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Heat Insulation Performance of Lattice Thermal Protection Structure with Reinforced Plate

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Abstract A lightweight lattice structure is proposed, which can be applied to the thermal protection system of high speed aircraft. The structure uses carbon fiber reinforced silicon carbide ceramic matrix composite as the framework, and the inner cavity can be filled with heat insulation materials with small thermal conductivity. In order to study the heat insulation performance of the structure, the three-dimensional finite element heat transfer model of the lattice structure with and without heat insulation material was established. Abaqus software was used to calculate the temperature distribution and change of the lattice structure under different temperature boundary conditions. The equivalent thermal conductivity of the lattice structures under different temperature boundary conditions is defined and calculated. The results show that the heat insulation effect of the lattice structure is improved obviously with the addition of heat insulation materials, but the time required to reach the stable state is increased. Without heat insulation materials, the strength of cavity radiation is greatly affected by the temperature boundary conditions on the top surface and positively correlated. Increasing heat insulation materials can effectively block the generation of cavity radiation, thus enhancing the heat insulation effect. The conclusion provides a foundation for further application of the lattice structure in thermal protection system of high speed aircraft.

1. Introduction

In the past few years, high-speed aircraft have received extensive attention and research, which need to withstand the dual test of aerodynamic heating and pressure during supersonic flight, and the environment in which high-speed aircraft are located is extremely harsh. Therefore, to deal with this environment, the thermal protection system is particularly important. In recent years, with the advancement of thermal protection technology, integrated thermal protection system has emerged, which can not only prevent the high temperature from being transmitted to the inside without affecting the internal equipment, but also withstand aerodynamic pressure to maintain the aerodynamic shape of the aircraft.

Among them, the research on thermal insulation performance is one of the more important aspects in the development of high-speed aircraft, and domestic and foreign scholars have studied the thermal insulation performance of multi-layer structure, honeycomb structure and non-reinforced plate lattice structure. Moreover, Ding Chen et al. [0] proposed a numerical method for calculating the heat transfer of a multilayer structure, studying the temperature distribution of the multilayer structure during aerodynamic heating. Zheng [2] tested the heat transfer performance of the honeycomb sandwich panel at 900°C. Wei et al. [3] used experiments and numerical simulations to study the thermal insulation performance of the lattice structure without reinforcement. However, there are few studies on the thermal insulation performance of the lattice structure with reinforced plates.

In this paper, a lattice thermal protection structure with reinforced plates is proposed, which adopts C/SiC composite materials, and a three-dimensional finite element heat transfer model of lattice structure is established. Moreover, the temperature distribution of the lattice structure and the law of lattice structure changing with time under four different temperature boundary conditions are studied. Then, the equivalent thermal conductivity of the lattice structure is defined and calculated. According to the conclusion, the thermal insulation performance of the lattice structure can be understood more clearly, which provides a foundation for further applying the lattice structure to the thermal protection system of high-speed aircraft.

2. Numerical Calculation Method

2.1. Finite Element Model

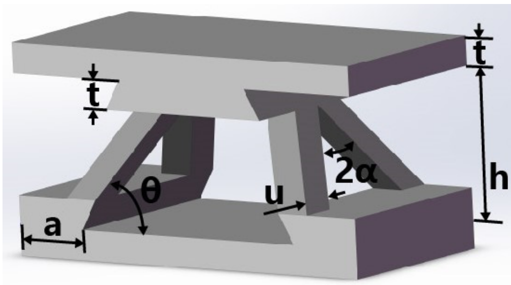


Fig.1 Unit cell of lattice structure

In Figure 1, the cells of the lattice structure are composed of upper and lower panels and a lattice core with a reinforcing plate in the middle, and the thermal insulation material can be filled in the upper and lower panels. Besides, there are six independent geometric parameters in the cell, which are listed in Table 1. In this paper, 2x2 cells are selected for calculation in the length and width, and the grid that is divided when there is no insulation material is shown in Figure 2. Moreover, the heat transfer unit DC3D8 and a small amount of DC3D6 are adopted, and the upper and lower panels and the reinforcing plate are divided into three units in the thickness direction. In addition, the core rod is divided into three units in length and width. The grid that is divided when there are heat insulation materials is shown in Figure 3, using all heat transfer units DC3D4.

Table 1 Geometric parameters of unit cell

a/mm	t/mm	θ/°	h/mm	α/°	u/mm
5	2	60	10	30	2.5

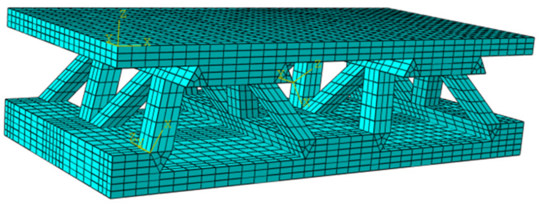


Fig.2 Grid without heat insulation material

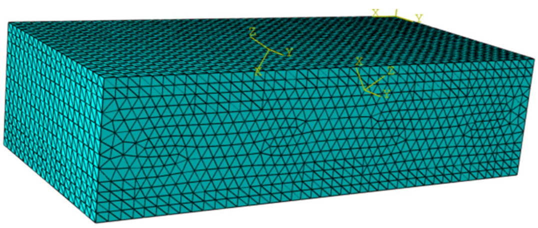


Fig.3 Grid with heat insulation material

2.2. Materials

The lattice structure uses C/SiC composite material, and the insulating material filled in the middle adopts glass wool, whose thermal properties are shown in Table 2. Therefore, the area density of the lattice structure without heat insulation material is 12.71 kg/m^2, reducing the surface density of some thermal protection structures compared with Kai Wei et al. [4] and meeting the requirements of lightweight thermal protection structures.

2.3. Heat Transfer Boundary Conditions

When there is no heat insulation material, the initial temperature of the entire structure is 25°C, and the upper surface is subject to temperature boundary conditions of 1000°C, 1200°C, 1400°C and 1600°C. Moreover, cavity radiation is applied to the cavity between the upper and lower panels, and the lower surface is radiated to dissipate heat from the surface of the external environment in which the temperature is 25°C. Adiabatic boundary conditions are applied to the rest of the structure.

Except for the cavity radiation, the boundary conditions when there is heat insulation material are exactly the same as those without heat insulation material.

3. Results and Discussions

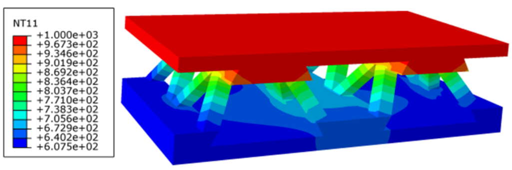
The temperature distributions without heat insulation material and after adding heat insulation material are respectively shown in Figure 4 and Figure 5, and the heat transfer time is both 1300s.

Table 2 The thermal properties of C/SiC composite [3] and heat insulation material [5]

Materials	Density/(kg·m^{-3})	Specific Heat/(J·kg^{-1}·°C^{-1})	Emissivity	Thermal Conductivity/(W·m^{-1}·°C^{-1})		
				λ_x	λ_y	λ_z
C/SiC	2100	1420	0.8	5	5	14.5
glass wool	26	1000	/	0.033		

The upper surface temperature boundary condition is 1000°C, and the temperature distribution is similar under other temperature boundary conditions. Moreover, under different temperature boundary conditions, the temperature distribution at the bottom of the lattice structure without heat insulation material presents the characteristics that is high in the middle and low around it. When there are heat insulating materials, the temperature is periodically distributed along the length, and there are many areas with higher temperature.

(a)



(b)

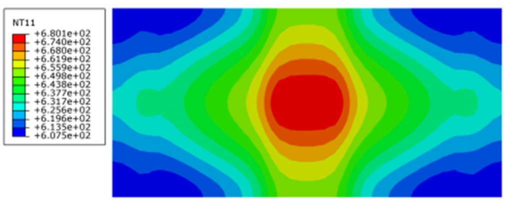


Fig.4 Temperature distribution without heat insulation material (a)overall structure (b)bottom

（a）

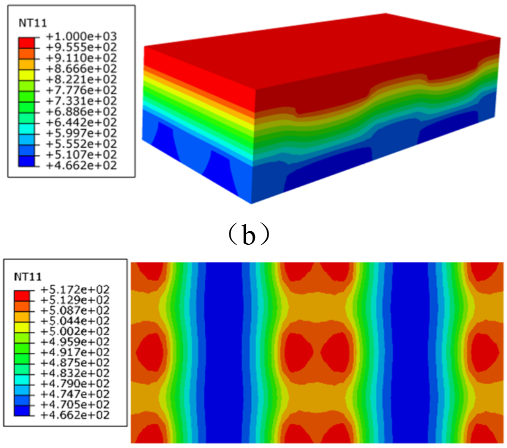


Fig.5 Temperature distribution with heat insulation material (a)overall structure (b)bottom

As is shown in Figure 6, Figure 7 and Table 3, regardless of the thermal insulation materials, the maximum temperature of the lower surface of the structure gradually increases to a stable value with the increase of time under four different temperature boundary conditions. Moreover, the higher the boundary condition of the upper surface temperature is, the higher the maximum temperature of the lower surface when it is stable will be. However, the shorter the time required to reach a steady state will be, namely the maximum temperature of the lower surface reaches 95% when it is stable.

After adding heat insulation material, under four different temperature boundary conditions, the maximum temperature of the lower surface drops significantly, and the higher the boundary condition of the upper surface temperature is, the greater the decline will be. On the contrary, after adding the thermal insulation materials, the time required to reach a steady state under the four different temperature boundary conditions has increased.

According to Fourier's law, namely the heat flow density at any point in the system is proportional to the temperature gradient at that point with the opposite direction, and the proportional coefficient is the thermal conductivity of that point, the equivalent thermal conductivity of object is defined as the ratio of the average heat flux density of the object to the average temperature gradient. Moreover, for the lattice sandwich structure, the equivalent thermal conductivity in the thickness direction is the ratio of the average heat flux density in the thickness direction to the temperature gradient in the thickness direction. The abaqus script is written in python language to process and calculate the output database file, and the equivalent thermal conductivity of the lattice sandwich structure under different temperature boundary conditions can be obtained in the steady state, as is shown in Table 4. What is more, it can be obtained from Table 4 that after adding heat insulation materials, under four different temperature boundary conditions, the equivalent thermal conductivity of the lattice sandwich structure has been significantly reduced, greatly improving the heat insulation performance. In addition, with the increase of the upper surface temperature, the equivalent thermal conductivity of the structure without thermal insulation material increases obviously, and the thermal insulation performance decreases. However, there is almost no change when there is heat insulation material. The possible reason is that with the increase of the upper surface temperature, the unique cavity radiation of the structure without heat insulation material strengthening, increasing the equivalent thermal conductivity. When there is a thermal insulation material, the thermal insulation material blocks the occurrence of cavity radiation, and the equivalent thermal conductivity has almost no change. Therefore, when there is no heat insulation material, the intensity of the unique cavity radiation of the structure is greatly affected by the temperature of the upper surface, which is positively correlated. What is more, adding thermal insulation materials can effectively block the cavity radiation, enhancing the thermal insulation effect of the structure.

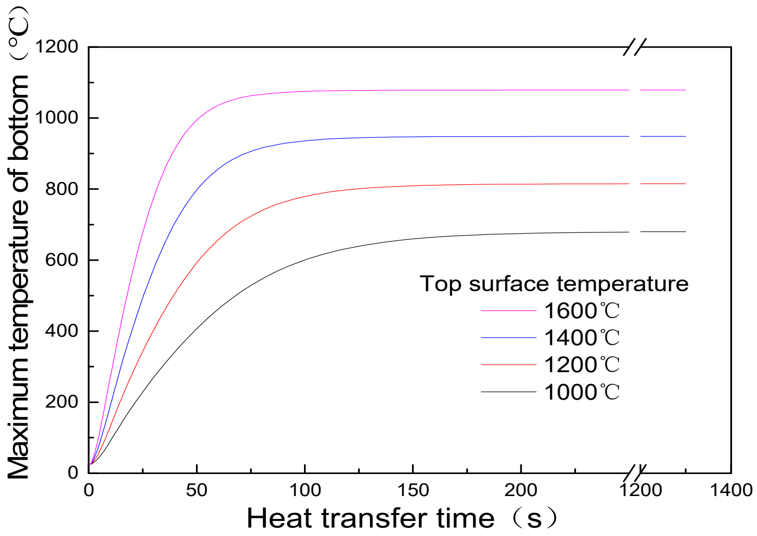


Fig.6 Curve of maximum temperature of bottom over time without heat insulation material

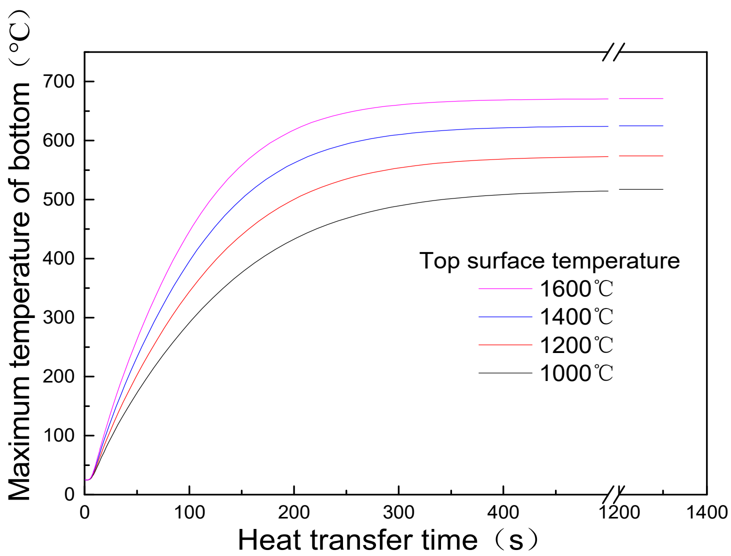


Fig.7 Curve of maximum temperature of bottom over time with heat insulation material

Table 3 Temperature in the steady state and the time required for stabilization

T_t/°C		1000	1200	1400	1600
T_{bmax}/°C	without heat insulation material	680.07	814.79	948.18	1078.54
	with heat insulation material	517.17	574.10	624.90	670.93
	effect of increasing insulation	reduce 162.9	reduce 240.69	reduce 323.28	reduce 407.61

	material				
t/s	without heat insulation material	137	103	76.17	57.04
	with heat insulation material	312.2	276.1	253.3	236.9

Notes: T_t is top surface temperature boundary condition; T_{bmax} is the highest temperature of bottom surface in the steady state; t is the time required to reach a steady state.

Table 4 Equivalent thermal conductivity

T_t/°C		1000	1200	1400	1600
equivalent thermal conductivity/(W·m^{-1}·°C^{-1})	without heat insulation material	2.04	2.78	3.63	4.59
	with heat insulation material	0.26	0.26	0.26	0.26

Notes: T_t is top surface temperature boundary condition.

4. Conclusions

In the research of this paper, the lattice structure of carbon fiber reinforced silicon carbide ceramic matrix composite is proposed as the thermal protection system of high-speed aircraft. Moreover, under four different temperature boundary conditions, the heat transfer finite element analysis is carried out on the lattice structure without heat insulation material and the lattice structure with heat insulation material. The main conclusions are as follows.

(1) The surface density of the proposed C/SiC lattice structure is 12.71 kg/m^2, realizing the lightweight design of the thermal protection system.

(2) Under the same temperature boundary conditions, after adding heat insulation materials, the maximum temperature of the lower surface in the lattice structure decreases significantly, while the time required for the maximum temperature to reach a stable state increases.

(3) When there is no heat insulation material, the intensity of the cavity radiation that is unique to the structure is greatly affected by the temperature of the upper surface, and it is positively correlated. Moreover, it can effectively block the generation of cavity radiation to add the thermal insulation materials, enhancing the thermal insulation effect of the structure.

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