

Numerical simulation research on surface radiation heat calculation of spacecraft in orbit whole course

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Abstract: The surface radiation heat simulation program based on Microsoft VC++ 6.0 for spacecraft in whole orbit course was presented. Due to complexity of spacecraft structure, the spacecraft structures were decomposed to relatively regular parts. Automatic generation of calculation grid was conducted by using structured grid and unstructured technology. Simulation mainly solved automatic grid generation for arbitrary surface and data transmission between arbitrary shape interfaces, and the geometry structure, physical process, calculation accuracy and efficiency were considered. View factors and radiation transfer coefficients were calculated by combining finite element method and ray uniform distribution. According to the position of surface cells, external heat flux was calculated with integral method for non shaded surface and with ray uniform distribution method for shaded surface. As the spacecraft surface was wrapped with multilayer insulation material, the temperature field of multilayer insulation material was calculated with nodal network method and finite volume method. The temperature of other parts without wrap was calculated with finite element method. The temperature of unconnected regions available with radiation heat transfer relations was analyzed, and the calculation formulae were deduced. Numerical experiment shows that the simulation program is correct and effective.

Key words: spacecraft; radiation; heat calculation; whole course; numerical simulation

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Introduction

Space target detection technology has become more and more important. Detecting space target through infrared radiation characteristics are an effective method. Because the infrared radiation of spacecrafts in low earth orbit is much higher than the infrared radiation of universe background and the orbit is fixed, anti-satellite weapons generally intercept target primarily through infrared radiation characteristics^[1]. The method of research on infrared radiation characteristics of space targets mainly includes actually surveying, theory analyzing and numerical simulation. The actual surveying needs long period, high outlay and a series of high-tech research

foundation^[2]. Now China can't realize this method completely. For development of computer technology and numerical simulation, combination of theory analysis and numerical simulation becomes common method. This method not only provides correlative data quickly for design reference of early warning and detection system, but also can save a great quantity of manpower and material resources. Surface radiation heat calculation of spacecraft in orbit provides foundational data and theory basis^[3-4]. In the heat calculation of spacecraft surface radiation, view factors and external heat flux calculation can provide boundary condition and foundational parameters for temperature and stress field calculation, the precision of view factors and external

heat flux will affect precision of results^[5-6]. But the view factors and external heat flux calculation needs much time, improving calculation precision and efficiency of view factors and external heat flux can quicken heat analysis and calculation process greatly. This paper mainly researches the method of improving the calculation efficiency^[7-13].

Numerical simulation on surface radiation heat calculation of spacecraft in orbit whole course is researched in this paper. The key simulation technology is analyzed particularly. At last, the surface radiation heat simulation program based on Microsoft VC++ 6.0 for spacecraft in orbit whole course is developed.

1 Constitution and function of simulation system

The simulation program uses modularization design. The main function modules of simulation system are shown in Fig 1. Their function and characteristic are shown as the following.

1) Trajectory calculation module: This module can provide the trajectory parameters of target for surface heat flux module. This module existing independently can improve the applicability of program.

2) Surface grid generation module and temperature field grid generation module: The surface grid generation module generates the surface triangle elements of target for view factors and external heat flux calculation. This module adopts structured and unstructured grid generation method and combines grids of different parts into the whole grids of spacecraft. The temperature field grid generation module can generate finite element grids and control volume grids.

3) External heat flux and view factors calculation module: These two modules consume a great deal of calculation time. The view factors only need to be calculated one time, but the external heat flux needs to be calculated in every time step. In the simulation process, calculation frequency of external heat flux is changeable according to varying speed. If it varies slowly, the

external heat flux can be calculated every several time steps.

4) Multilayer insulation material temperature field calculation module and unconnected region temperature field calculation module: The first module specially calculates multilayer insulation material temperature field with nodal network method and finite volume method. For complex structures, this module simplifies the heat transfer model, so it can calculate the surface temperature of many complex components. The temperature of large structures is calculated by the finite element method. This paper combines finite volume method, finite element method and nodal network method to calculate the surface temperature of spacecraft.

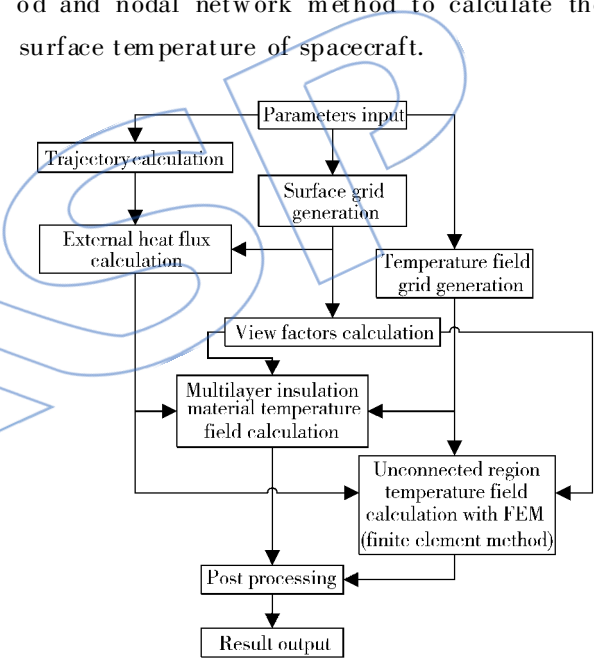


Fig 1 Constitution of simulation system

2 Geometry model and grids generation

2.1 Geometry model decomposition and simplification

Radiation heat calculation is the main part of heat calculation for spacecraft in orbit. It is helpful for the whole spacecraft heat calculation to raise surface radiation heat calculation efficiency. Generally, the spacecraft has complex structures, so this paper decomposes and simplifies the simulation model at first.

The accurate theory calculation according to real geometry structure is too complex and workload is also large. The simulation and experiment show that it is not necessary to consider all influencing factors. It needs simplification when constructing geometry model. The simplification principles include:

1) Simple structure is used to substitute the structures that will bring shadow but not join in radiation heat transfer. The substitute principle is the two structures have the same shadow effect. For example, regular bodies substitute irregular bodies, surfaces substitute solids, planes substitute complex surface, and so on.

2) The assistant planes need to add if the simplified model has cavum. This can avoid making mistakes when ray tracking simulates. The adding principle is the simplified model is close, the assistant planes have the same radiation heat transfer effect.

3) All surfaces that join in radiation heat transfer are regularized to rotating surface, quadrangle, so the structured grid generation method can be used. This paper mainly researches the surface grid generation. The triangle not only can express the spacecraft surface well, but also can simplify the shadow judgment. So this paper chooses triangle as grid element type. The triangle elements used to calculate view factors are different from the elements used to calculate temperature and stress field which need to satisfy deformation compatibility condition. The triangle elements of this paper can have intersection points and repeated nodes. As shown in Fig 2, the elements E_2 , E_3 and E_1 can have intersection node N_i . The nodes N_1 and N_2 can be numbered repeatedly. Based on the characteristics above, the surface grids generation becomes much easier. When surface grids of subregions are merged to unitary grids of spacecraft, it is not necessary to adjust the nodes and elements of subregions.

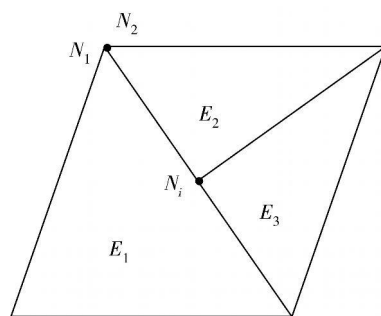


Fig. 2 Sketch map of triangle grid

2.2 Structured grids of subregions generation

This paper uses transfinite interpolation method to generate radiation triangle grids of subregions that can be regularized to curved side quadrilaterals or rotating surfaces.

As shown in Fig. 3, L_1 , L_b , L_r and L_t are four sides of plane curved side. $X_1(i)$, $Y_1(i)$, $X_r(i)$ and $Y_r(i)$ ($1 \leq i \leq N_y$) are node coordinates of the sides L_1 and L_r . N_y is the number of nodes of L_1 , L_r . $X_b(j)$, $Y_b(j)$, $X_t(j)$ and $Y_t(j)$ ($1 \leq j \leq N_x$) are node coordinates of the sides L_b and L_t . N_x is the number of nodes of L_b , L_t .

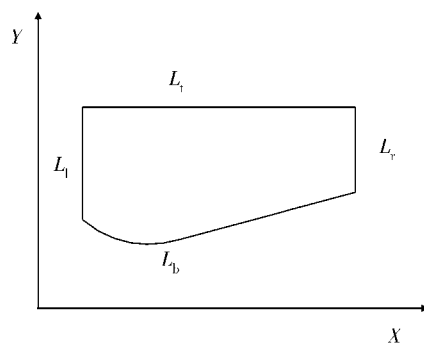


Fig. 3 Sketch map of curved side quadrilateral

The formulae of grid nodes coordinates for plane curved side quadrilaterals are

$$\begin{aligned}
 X(i, j) = & \left(1 - \frac{i}{N_y} \right) X_b(j) + \frac{i}{N_y} X_t(j) + \\
 & \left(1 - \frac{j}{N_x} \right) X_1(i) + \frac{j}{N_x} X_r(i) - \left[\frac{ij}{N_x N_y} X_t(N_x) + \right. \\
 & \left. \frac{j}{N_x} \left(1 - \frac{i}{N_y} \right) X_b(N_x) + \frac{i}{N_y} \left(1 - \frac{j}{N_x} \right) X_t(1) + \right. \\
 & \left. \left(1 - \frac{i}{N_y} \right) \left(1 - \frac{j}{N_x} \right) X_b(1) \right] \quad (1)
 \end{aligned}$$

$$\begin{aligned}
 Y(i, j) = & \left(1 - \frac{i}{N_y}\right) Y_b(j) + \frac{i}{N_y} Y_t(j) + \\
 & \left(1 - \frac{j}{N_x}\right) Y_l(i) + \frac{j}{N_x} Y_r(i) - \left[\frac{ji}{N_x N_y} Y_t(N_x) + \right. \\
 & \left. \frac{j}{N_x} \left(1 - \frac{i}{N_y}\right) Y_b(N_x) + \frac{i}{N_y} \left(1 - \frac{j}{N_x}\right) Y_l(1) + \right. \\
 & \left. \left(1 - \frac{i}{N_y}\right) \left(1 - \frac{j}{N_x}\right) Y_b(1)\right] \quad (2)
 \end{aligned}$$

For the rotating surface, L_x is generatrix. $X_x(i)$, $Y_x(i)$ ($1 \leq i \leq N_x$) are node coordinates of the side L_x . N_x is the number of nodes of side L_x and N_y is the number of nodes of rotating direction.

The formulae of grid node coordinates for rotating surface are

$$X(i, j) = X_x(i) \quad (3)$$

$$Y(i, j) = Y_x(i) \cos\left(\frac{2j\pi}{N_y}\right) \quad (4)$$

$$Z(i, j) = Y_x(i) \sin\left(\frac{2j\pi}{N_y}\right) \quad (5)$$

3 Physical and mathematical models analysis

3.1 View factors and external heat flux calculation

View factors and radiation transfer coefficients are calculated by combining finite element method and ray uniform distribution based on surface triangle grids. It can improve calculation precision and efficiency. The detailed analysis and deduction are expatiated on in reference [14] by author of this paper.

According to position of surface cells, external heat flux is calculated with integral method for no shaded surface and with ray uniform distribution for shaded surface. This method can improve calculation efficiency greatly. The detailed analysis and deduction are expatiated on in reference [15] by author of this paper.

3.2 Finite element analysis and calculation for unconnected region

Generally, finite element method is used to calculation the temperature field of connected region. But the unconnected regions have heat ex-

change in the style of radiation. As shown in Fig 4, without radiation heat exchange, the temperature field of region D_1 and D_2 can be calculated with finite element method respectively. When radiation heat exchange needs to be considered, the temperature field of regions D_1 and D_2 must be calculated as integer. This paper will analyze and deduce the finite element method formulae of temperature field of unconnected regions based on Galerkin method^[16,17].

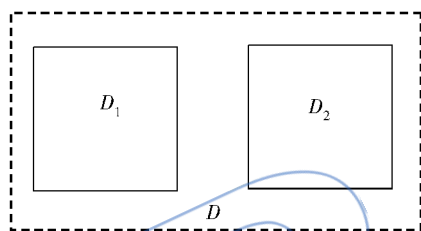


Fig 4 Sketch map of unconnected regions

Based on Galerkin method, the temperature of connected region D satisfies the following condition

$$\begin{aligned}
 & \iiint_V \left[k \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \right. \\
 & \left. q_v - \rho c_p \frac{\partial T}{\partial t} \right] dx dy dz = 0 \quad (6)
 \end{aligned}$$

Where W_l is weighted function. It is defined as

$$W_l = \frac{\partial T}{\partial T_l} \quad (l = 1, 2, \dots, n) \quad (7)$$

where n is the number of nodes. The Eq. (6) can be rewritten as

$$\begin{aligned}
 & \iiint_V \left(\frac{\partial}{\partial x} P + \frac{\partial}{\partial y} Q + \frac{\partial}{\partial z} R \right) dx dy dz - \\
 & \iiint_V \left(\frac{\partial W_l}{\partial x} \frac{\partial T}{\partial x} + \frac{\partial W_l}{\partial y} \frac{\partial T}{\partial y} + \frac{\partial W_l}{\partial z} \frac{\partial T}{\partial z} \right) dx dy dz + \\
 & \iiint_V \left(q_v - \rho c_p \frac{\partial T}{\partial t} \right) dx dy dz = 0 \quad (8)
 \end{aligned}$$

where

$$P = W_l \frac{\partial T}{\partial x}, \quad Q = W_l \frac{\partial T}{\partial y}, \quad R = W_l \frac{\partial T}{\partial z}$$

Based on Gauss formulae, the following equation can be obtained from Eq. (8)

$$\iiint_V \left[\frac{\partial}{\partial x} \left(W_l \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(W_l \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(W_l \frac{\partial T}{\partial z} \right) \right] dx dy dz =$$

$$\iint_C (P dx dy + Q dy dz + R dx dy) =$$

$$\iint_C W_l \frac{\partial T}{\partial n} dS \quad (9)$$

where, C is the boundary of calculation region D . $\mathbf{n}$ is unit vector of outer normal direction of C . The functional of D is defined as

$$J_D = J_D[T(x, y, z, t)] \quad (10)$$

The partial derivative of functional J_D to T_l can be obtained from Eq. (9) and Eq. (10)

$$\frac{\partial J_D}{\partial T_l} = \iiint_V \left[\frac{\partial W_l}{\partial x} \frac{\partial T}{\partial x} + \frac{\partial W_l}{\partial y} \frac{\partial T}{\partial y} + \frac{\partial W_l}{\partial z} \frac{\partial T}{\partial z} \right] -$$

$$W_l \left[q_v - \rho c_p \frac{\partial T}{\partial t} \right] dx dy dz - \iint_C W_l \frac{\partial T}{\partial n} dS =$$

$$\iiint_V (x, y, z, t) dx dy dz -$$

$$\iint_C H(x, y, z, t) dS = 0 \quad (11)$$

As shown in Fig. 3, region D includes region D_1 and D_2 , Eq. (11) can be written as

$$\frac{\partial J_D}{\partial T_l} = \frac{\partial J_{(D_1 + D_2)}}{\partial T_l} = \frac{\partial J_{D_1}}{\partial T_{l_1}} + \frac{\partial J_{D_1}}{\partial T_{l_2}} + \frac{\partial J_{D_2}}{\partial T_{l_2}} + \frac{\partial J_{D_2}}{\partial T_{l_1}} \quad (12)$$

If region D_1 and D_2 have no radiation heat exchange, Eq. (13) and Eq. (14) can be obtained

$$\frac{\partial J_{D_1}}{\partial T_{l_2}} = 0 \quad (13)$$

$$\frac{\partial J_{D_2}}{\partial T_{l_1}} = 0 \quad (14)$$

In consideration of radiation heat exchange between region D_1 and D_2 , Eq. (13) and Eq. (14) can be rewritten as

$$\frac{\partial J_{D_1}}{\partial T_{l_2}} = - \iint_{\Delta C} H(x, y, z, t) dS \quad (15)$$

$$\frac{\partial J_{D_2}}{\partial T_{l_1}} = - \iint_{\Delta C} H(x, y, z, t) dS \quad (16)$$

It is known through the analysis above that the temperature of unconnected regions which

have radiation heat exchange can be calculated with the uniform grids. Through the analysis above, it is known that if the region D has more than two subregions, the method is also true.

Based on variation principle, the functional of region D can be expressed as

$$J(T) = \iiint_V \frac{\alpha}{2} \left[\left(\frac{\partial T}{\partial x} \right)^2 + \left(\frac{\partial T}{\partial y} \right)^2 + \left(\frac{\partial T}{\partial z} \right)^2 \right] -$$

$$Q_v T + \rho c_p \frac{\partial T}{\partial t} T dx dy dz + \iint_C \left[\frac{1}{2} T^2 - T_f T \right] dS \quad (17)$$

After D is discretized to finite elements,

$J(T)$ is the integral of all elements as

$$J = \sum J^e \quad (18)$$

The integral of element e is

$$J^e(T) = \iiint_V \frac{\alpha}{2} \left[\left(\frac{\partial T}{\partial x} \right)^2 + \left(\frac{\partial T}{\partial y} \right)^2 + \left(\frac{\partial T}{\partial z} \right)^2 \right] -$$

$$Q_v T + \rho c_p \frac{\partial T}{\partial t} T dx dy dz + B \quad (19)$$

For the first and third boundary conditions, B is defined as

$$B = \iint_C \left[\frac{1}{2} T^2 - T_f T \right] dS \quad (20)$$

For the second boundary condition, B is defined as

$$B = \iint_C q T dS \quad (21)$$

For the radiation boundary condition, B is defined as

$$B = \iint_C \left(\varepsilon \frac{1}{5} T^5 - \sum_{n=1}^N \varepsilon_n B_n T_n^4 \right) T dS \quad (22)$$

Where ΔD is region which element e includes. ΔC is the area of boundary element. α and T_f are convection exchange coefficient and fluid temperature. For the first boundary condition, α is infinite. q is boundary heat flux. ε is surface emissivity of ΔC . ε_n is surface emissivity of element n . B_n is radiation transfer coefficient of element n to ΔC . T_n is effective radiation temperature of element n . The element n belongs to region D or not. If it doesn't belong to region D , its temperature is constant. The derivative of J to T in element e can be obtained from Eq. (17)

$$\frac{\partial J_e}{\partial T_i} = \iiint_V \left[\frac{\partial T}{\partial x} \frac{\partial}{\partial T_i} \left(\frac{\partial T}{\partial x} \right) + \frac{\partial T}{\partial y} \frac{\partial}{\partial T_i} \left(\frac{\partial T}{\partial y} \right) + \frac{\partial T}{\partial z} \frac{\partial}{\partial T_i} \left(\frac{\partial T}{\partial z} \right) \right] - Q_v \frac{\partial T}{\partial T_i} + \frac{\partial T}{\partial t} \frac{\partial T}{\partial T_i} \Bigg\} dx dy dz + \frac{\partial B}{\partial T_i} \quad (23)$$

Where $\frac{\partial B}{\partial T_i}$ can be obtained from Eq. (20), Eq. (21) and Eq. (22). T^4 is treated with the following method

$$\left. \begin{aligned} T^4 &\cong 4T_r^3 T - 3T_r^4 \\ T_r &= \frac{1}{K} \sum_{i=1}^K T_i \end{aligned} \right\} \quad (24)$$

Where K is node number of boundary ΔC of element e .

According to extremum condition of functional, the following equation can be obtained

$$\sum \frac{\partial I_e}{\partial T_i} = 0 \quad (25)$$

Based on finite element method principle, the assembled stiffness matrix, capacitance matrix and heat load vector can be obtained as follows

$$\mathbf{HT} + \mathbf{CT} = \mathbf{p} \quad (26)$$

This paper uses the following format to deal with $\frac{\partial T}{\partial t}$

$$\left(\mathbf{H} + \frac{\mathbf{C}}{\Delta t} \right) \mathbf{T}_t = \mathbf{p}_t + \left(\frac{\mathbf{C}}{\Delta t} \right) \mathbf{T}_{t-\Delta t} \quad (27)$$

Where the subscript t denotes calculation time step, $t - \Delta t$ denotes the last time step, Δt denotes step length.

Because $\mathbf{H}$ and $\mathbf{p}$ contain unknown temperature T , Eq. (19) needs to be solved with iterative method. In every time step, Eq. (19) may be rewritten as

$$\left(\mathbf{H} + \frac{\mathbf{C}}{\Delta t} \right)_t^n \mathbf{T}_t^{n+1} = \mathbf{p}_t^n + \left(\frac{\mathbf{C}}{\Delta t} \right)_t^n \mathbf{T}_{t-\Delta t}^n \quad (28)$$

where superscript n denotes the n th iteration in t time step.

3.3 Multilayer insulation material heat calculation

As shown in Fig. 5, the spacecraft surface is wrapped with multilayer insulation material.

The multilayer insulation material is not a kind of real material. It has no continuous structure and symmetrical properties. It is a combined material made up of many reflection foils and spacers. Between reflection foils, there are many spacers of different types and thickness. The equivalent thermal conductivity is not only related to the types and thickness of reflection foils and spacers, but also related to number of layers, temperature of cold surface and heat surface, compressed load and vacuum degree^[18-19]. If this parameter is used to calculate unsteady temperature field, rather great error will be brought. Effective emissivity ϵ_{eff} is used to denote insulation capability of multilayer insulation material in this paper. The multilayer insulation material can be treated as thermal control coatings whose emissivity is ϵ_{eff} . Thermal analysis and calculation structure is shown in Fig. 5. The heat balance equations are

$$q_s \epsilon = \rho_{c p_1} \epsilon \frac{dT_1}{dt} + \epsilon_{\text{eff}} \sigma (T_1^4 - T_2^4) + \epsilon \sigma T_1^4 \quad (29)$$

$$\epsilon_{\text{eff}} \sigma (T_1^4 - T_2^4) = \rho_{c p_2} \epsilon_2 \frac{dT_2}{dt} + \epsilon \sigma T_2^4 \quad (30)$$

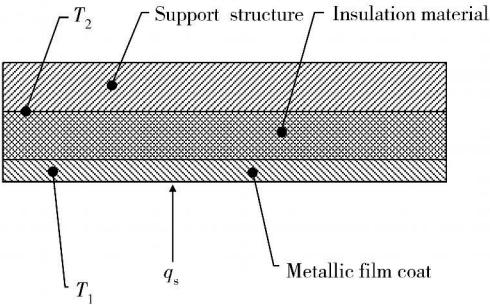


Fig. 5 Multilayer insulation material wrap scheme

4 Simulation result and analysis

The program for calculating view factors and external heat flux has been tested and validated in references [14-15].

This paper mainly analyzes calculation precision and efficiency of temperature field. The model satellite is shown as Fig. 6. The main body of satellite is wrapped with multilayer insu-

lation material except radiating surface. The surface temperature fields of unwrapped region and solar panel are calculated with finite element method of unconnected region.

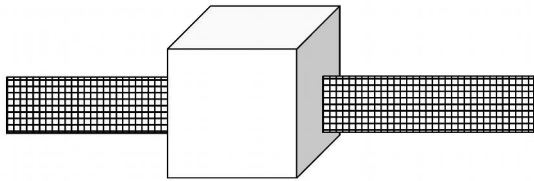


Fig. 6 Model satellite scheme

The orbit parameters are given in Table 1.

Table 1 Orbit parameters

$i/(^{\circ})$	$\Omega/(^{\circ})$	a/km	e	$\omega/(^{\circ})$	$\varphi/(^{\circ})$	T_p/s
50	40	6781	0.00085	40	0	0

Where i is the orbit inclination; Ω is the ascending node right ascension; a is the major semi axis of orbit; e is the eccentricity; ω is the angular separation between ascending node and perigee; φ is solar longitude; T_p is the time when the satellite is on perigee.

The satellite attitude control includes: (1) the principle axis is in the orbit plane and points at the flying direction; (2) the coordinate axis X points at the earth's core all the time; (3) the angle between the principle axis and ligature of satellite the earth is a constant.

The iteration precision of temperature field is 0.001. The errors of temperature field iteration calculation are given in Fig 7, Fig 8 and Fig 9. The temperature of internal and outside face of multilayer insulation material is shown as Fig 10 and the temperature of nightside and sunny side of solar panel is shown as Fig 11.

As shown in Fig 7, Fig 8 and Fig 9, the convergence rate of temperature field calculation of the method in this paper is very fast. When the number of temperature field iteration increases from two times to four times, the temperature error is reduced by more than three orders of magnitude. Because the radiation term is line-

arized and loaded to the stiffness matrix and the major diagonal elements of the stiffness matrix dominate, the iteration rate is very fast. The convergence rate is slower when the time step length is longer with the same iterations. Because the temperature increment is larger in a longer time step length, the temperature field calculation needs more iteration. It is need to be pointed that the total iterations are related to type of materials and boundary condition, but the temperature error is reduced by more than one order of magnitude.

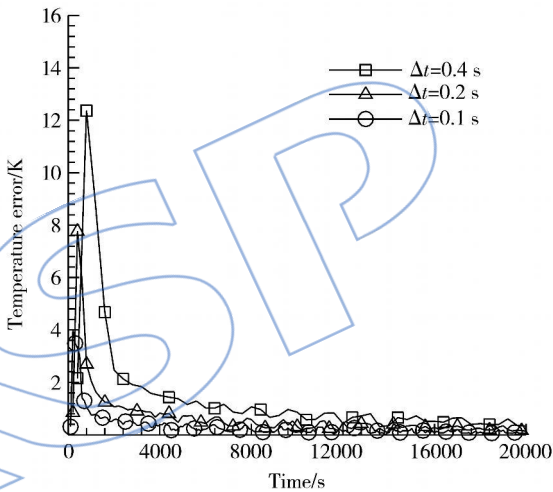


Fig. 7 Temperature error of 2 iterations

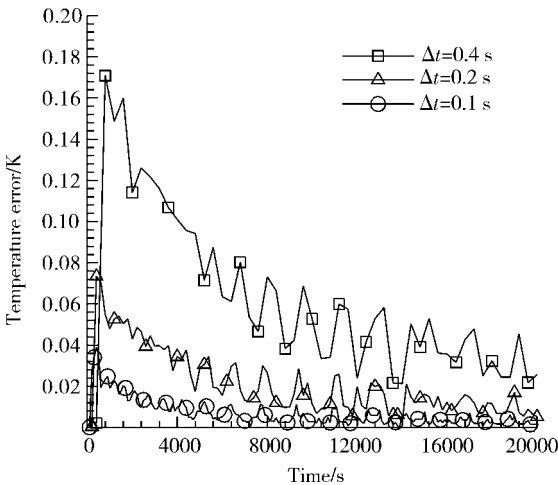


Fig. 8 Temperature error of 3 iterations

The highest and lowest temperature of the multilayer insulation material face is shown in Fig 10 and temperature of the solar panel is shown in Fig 11. The temperature has the same

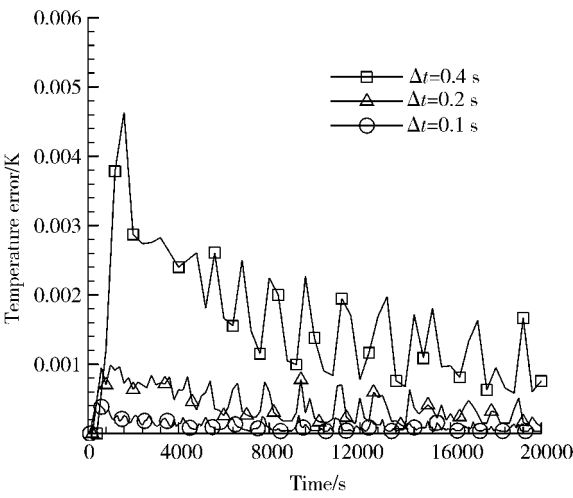


Fig. 9 Temperature error of 4 iterations

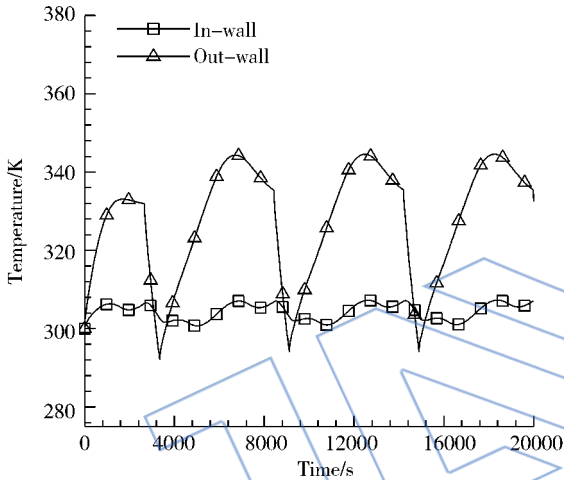


Fig. 10 Temperature of internal and outside face of multilayer insulation material

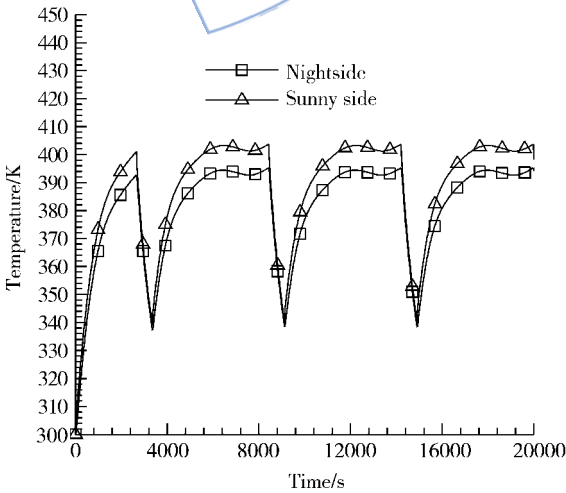


Fig. 11 Temperature of night side and sunny side of solar panel

variation period as spacecraft orbit. The temperature of outside surface is affected by external heat flux and the temperature of internal surface is almost constant. Because the thermal conductivity of solar panel is high, the temperature difference between nightside and sunny side is slight.

5 Conclusions

1) The surface radiation heat simulation program based on Microsoft VC++ 6.0 for spacecraft in orbit whole course has been developed. From the calculation example, it has been confirmed that the program is accurate.

2) The finite element method for unconnected regions is reliable and the convergence rate of temperature field iteration is very fast.

3) The temperature field calculation model of multilayer insulation material is rational.

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