Thermal performance affected by the mesoscopic characteristics of the ceramic matrix composite for hypersonic vehicle

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Abstract. The rigorous thermal environment brought by long-time high-speed flight is imposed severe requirements on the structural bearing capacity and structural thermal safety of the aircraft. The integrated non-ablative thermal protection system based on continuous fiber-reinforced ceramic matrix composites is becoming a hot spot on the design of aircraft structures. However, the multi-scale, non-linear, non-uniform features of such materials, as well as complex thermal and mechanical characteristics, pose serious challenges to structural design and evaluation. Under the aero heating environment, the non-uniform temperature rising and thermal matching between different components in the continuous fiber-reinforced ceramic matrix composites are extremely complicated, which has a significant influence on the thermal safety performance of the structure. In this paper, based on the commonly used 3D orthogonal weaving process and the thermal characteristics prediction method of fiber bundles considering the effect of PyC interface layer, the fluid-structural strong thermal coupling characteristics of different woven parameters in typical aircraft structure is carried out. Quantitatively characterizing the heat transfer characteristics of this new material under the actual flight condition of the aircraft can further to improve the accuracy of the thermal property parameters obtained based on the ground test. The analysis results show that increasing the proportion of fiber bundles in a certain direction is the most effective method to increase the thermal conductivity in this direction. At the same time, the arrangement of the coupling yarns will also have a greatly influence on the thermal conductivity of the material. These results is of great significance for the design of the materials.

1. Introduction
With the development of scramjet engine and combined-cycle power engines, the concept of hypersonic airliners has gradually come to reality, and has attracted much attention of scientific researchers in many countries. Different from the traditional subsonic airliner based on the aluminum alloy and resin-based fiber-reinforced composite materials, the severe aerodynamic/aerothermal loads brought by long-time high-speed flight have imposed stricter requirements on structural safety [1]. The sharp leading edge demanding by the aerodynamic requirements will cause a high heat flux on the surface of the aircraft structure. Coupled with long-time hypersonic flight in the atmosphere, a large amount of heat will be accumulated, which will cause serious temperature rising and high temperature gradient in the aircraft structure [2]. The structure must be protected by a good thermal protection system to maintain the load-bearing structure of the aircraft within the allowed temperature range. The non-ablation thermal protection system based on the continuous fiber-reinforced ceramic matrix
composite material is becoming a hot spot on the development of hypersonic aircraft structural design [3].

The continuous fiber-reinforced ceramic matrix composites have excellent characteristics such as high temperature resistance, low density, high specific strength, high specific modulus, oxidation resistance and ablation resistance, and have inherent advantages in thermal protection and structural strength properties. However, such new materials often have some new features such as multi-scale, non-linearity and non-uniformity, as well as complex thermal and mechanical characteristics [4], which pose new challenges to the traditional aircraft structure design and evaluation. Due to the difficulty of manufacturing this kind of materials, and the parameter adjustment under different production processes or even the same production process will have a greatly influence on the material's fiber bundle structure in the microscopic and woven structure in the mesoscopic [5], which will affect the material's macroscopic thermal/mechanical characteristics. As a result, most of the existing researches on the prediction macro properties of this kind of materials are qualitatively given by experimental tests and observations [6, 7]. At the same time, there is also a large degree of limitation on the prediction of the thermal/mechanical properties [8] considering the fluid-thermal-solid coupling environment where the aircraft actually flies. The non-uniform temperature rising of the structure caused by the influence of aerodynamic heating on the material, and the problem of thermal matching between different components in the material is also extremely complicated. So it is difficult to accurately describe and predict the performance of existing models [9].

This paper takes the typical integrated thermal protection structure unit using the continuous fiber-reinforced ceramic matrix composites as the research object, based on the existing fiber weaving process [10] and the established prediction results of fiber bundle thermal properties considering the interface layer effect [11]. The research on the influence of weaving form on the macro-thermal characteristics of materials provides support for the application and evaluation of such materials in aircraft design.

2. Cross scale modeling

The continuous fiber-reinforced ceramic matrix composites are mainly composed of fiber bundle and SiC matrix. The C/SiC composite material used the carbon fiber bundle, and the SiC/SiC composite material used the silicon carbide fiber bundle. The thermophysical parameters of this kind of material are affected by the physical properties of the fiber bundle itself and the characteristic of the woven structure. Either side will affect the final analysis. Therefore, the thermal characteristics of this kind of materials need to be analyzed from two levels: micro-to-meso scale and meso-to-macro scale. First, the microscopic characteristics of the carbon fiber bundles composed of filaments and matrix structures are modeled and analyzed from the microscopic scale. Then, the macroscopic characteristics of the macro woven structures formed by fiber bundles and matrix are modeled and analyzed from the macroscopic scale. As for the modeling and analysis of the micro-mechanical fiber bundle thermal characteristics, a lot of research work had been carried out, so only a brief description is given here.

2.1. Micro-to-meso scale modeling

There are so many manufacturing processes for ultra-high temperature thermal protection materials using in space aircraft. The Chemical vapor deposition (CVD) is currently a relatively mature and effectively applied manufacturing process, which is a well-established and industrially advanced technology that uses gaseous materials to generate solid deposits on a solid surface by chemical reactions. It's an important process for preparing this kind of materials. In the presence of fiber bundle preform, CVD takes place in between the fibres and their individual filaments and therefore is called chemical vapor infiltration (CVI).
In order to study the material parameters at the micro-scale, it is necessary to make homogeneous assumptions on the structure. The regular hexagonal arrangement model is a commonly used arrangement model of this structural form, which can well describe the tight circumferential state of the fiber bundle. Based on this, the basic geometric parameters and thermophysical parameters of the fiber bundle under the hexagonal arrangement model can be obtained.\[ S_{\text{fiber}} = \pi r^2 \] \[ S_{\text{PyC}} = \pi (r+d)^2 - \pi r^2 \] \[ V_f = \pi r^2 / 2\sqrt{3}b^2 \]

Where, $S_{\text{fiber}}$ is the fiber area; $S_{\text{PyC}}$ is the interface layer area; $V_f$ is the filament volume fraction. According to the law of mixed rate, the longitudinal thermal conductivity can be determined:

\[ k_Z = k_f V_f + k_{\text{PyC}} V_{\text{PyC}} + k_m V_m \]

Where, $V_f$, $V_{\text{PyC}}$ and $V_m$ are the volume fraction of filament, interface layer and matrix, respectively.

For the transverse heat transfer coefficient, there is no unified formula. The reference [3] used the concept of series and parallel thermal resistance to determine the upper and lower limits of the transverse thermal conductivity:

\[ k_{XY,\text{lower}} = 1 / \left( V_f / k_f + V_m / k_m \right) \]

\[ k_{XY,\text{upper}} = V_f k_f + V_m k_m \]

As a result, the thermophysical parameters of the fiber bundle will change according to the change in fiber diameter, PyC interface layer thickness, and fiber filament volume fraction. According to the calculation results in reference [10], this paper selects the thermophysical properties at a fiber volume fraction of 60% for the woven structure analysis. The thermal properties parameters of the fiber bundle are shown in the following table.

| Table 1. Thermal properties of fiber bundle |
|--------------------------------------------|
| Density (g/cm$^3$) | Thermal conductivity (W/m·K) | Specific heat $C_p$ (J/Kg·K) |
|---------------------|-----------------------------|-----------------------------|
| 1760                | $k_f=8.0$                   | 711                          |
|                     | $k_{\text{PyC}}=1.0$       |                             |

2.2. Meso-to-Macro scale modeling

The woven structure is the main factor that affects the thermophysical properties of continuous fiber-reinforced ceramic matrix composites on the meso-scale. 3D woven composite material as an advanced composite material were developed in the 1980s. It uses 3D weaving technology and uses high-performance fibers such as carbon fibers, quartz fibers, silicon carbide fibers, and glass fibers.
The 3D weaving is the method of producing 3D woven preforms that have certain thickness, shape and inner pattern design. Preforms woven by 3D weaving technology have 3 (X-Y-Z) sets of yarns instead of 2 (X-Y) compared to traditional weaving technology. It is possible to manufacture near net shape and complex net shape preforms directly from the 3D weaving machine. So that the fibers are intertwined with each other in space to form a non-layered, overall network prefabricated structure. In theory, the 3D woven composite materials can reach any thickness and can be braided into preforms with various shapes, thereby avoiding fiber damage caused by post processing.

There are several types of 3D woven composite materials that are commercially available, which can be classified according to their weaving technology. One main type is 3D interlock woven and the other is 3D orthogonal woven. 3D interlock fabrics are woven by interlacing the warp, weft and Z-binder yarns to create a fully interlocked fabric, which is reproduced on the traditional 2D loom. It can pass the Z yarn of the loom through all thicknesses or layers of the fabric. 3D orthogonal fabric is produced on a special 3D loom. The structure of the 3D orthogonal fabric is composed of three different groups of yarns, warp (Y yarn), weft (X yarn) and binder (Z yarn). The Z yarn is placed in the thickness direction of the preform. In 3D orthogonal fabrics, there is no interweaving between warp and weft yarns, and they are perpendicular to each other. Binder yarns, on the other hand, combine warp and weft layers by weaving (moving up and down) on the weft in the Y direction. Interlacing occurs on the top and bottom surfaces of the fabric. Theoretically speaking, using Texgen production process to manufacture orthogonal or interlock weaving structures are more suitable for continuous fiber-reinforced ceramic matrix composites made by CVI process. The commonly used weaving structure is shown in Figure 2 below.

![Figure 2. Composite weaving forms of continuous fiber reinforced ceramic matrix composites.](image)

According to the characteristics of the woven structure of continuous fiber-reinforced ceramic matrix composite materials, this paper constructs a 3D orthogonal woven structure as shown in the figure 3. According to the needs of heat transfer analysis, 3-layers, 5-layers and 7-layers woven structures were formed. In order to enhance the repeatability of the analysis in the X-Y plane, the number of fiber bundles in the warp and weft directions is 7 and 5, respectively, and the length and width are 7mm and 5mm, respectively. Other process parameters are shown in Table 2 below.

| Table 2. Parameters of weaving structures |
|-----------------------------------------|
| weft layers | warp layers | Yarn width / mm | Yarn height / mm | Model thickness / mm |
|-------------|-------------|-----------------|------------------|---------------------|
| 3 layers structure | 3 | 2 | 0.8 | 0.1 | 0.7 |
| 5 layers Structure | 5 | 4 | 0.8 | 0.1 | 1.1 |
| 7 layers structure | 7 | 6 | 0.8 | 0.1 | 1.5 |

![Figure 3. The 3-layers / 5-layers / 7-layers analysis structure.](image)
3. Thermal properties calculation method

The calculation of equivalent thermophysical parameters is based on the numerical calculation of the three-dimensional solid heat conduction equation [12].

\[
\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( k_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k_z \frac{\partial T}{\partial z} \right)
\]  

Where, \(\rho\) is the mass density, \(T\) is the temperature, \(C_p\) is the specific heat capacity, \(k_x\), \(k_y\), and \(k_z\) are the thermal conductivity in the direction of the coordinates, respectively. The calculation conditions are based on the principle of experimental measurement of thermal conductivity. In the equivalent heat transfer direction, the upper surface is heat flow boundary, the lower surface is isothermal boundary, and the surrounding walls are symmetrical boundaries.

When the heat transfer reaches steady state, the equivalent thermal conductivity can be calculated according to the Fourier heat conduction law.

\[
k_{\text{eff}} = \frac{q d_c}{T_{\text{up}} - T_{\text{down}}}
\]  

Where, \(q\) is the heat flux, \(d_c\) is the heat transfer distance, \(T_{\text{up}}\) and \(T_{\text{down}}\) is the upper and lower surface temperature respectively. The equivalent heat capacity based on the principle of energy conservation is

\[
C_{p\text{eff}} = \frac{\sum_{i=1}^{n} \rho_i C_{p_i} V_i}{\rho_{\text{eff}} V}
\]  

\[
\rho_{\text{eff}} = \frac{\sum_{i=1}^{n} \rho_i V_i}{V}
\]

Where, \(V\) is the volume, the subscript "eff" indicates equivalence, the subscript "i" indicates the component number.

4. Results and discussion

In the mesoscale model of the 3D orthogonal woven composite material constructed in this paper, the fiber bundles are respectively arranged in the X direction and the Y direction parallel to the coordinate axis direction, and there is a binder yarn in the Z direction. Therefore, the analysis of heat transfer characteristics in this paper will be based on the X-Y plane and Z-axis direction. The thermal properties of the SiC matrix used in the analysis are shown in Table 3.

| Table 3. Thermal properties of SiC matrix |
|----------------------------------------|
| Density (g/cm³) | Thermal conductivity (W/m·K) | Specific heat \(C_p\) (J/Kg·K) |
|-----------------|-----------------------------|-----------------------------|
| 1046            | 0.18                        | 1008                        |

4.1. Heat transfer characteristics of X-Y plane

From the three models with different thickness built in this paper, it can be seen that the mesoscopic woven structure is basically the same. The fibers are all arranged along the axis in the X and Y directions. Of course, there are small differences in the X direction because of the different binder yarn in the Z direction.

According to the numerical results shown in Table 4 below, it can be known that the thermal conductivity in the X direction is significantly smaller than the thermal conductivity in the Y direction for the three different layer thickness models. These results are also directly related to the number of
fiber bundles and the area ratio of fiber bundle in this direction. The main reason for this difference is the presence of Z-binder yarns in the X direction, which occupies a considerable cross-sectional area.

At the same time, from the numerical results of different thickness models, we can also see that with the increasing of the layer thickness, the proportion of the fiber interface and the thermal conductivity in the X and Y directions have increased to a certain extent. However, the rate of increase of thermal conductivity is significantly less than the rate of increase of fiber bundles, which is basically consistent with the proportion characteristics of the fiber interface area.

| Table 4. The results of thermal conductivity in the X-Y plane |
|---------------------------------------------------------------|
| Direction            | Thermal conductivity (W/m·K) | The number of fiber bundles | Area ratio of fiber bundles |
|                      | X        | Y        | X   | Y   | X   | Y   |
| 3-layers structure   | 1.282    | 2.403    | 11  | 15  | 14.1% | 26.9% |
| 5-layers structure   | 1.460    | 2.490    | 19  | 25  | 15.5% | 28.6% |
| 7-layers structure   | 1.507    | 2.662    | 27  | 35  | 16.2% | 29.3% |

It can also be seen from the temperature field results of the different calculation models that, taking the X direction results as an example, due to the large thermal conductivity coefficient along the fiber bundle direction, most of the heat is transferred by the fiber bundle, and as the model thickness increasing (The area ratio of the fiber bundles is increased), the more heat is transferred through the fiber bundle, the smaller the temperature difference between the two opposing surfaces in the X direction. Compared with the thickness of the 7-layers model, the thickness of the 3-layers model has more than doubled (from 0.7mm to 1.5mm), and the temperature difference has been reduced by more than a half.

![Figure 4. Temperature field in the X direction of the 3-layers model.](image-url)
Figure 5. Temperature field in the X direction of the 5-layers model.

Figure 6. Temperature field in the X direction of the 7-layers model.
Taken together, the heat transfer performance in the X-Y plane is directly determined by the area ratio of the fiber bundles in the X and Y direction. If you need to improve the thermal conduction performance in a certain direction, you can increase the proportion of fiber bundles in that direction through a reasonable weaving process, and vice versa. Of course, there is also an upper limit to the proportion of the cross-sectional area of the fiber bundles in the woven structure, and a reasonable ratio must be considered in the actual weaving process.

4.2. Heat transfer characteristics of Z-axis direction

From the perspective of the weaving structure in the mesoscopic, there are no fiber bundles arranged in the Z direction along the axial direction, and only the binder yarns arranged in the X direction. In the calculation models of different thicknesses, each model has only three bundles of binder yarns. The numerical results of the thermal conductivity of the material in the Z direction are shown in Table 5. The numerical value of the thermal conductivity in the X direction is significantly smaller than the thermal conductivity in the X-Y plane, and is slightly higher than the thermal conductivity of the SiC matrix material. As the thickness of the calculation models increasing, the thermal conductivity will continue to decrease. This is due to the fact that the heat transfer performance cannot be effectively increased with the increasing of the thickness of the models under the condition that the number of binder yarns is unchanged. From the cloud diagram of the heat transfer temperature field in the Z direction, it can also be seen that the position of the binder yarns effectively improves the heat transfer performance, making the temperature of the heating surface position near the binder yarns is lower than other positions, and the temperature gradient in the Z direction near these positions is reduced.

Table 5. The results of thermal conductivity in the Z direction

|        | Thermal conductivity in the Z direction (W/m·K) |
|--------|-----------------------------------------------|
| 3-layers structure | 0.370                                         |
| 5-layers structure  | 0.266                                         |
| 7-layers structure  | 0.217                                         |

Figure 7. Temperature field in the Z direction of the 7-layers model.
5. Conclusion

With continuous fiber-reinforced ceramic matrix composites receiving widespread attention and extensive use in the new generation of hypersonic aircraft thermal protection structures, the macro-thermodynamic properties of the material and its optimization research work have gradually received much attention of researchers. Based on the existing fiber weaving process, three kinds of 3D orthogonal weaving models with different thicknesses suitable for this kind of material are established. Based on the established prediction method of fiber bundle thermal characteristics considering the effect of PyC interface layer, the influence of material weaving structure on the macro thermal characteristics of materials has been studied. The results show that if it is necessary to increase the thermal conductivity in any direction, increasing the proportion of fiber bundles in that direction is the most direct way. At the same time, the arrangement of the binder yarn will also have a greater impact on the macroscopic thermal conductivity of the composite material. The above results are of great significance for the design of thermal protection materials.

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