The Heat Transfer Analysis for Distribution Channel of Platelet Nosetip

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Abstract. The heat transfer model of difference in temperature is used in the heat transfer analysis for platelet nosetip. The temperature distribution of platelet construction unit and transpiration cooling medium is got by analytical solution. Hot dipping depth is used for range of influence. The results show that the maximum temperature and hot dipping depth decrease with transpiration flux increasing, and decreasing trend of hot dipping depth is slowing. Hot dipping depth and the maximum temperature increase with the heat flux on the wall increasing, and increasing trend of hot dipping depth is slowing. Temperature increasing trend of platelet construction unit in heat-affected zone is slowing with thermal conductivity of structural material increasing. The temperature change tendency is basically unchanged with the length of distribution channel increasing, but only heat-affected zone of platelet move some distance to the exit. So simply increasing the length of the distribution channel does not improve the thermal protective effect.

1. Introduction

High-speed aircraft, such as return capsules, space shuttles, intercontinental missiles, etc., enter the atmosphere from outer space at supersonic or hypersonic speeds. The aircraft produces a strong compression of the air in front. The friction, most of the kinetic energy is converted into heat, which causes the temperature of the air around the aircraft to rise sharply. Therefore, hypersonic aircraft faces a very serious aerodynamic heating environment during flight, especially the head of the aircraft. Hence, aircraft thermal protection technology has become one of the key issues restricting the development of hypersonic vehicles [1].

The current thermal protection methods mainly include three categories: active thermal protection methods, passive thermal protection methods, and semi-passive thermal protection methods. Passive thermal protection methods mainly include ablative thermal protection and high temperature thermal protection materials, but whether it is ablative thermal protection, high temperature thermal insulation materials, or multi-layer insulation systems, it is necessary to increase the mass of the spacecraft with aerodynamic heat increasing, which becomes a limitation to the application scope and application prospect of the thermal protection method. The semi-passive thermal protection method mainly includes guided thermal protection method [2], which uses a high-temperature heat pipe [3] or a high-conductivity material [4-6] to guide the heat in the high temperature region of the leading edge of the aircraft to a low temperature region to achieve thermal protection against the leading edge. It is limited
by the heat dissipation capability of the low temperature zone. The active thermal protection methods have become a hot area, mainly including transpiration cooling and reverse jetting. The transpiration cooling is the injection of a small mass thermal protection medium into the surface of the aircraft through the flow channel. The surface of the aircraft is protected by the heat absorption of the working medium and the thermal insulation layer formed. According to the different structure of transpiration cooling, it can be divided into porous transpiration cooling and platelet transpiration cooling. The application of porous materials cooling is limited because they cannot restrain the expansion of local overheating [7]. However, the inverse spray thermal protection structure has poor thermal protection effect outside the stagnation point, especially when the flight angle of attack is large [8].

Since the 1960s, foreign researchers have summarized the previous experimental results of the transpiration cooling into the boundary conditions, and gradually focused their attention on the study of the internal temperature field of the platelet structure, discussed the influence of parameters of the transpiration structure on the thermal protection effect [9-10].

In this paper, the platelet structure unit of transpiration nosetip is taken as the research object, and the flow path of platelet structure unit is modeled and the governing equation of laminar structure is obtained by using the temperature difference heat transfer model. Then, the governing equations and boundary conditions are solved to obtain the temperature distribution of the platelet structure. The hot dipping depth is used to characterize the influence range of thermal flow on the platelet transpiration nosetip. The influence of the length of the distribution channel and the amount of transpiration on the temperature distribution of the platelet structure is discussed.

2. Platelet Structure Unit of the Nosetip

Figure 1. Platelet structure

Figure 2. Structure of the platelet transpiration nosetip stacking of the platelet
The structure units of platelet transpiration noetip are shown in Fig.1. The platelet structure is divided into two types: A and B. The structure of platelet noetip is shown in Fig.2. The stacking mode of platelet is shown in Fig.3, first placing the a-type platelet, then the b-type platelet. The number from the bottom is A1, B1, A2, B2, etc. The nosetip has an anti-jet channel in the middle and an outlet in the head.

3. Physical model

3.1. Basic Assumptions
The heat transfer between cooling medium and platelet structure is convection heat transfer, ignoring radiation heat transfer. The flow of the cooling medium after entering the distribution channel is one-dimensional. The deformation of platelet structure due to heat is not considered.

3.2. Governing Equations

A distribution flow area is taken out for study, and the coordinates are shown in Fig.4. The energy conservation equation of platelet structure is expressed by

$$\lambda \frac{d^2 T_s}{dx^2} - \frac{h_s C}{A_s} (T_s - T_j) = 0$$  \hspace{1cm} (1)
Where, $\lambda_s$ is thermal conductivity of platelet structure materials, $h_L$ is convection heat transfer coefficient between platelet structure and cooling medium, $A_t$ is the cross sectional area of platelet structure, $T$ is temperature, $s$ stands for platelet structure, $c$ stands for cooling medium.

The energy conservation equation of cooling medium is expressed by

$$\lambda_c \frac{d^2T_c}{dx^2} - \rho_c \mu_c C_{pc} \frac{dT_c}{dx} + \frac{h_c C}{A_c} (T_s - T_c) = 0$$

(2)

Where, $C$ is the wetted perimeter length of the platelet structure infiltrated by cooling medium, $\delta_s$ is the thickness of platelet structure.

The boundary condition of the platelet distribution channel is expressed by

$$x = 0: \begin{cases} T_c = T_{c,0} \\ T_s = T_{s,0} \end{cases} \quad x = L: \begin{cases} \lambda_s \frac{\partial T_s}{\partial x} = q \\ qA_s + qA_c = \dot{m}C_{pc}(T_{c,L} - T_{c,0}) \end{cases}$$

(3)

Where, $q$ is the aerodynamic heat of free flow. It is noting that, when $q$ is constant, in order to ensure the thermal protection effect, the cooling medium flow in the single platelet channel must be greater than a certain value. In this paper, $q$ is given as the boundary condition, and the valve $q$ is calculated by Fay-Riddle formula. The temperature distribution of platelet structure and cooling medium can be obtained by the above equations.

3.3. Boundary Conditions

The structure parameters of platelet structure are shown in table 1, and the parameters of transpiration medium shown in table 2.

**Table 1.** Parameters of the platelet structure

| Material | 1Cr18Ni9Ti |
|----------|------------|
| Design temperature | <1000K |
| Specific heat | 460 J/(kg·K) |
| Density | 7900 kg/m³ |
| Thermal conductivity | 20 W/(m·K) |
| Wall heat flow | 5.3MW/m² |

**Table 2.** Parameters of transpiration medium

| Transpiration medium | H₂ |
|----------------------|----|
| Specific heat | 14436 J/(kg·K) |
| Thermal conductivity | 0.210 W/(m·K) |
| Inlet temperature | 150K |
| Density | 0.2025 kg/m³ |
| Outlet pressure | 117317.6 Pa |

4. Results Analysis

The working mechanism of platelet transpiration cooling nozetip requires that the heat affected zone of aerodynamic heat must be restricted in the distribution channel to prevent local overheating. The hot dipping depth $D_T$ is used to characterize the thermal range.

$$D_T = L - x |_{T_s(x) = 0.001}$$

(4)

Where, $L$ is the length of distribution channel.
The temperature distribution of platelet structure and cooling medium along the flow direction are shown in the Fig.5. At the transpiration outlet, the temperature of the platelet structure is 918k, the temperature of the cooling medium is 770k, and the corresponding hot dipping depth is 2.0mm. It can be found that the temperature of the platelet structure is basically unchanged within the range of the thermal immersion depth less than 2mm, indicating that the influence of heat flow on the structure temperature at this point can be ignored. The temperature distribution of the platelet structure when other parameters remain unchanged and only the transpiration flow changed is shown in Fig.6. It can be found from the picture that the temperature at the transpiration outlet increases continuously with the decrease of the transpiration flow, and the platelet structure temperature changing more violently in the thermal affected zone, and the hot dipping depth increasing with the decrease of the transpiration flow(in Fig. 7). The hot dipping depth increases gradually with the decrease of transpiration flow.

The temperature distribution of the platelet structure when other parameters remain unchanged and only the length of the distribution channel changed is shown in Fig.8. It can be found that the increase the length of the distribution channel did not change the change trend of the temperature of the platelet structure, but merely shifted the temperature change curve to the transpiration outlet for a certain distance. Therefore, increasing the length of the distribution channel cannot increase the effect of thermal protection. On the contrary, considering the limitation of the overall mass of the aircraft, the length of the distribution channel should be reduced in the design stage on the premise of guaranteeing the hot dipping depth.
The temperature distribution of the platelet structure under the condition that the parameters remain unchanged and the heat flow on the wall only changed is shown in Fig.9. It can be found that the maximum temperature of the platelet structure increases with the increase of heat flow and temperature of the platelet structure changes more violently in the heat affected zone. The hot dipping depth increases with the increase of the wall heat flow, but the immersion of hot dipping depth decreases (in Fig.10).

The temperature distribution of the platelet structure when other parameters remain unchanged and only the material of the platelet structure is changed is shown in Fig.11. It can be found that the temperature rise trend of platelet structure slows down in the thermal affected zone with the increase of thermal conductivity of materials, and hot dipping depth increases continuously. The temperature distribution of the platelet structure when other parameters remain unchanged and only the thermal conductivity of the material is changed is shown in Fig.12. It can be found that the increase trend of hot dipping depth slows down with the increase of thermal conductivity.

5. Conclusion
In this paper, the mathematical model of the platelet nosetip is established, and the temperature distribution of the platelet structure is obtained. At the same time, the influence range of wall heat flow on the platelet structure is studied by the hot dipping depth. The results show that the maximum
temperature and hot dipping depth decrease with transpiration flux increasing, and decreasing trend of hot dipping depth is slowing, hot dipping depth and the maximum temperature increase with the heat flux on the wall increasing, and increasing trend of hot dipping depth is slowing, temperature increasing trend of platelet construction unit in heat-affected zone is slowing with thermal conductivity of structural material increasing.

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