solar radiation $E_{\text{sunref}}$, and the scattering of the atmosphere to the solar radiation $E_{\text{sunsc}}$, so the total illumination of the solar radiation received by the skin is

$$E_{\text{sun}} = E_{\text{sundir}} + E_{\text{sunsc}} + E_{\text{sunref}} \tag{2}$$

$E_{\text{sun}}$ has to do with weather conditions, the sun's position, the height angle and the relative position of the irradiated surface.

So the solar radiation heat flux received by the target surface is

$$Q_{\text{sun}} = \alpha_{\text{skin}} E_{\text{sun}} \tag{3}$$

where $\alpha_{\text{skin}}$ is the absorption of the skin surface, and $\alpha_{\text{skin}} = \varepsilon_{\text{skin}}$.

### 3.3 Earth radiation

The radiation from the ground is $E_{\text{ground}}$, then the radiation heat flux that each surface of the airship receives from the ground is

$$Q_{\text{ground}} = \alpha_{\text{skin}} E_{\text{ground}} F_{\text{ground-j}} \tag{4}$$

where $F_{\text{ground-j}}$ is the angular coefficient of airship surfaces to ground radiation.

### 3.4 Sky radiation

The atmospheric radiation received by the skin surface is composed of the direct radiation $E_{\text{sky}}$ from the atmosphere and the atmospheric radiation through the earth $\rho_{\text{ground}} E_{\text{sky}}$, then the radiation heat flux each surface of the airship receiving is

$$Q_{\text{sky}} = \alpha_{\text{skin}} (E_{\text{sky}} F_{\text{sky-j}} + \rho_{\text{ground}} E_{\text{sky}} F_{\text{ground-j}}) \tag{5}$$

where $F_{\text{sky-j}}$ is the angular coefficient of airship surfaces to atmospheric radiation, $\rho_{\text{ground}}$ is the reflection of the ground radiation.

### 3.5 Convective heat transfer

There is a temperature difference between the airship skin and the air, and convective heat transfer occurs. Assuming that the air temperature is $T_a$, the temperature of the $(i, j)$ unit on the surface of the airship is $T_{i,j}$. The heat $Q_{\text{outside}}$ generated by the convective heat transfer between the surface of the airship and the atmosphere near the surface of the skin is

$$Q_{\text{outside}} = h_a (T_a - T_{i,j}) \tag{6}$$

where $h_a$ is the heat transfer coefficient of the airship surface skin and the nearby air, its value is 0.4.
4. Skin temperature field

4.1 Heat conduction differential equation
When there is no inner heat source and the height and width of the plane partition is much larger than
the thickness, and the basic equation of the airship skin temperature field can be simplified to
one-dimensional heat conduction differential equation without inner heat source[5].

\[
\rho c \frac{\partial T}{\partial \tau} = k \frac{\partial^2 T}{\partial x^2}
\]  \hspace{1cm} (7)

In the formula (7), \( c \) is the specific heat; \( \rho \) is density; \( \tau \) is time; \( k \) is the thermal conductivity.

4.2 Establishment of boundary conditions
According to the analysis of the heat exchange between the skin surface and the environment, the
outer boundary condition is obtained.

\[
k \frac{\partial T}{\partial r} \bigg|_{\text{outer}} = Q_{\text{sun}} + Q_{\text{ground}} + Q_{\text{sky}} + Q_{\text{outside}} - Q_{\text{self}}
\]  \hspace{1cm} (8)

Where \( r \) is the outer normal direction of the boundary outer edge, the inner wall (the inner boundary)
temperature is generally considered to constant temperature.

\[
T \bigg|_{\text{inner}} = T_0
\]  \hspace{1cm} (9)

4.3 Numerical calculation and results of skin temperature

4.3.1 Numerical calculation
The skin thickness is \( X \), and it can be divided into \( n \) thin layers, then the thickness of a thin layer is
\( \Delta x = X/n \), if the calculation time \( t = m\Delta \tau, m = 0,1,2,3 \cdots \), then at the time \( t \), the center
temperature of the \( i \) layer can be expressed as \( T(m,i) \), as shown in Figure 4.

![Fig.4 Partitions and nodes of skin heat conduction](image)

Through using the backward difference scheme[6], the heat conduction differential equation (7) is
dispersed to

\[
\rho c \frac{T(m+1,i) - T(m,i)}{\Delta \tau} = k \frac{T(m+1,i+1) + T(m+1,i-1) - 2T(m+1,i)}{(\Delta x)^2}
\]  \hspace{1cm} (10)

To the boundary node, according to the energy balance the node equation can be expressed as

\[
\rho c \frac{T(m+1,0) - T(m,0)}{\Delta \tau} \cdot \frac{\Delta x}{2} = k \frac{T(m+1,0) - T(m+1,0)}{\Delta x} + Q_{\text{sun}}^{m+1} + Q_{\text{sky}}^{m+1} + Q_{\text{outside}}^{m+1} - Q_{\text{self}}^{m+1}
\]  \hspace{1cm} (11)

For the initial condition, the skin temperature can be considered as a linear distribution along the
thickness direction.

\[ T(0,i) = T_2 + i \frac{T_1 - T_2}{n} \quad (i = 0,1,2\cdots n) \]  

(12)

where \( T_1 \) and \( T_2 \) is initial temperature of inner and outer surfaces respectively.

By using the implicit scheme, the differential equations of all nodes are solved iteratively, then the temperature \( T(m,0) \) of the skin outer surfaces can be obtained at any time.

4.3.2 Numerical results
The above thermal differential equation can be solved by using MATLAB software[7]. The time is 9:00 am on July 1, 2018. The position of the airship is \( (N 30^\circ, \ E 120^\circ) \), and the flying height of the airship is 30km. Through calculation, the airship surface temperature is obtained, what is shown in the figure 5 and figure 6.

![Fig.5 Grayscale map of airship surface temperature at 9:00 am](image)

![Fig.6 Temperature curve of the airship surface at 9:00 am](image)

(a) xoy plane  
(b) xoz plane

5.Calculation results and analysis of infrared radiation
Usually the airship skin can be considered as a gray body, and the infrared radiation of the airship contains its own radiation and reflection of environmental radiation.
5.1 Infrared radiation calculation

In the daytime, the environment infrared radiation which is received by any face of the model is

\[
E_{\text{bg} - j}^{\Delta \lambda} = E_{\text{sun}}^{\Delta \lambda} + E_{\text{ground}}^{\Delta \lambda} F_{\text{ground} - j} + E_{\text{sky}}^{\Delta \lambda} F_{\text{sky} - j} + \rho_{\text{ground}} E_{\text{sky}}^{\Delta \lambda} F_{\text{ground} - j}
\]  

(13)

Then the reflective infrared radiation of skin to environment radiation is

\[
M_{\text{ref} - j}^{\Delta \lambda} = \rho_{\text{skin}} E_{\text{bg} - j}^{\Delta \lambda}
\]

(14)

where the skin reflectivity \( \rho_{\text{skin}} = 1 - e_{\text{skin}} \).

Therefore, the infrared radiation intensity of any face in a certain direction \( \theta \) due to reflecting the environment radiation can be expressed as

\[
I_{\text{ref} - j}^{\Delta \lambda} = \frac{M_{\text{ref} - j}^{\Delta \lambda}}{\pi} \cos \theta \cdot A_j = \frac{\rho_{\text{skin}} E_{\text{bg} - j}^{\Delta \lambda} \cdot A_j \cdot \cos \theta}{\pi}
\]

(15)

The self infrared radiation intensity of any face in a certain direction \( \theta \) can be expressed as

\[
I_{\text{self} - j}^{\Delta \lambda} = \frac{M_{\text{self} - j}^{\Delta \lambda}}{\pi} A_j \cos \theta
\]

(16)

Therefore, the total infrared radiation intensity of any face in a certain direction \( \theta \) is

\[
I_{\theta - j}^{\Delta \lambda} = I_{\text{ref} - j}^{\Delta \lambda} + I_{\text{self} - j}^{\Delta \lambda} = \frac{\cos \theta}{\pi} \cdot A_j \cdot (\rho_{\text{skin}} E_{\text{bg} - j}^{\Delta \lambda} + M_{\text{self} - j}^{\Delta \lambda})
\]

(17)

The detection direction is \( \vec{r}_\theta \), then with the change of \( \theta \) [8], the intensity distribution of the entire airship skin in the XOY section is

\[
I^{\Delta \lambda} = \sum_{j=0}^{2\omega-1} I_{\theta - j}^{\Delta \lambda} \cdot \max[\vec{r}_j \cdot \vec{r}_\theta, 0]
\]

(18)

In the above expressions all of \( \Delta \lambda \) represent \( 3 \sim 5 \mu m \) or \( 8 \sim 14 \mu m \).

5.2 Calculation results and analysis of infrared radiation

Fig.7 Distribution of airship infrared radiation intensity of at 9:00 am
Figure 7 is the mid and far infrared radiation intensity distribution of the airship skin at 9:00 am on July 1, 2018 while the airship aviates. It can be seen from the figure 7, the maximum infrared radiation of the airship surface is $8670.8 \ W \cdot sr^{-1}$ in the 3-5μm, and the minimum value is $8480.7 \ W \cdot sr^{-1}$. The maximum value of infrared radiation in the 8-14μm is $22253 \ W \cdot sr^{-1}$, and the minimum value is $8531.3 \ W \cdot sr^{-1}$. The infrared radiation of the airship is mainly the infrared radiation that reflects the environment. In the infrared radiation of the reflective environment, the proportion of the infrared radiation received by the skin from the solar radiation is the largest, and the radiation of the airship skin is relatively small for the reflection of the ambient radiation. The impact on the infrared radiation intensity of the airship is relatively small. From the comparison of the two figures, we can see that the skin has more radiation in the 8-14μm than in the 3-5μm, but their spatial distribution is almost the same regardless of the infrared radiation in which band. The infrared radiation of the airship is the strongest in the 80° direction and the weakest in the 200° direction. The infrared radiation is mainly concentrated in the 0°-150° direction, that is, in the upper half of the airship.

6. Conclusion
The geometric model of stratospheric airship was firstly constructed in this paper. Then, considering the influence of environmental radiation, the one-dimensional heat conduction differential equation of airship skin was established, the equation was solved by backward difference method, and the temperature distribution of airship skin was numerically calculated. On this basis, the spatial distribution of airship infrared radiation was further calculated. The results show that the infrared radiation intensity of the airship in the sunny face is higher than that in the shadow face, and the infrared radiation intensity of the airship in the 8~14μm is obviously higher than that in the 3-5μm.

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