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Impact of cabin environment on thermal protection system of crew hypersonic vehicle

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ABSTRACT

Hypersonic crew vehicles need reliable thermal protection systems (TPS) to ensure their safety. Since there exists relative large temperature difference between cabin airflow and TPS structure, the TPS shield that covers the cabin is always subjected to a non-adiabatic inner boundary condition, which may influence the heat transfer characteristic of the TPS. However, previous literatures always neglected the influence of the inner boundary by assuming that it was perfectly adiabatic. The present work focuses on studying the impact of cabin environment on the thermal performance. A modified TPS model is created with a mixed thermal boundary condition to connect the cabin environment with the TPS. This helps make the simulation closer to the real situation. The results stress that cabin environment greatly influences the temperature profile inside the TPS, which should not be neglected in practice. Moreover, the TPS size can be optimized during the design procedure if taking the effect of cabin environment into account.

1. Introduction

The development of hypersonic crew vehicle is a fundamental step toward the dream of low-cost and safety human access to space, as well as ultra-fast intercontinental transport. Several implementation programs have been carried out in this field. One is the NASA's X-38 program, which intended to develop a prototype emergency Crew Return Vehicle for the International Space Station [1]. Another representative plan is the conceptual Space-Liner that proposed by the Space Launcher Systems Analysis group of DLR in 2005 [2] and it is still under constant development.

The primary problem in designing hypersonic crew vehicles is to design reliable TPS to protect the airframe and the crew from severe aerodynamic heating. In TPS design process, one of the critical requirements is the accurate prediction of temperature field in the TPS structure over long durations. Finite element method (FEM) has been widely used in TPS thermal design and analysis process [3–11]. This method is more timesaving than the CFD approach. Its procedure is as follows: Firstly, calculating the aerodynamic heat flux history over simplified vehicle geometries along the flight trajectory, then treating it as the external boundary of the TPS, and finally analyzing the unsteady heat conduction in the TPS [12,13].

When the FEM is used to analyze the TPS, it is necessary to scrupulously define the thermal boundaries. For the external boundary, aerodynamic heating, radiative heat dissipation and heat conduction couple together, constituting a non-linear thermal boundary condition. We use a very simple approximation method to deal with the non-linear term and its error is also discussed. As for the inner boundary, almost all of the previous works set it as

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adiabatic by assuming that the TPS inner boundary is perfectly insulated [3–8,14–16]. However, in regard to the TPS that covers the cabin, its inner boundary is always cooled by the airflow in the cabin during hypersonic flight due to the relative large temperature gradient generally exists. Though the heat flux is relatively small, it is beneficial to maintain the TPS inner structural temperature within its acceptable limit. In other words, cabin airflow can be assumed as active cooling for TPS inner structure. Unfortunately, this cooling effect is always neglected with an adiabatic inner boundary condition, this results in a superfluous TPS size. If the cooling effect of cabin environment is involved in TPS thermal analysis process, the TPS size can be properly cut down for optimization purpose in spite of that a portion of heat may penetrate into the cabin. From this perspective, the inner boundary should be defined according to the real internal environment condition, not just be set as adiabatic.

The specific objective of this paper is to study and quantify the impact of cabin inner environment on the thermal performance of the TPS. Fulfilling this objective makes a contribution to realizing the importance of the fact that cabin environment should be taken into account in its TPS design process. In particular, case examples of the TPS over the crew cabin are investigated to explain the necessity of the present work.

2. Model

2.1. Cabin model

A conceptual schematic diagram of the crew cabin for a hypersonic vehicle is created to illustrate its general thermal environment as shown in Fig. 1a. The upper-wall is covered with a multilayer TPS to insulate the aerodynamic heating. It is assumed that the other walls are not directly exposed to the aerothermal environment. So they are set as adiabatic for simplicity. q_a and q_r are the convective heat flux and radiative heat flux on TPS external surface, respectively. q_{in_c} and q_{in_r} represent the heat transfer between TPS inner surface and cabin environment through convection and radiation. Crew members and avionics act as two typical heat sources (S_A and S_C). In addition, the exhaust heat in the cabin is carried away by the coolant (Q_{cool}) of the environment control system (ECS) to sustain the crew in a comfortable environment. Thus, the energy balance equation for the air in the cabin is

$$Cp_{air}m_{air}\frac{dT_{air}}{dt}=q_{in_c}A+q_{in_r}A+S_A+S_C-Q_{cool} \tag{1}$$

where Cp_{air} and m_{air} are respectively the specific heat and total mass of the air.

2.2. TPS model

Then we model the transient heat conduction in the TPS and define the boundary conditions on both sides. In general, the TPS is considered to consist of n layers as shown in Fig. 1b. Transient heat conduction in each layer is modeled by using following one-dimensional partial differential equation

$$\frac{\partial^2 T}{\partial x^2}=\frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{2}$$

with initial and boundary conditions

$$T(x,0)=F(x) \tag{3}$$

$$-\lambda\frac{dT}{dx}\bigg|_{x=0}=q_a-q_r=q_a-\varepsilon_{ex}\sigma(T|_{x=0})^4 \tag{4}$$

$$-\lambda\frac{dT}{dx}\bigg|_{x=L}=-q_{in_c}-q_{in_r}=-h^*(T|_{x=L}-T_{air})-\varepsilon_{in}\sigma\left\{\left(T|_{x=L}\right)^4-T_{in}^4\right\} \tag{5}$$

where $F(x)$ is the initial temperature distribution in the TPS; ε_{ex} is the emissivity of the external wall; σ is the Boltzmann constant; h^* is the convective heat transfer coefficient between the inner surface and the cabin air; T_{air} is the mean temperature of the cabin air; ε_{in} is the emissivity of the external wall; T_{in} is the temperature of the stuff in the cabin.

The thermal contact resistance at material interfaces is neglected. Hence, the thermal equilibrium equation at the s_th interface can be expressed as

$$\lambda_s\frac{dT_s}{dx_s}=\lambda_{s+1}\frac{dT_{s+1}}{dx_{s+1}} \tag{6}$$

2.3. Model discretization

Heat equation and its boundary conditions are then discretized by utilizing implicit Crank–Nicolson (C–N) finite difference scheme. The advantage of this discretization scheme is unconditionally stable and second-order accurate for transient heat conduction problems [17].

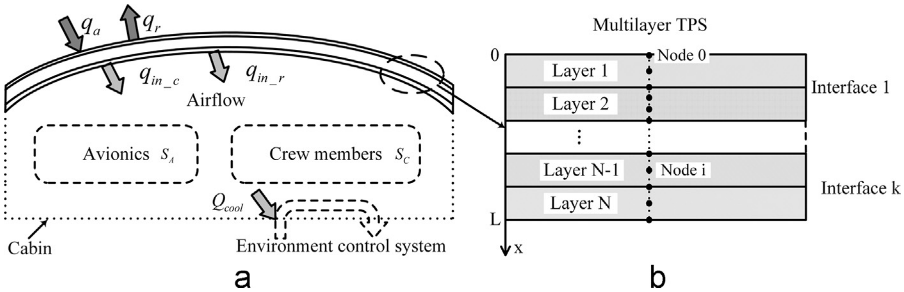

Fig. 1. (a) Conceptual schematic diagram of the crew cabin and its thermal environment; **(b)** 1-D finite difference model for a multilayer TPS.