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The TPS design of a reusable launch vehicle based on active cooling

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Abstract

At present, the TPS of flight vehicles is designed based on the radiation equilibrium condition. The approach is conservative and is unable to consider the influence of active cooling. In this paper, a TPS design method coupling active cooling of kerosene is developed. Such a method includes the calculation of aerodynamic heat, the design of passive TPS, and the determination of design parameters of active cooling system. A reusable launch vehicle and its typical trajectory is studied. The results show that 33% weight of passive TPS can be reduced by active cooling, and the required product of mass flow-rate per area and coolant temperature increase are between 2.1 and 4.9 ($K{\cdot}kg{\cdot}m^{-2}{\cdot}s^{-1}$).

Keywords: *TPS design, active cooling, reusable launch vehicle, aerodynamic heat*

Nomenclature

T – Temperature
Q – Heat
c – Heat capacity
h – Heat transfer coefficient
m_v – mass flow-rate
q – Heat flux
Greek
ε – The surface emissivity
σ – Stefan-Boltzmann constant
Subscripts
b – Bottom
c – Coolant
eff – Effective
W – Wall

1. Introduction

At present, during the design of thermal protection system (TPS) for a flight vehicle, the wall temperature is calculated based on the radiative equilibrium condition, which means no heat conduction into the vehicle or transferred by additional cooling system. This is a very conservative assumption. In this paper, a method is developed to design a TPS with consideration of bottom active cooling system.

2. Heat transfer model

The thermal equilibrium equation is shown in Eq. (1)

$$q = \varepsilon\sigma T_W{}^4 + q_{in} \tag{1}$$

where q is the aerodynamic heat flux, T_w is the wall temperature, σ =5.67 × 10-8 W/($m^2{\cdot}K^4$) is the Stefan-Boltzmann constant, ε is the surface emissivity, and q_{in} is the heat flux conducted into the vehicle. In this work, q is calculated by an engineering-based method [1].

In previous studies, q_{in} equals to 0 and the wall temperature is then overestimated. In this work, an active cooling is performed at the bottom of passive TPS (Fig. 1(a)), and thus q_{in} is assumed to be:

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$$q_{in} = h(T_b - T_c) \tag{2}$$

where h is the heat transfer coefficient of active cooling, T_b is the temperature of TPS bottom which is always a constrained parameter (e.g., <440K in this work), T_c is the temperature of cooling medium. In this work, T_w and T_b are two parameters that can be used to determine the scale of passive TPS (materials, thickness, etc.), and q_{in} is used to output the requirement of active cooling (coolant mass flow-rate, coolant temperature increase, etc.). However, for a flight vehicle, q_{in} as well as h should be related to T_w, which is different at different locations. Therefore, we need new formulation to express q_{in}.

Under this condition, a cooling channel is assumed to be under the TPS surface (Fig. 1(b)), and then q_{in} is:

$$q_{in} = h_{eff}(T_W - T_c) \tag{3}$$

where h_{eff} is the effective heat transfer coefficient. In Eq. (3), q_{in} is dependent on the wall temperature. Now, we have two equations (Eq. (1) and (3)) and two unknown parameters (T_w, q_{in}). h_{eff} is a design parameter and has the same value for the whole vehicle. q_{in} is the heat flux transferred by active cooling and its value is dependent on the aerodynamic heating level of different vehicle locations.

For a preliminary design of active cooling system, the mass flow-rate and temperature increase of the coolant should be the input data. Such two parameters can be evaluated by:

$$Q_{in} = m_f \cdot c \cdot \Delta T \cdot A \tag{4}$$

where Q_{in} equals to q_{in} multiplying heat transfer area, m_v, c and ΔT are the mass flow-rate per area, heat capacity and temperature increase of the coolant, respectively, A is the heat transfer area. In this work, the coolant is the fuel-kerosene. The product of m_f and ΔT which can be considered as cooling ability will be determined and output as the design requirement of the active cooling system.

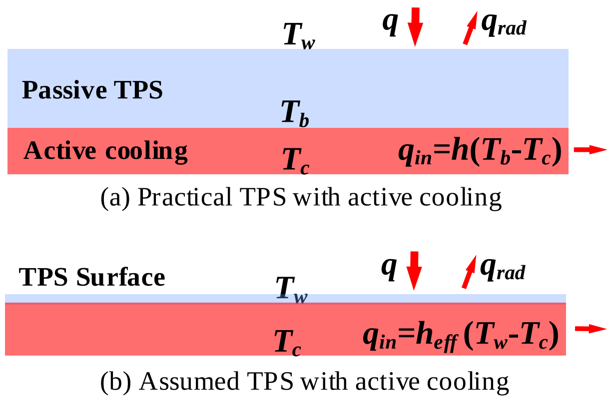

Fig. 1 Thermal equilibrium

In this work, based on the heat transfer model described above, a passive TPS is designed and the requirement of corresponding active cooling system is determined.

3. Flight vehicle

Figure 2 shows the vehicle and the trajectory studied in this work. The left part is the model of a hypersonic reusable launch vehicle designed by the authors. The black circle on the compression surface is a specific point M that will be considered in the calculation of this work. The vehicle has a length of 30 m, a wingspan of 15 m, and the width of the fuselage is 5 m. The structure of the vehicle is divided into several zones of different materials mainly consists of Ti-alloy, Al-alloy and resin based composites, and more detailed descriptions can be found for a similar vehicle in [1, 2].

The right part of Fig. 2 is its typical trajectory curve in a two-dimensional pattern. The vertical axis is the altitude, the bottom horizontal axis is the flight time while the top one is the flight range. It should be noted that the flight range is not in a linear scale, and the largest value is about 6600km and then the vehicle will return to the launch field. One can notice that the vehicle will reach 28 km height and its speed will increase from 0 to 8 Ma within 450 s, then it will fly to its highest altitude of about 50 km and accomplish its mission and return. The large amount of aerodynamic heat generated during the trans-atmospheric phase of its launch and re-entry gives rise of great challenges of TPS. In this work, the aerodynamic heat under the trajectory curve shown in Fig. 1 is calculated. The heat is then applied to analyze the thermal protection efficiency of the TPS structure proposed in this work.

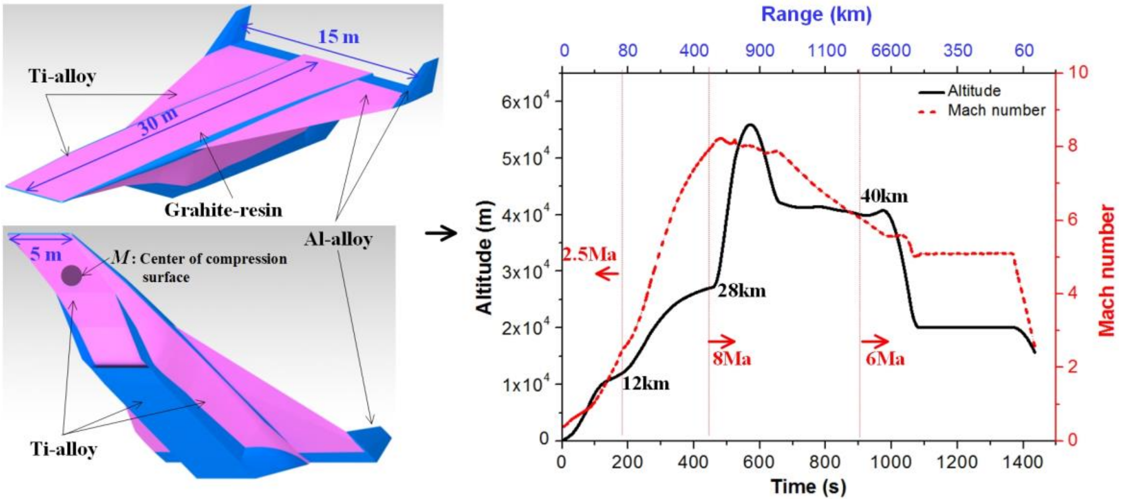

Fig. 2 The vehicle and trajectory

4. Results and discussions

Figure 3(a) and (b) show the calculated wall temperature with h_{eff} = 0 and 10 W/(m^2·K), respectively. As shown in the figure, the area with high temperature decreases when the active cooling is considered. The lower wall temperature will influence the design of passive TPS. Figure 4 shows the local heat transfer coefficient and the preliminary TPS of the whole vehicle. In Fig. 4(b), different colors indicate different TPS projects (or structures) with different TPS materials. Those TPS projects, i.e., AFRSI, TIMW, TI-HC, SA-HC, SA-HC2, TABI, AMHC, LI-900, AETB-8 and AETB-12 are the ones that used in Space Shuttle. The red is the highest temperature structure and the blue is the lowest one. It is clear that the portion of high-temperature structure decreases with the increase of active cooling, and the overall weight of TPS has a 33% decrease (4.8 t to 3.3 t) with the h_{eff} increases from 0 to 10 W/(m^2·K).

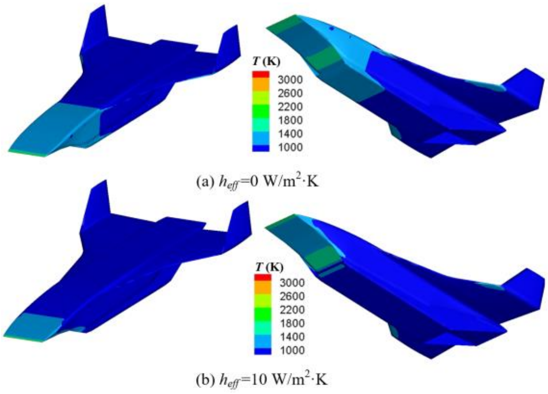

Fig. 3 The wall temperature

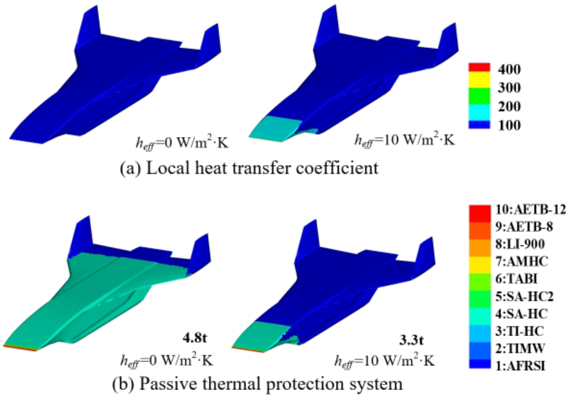

Fig. 4 The local *h* and passive TPS

It should be noted that the aerodynamic heating at the leading edge is much severer than other large-area region, and the results in Fig. (3) is just a rough prediction. However, its influence on the overall TPS weight is relatively small for its small area. Therefore, the specific TPS design for such region needs more consideration.

As discussed above, the active cooling will definitely decrease the TPS weight, however, the design of such a cooling system (heat exchanger) needs some basic input data, e.g. the mass flow-rate and temperature increase of the coolant. Figure 5 shows the finally designed TPS, and the active cooling parameter that can be used to further design a cooling system. It should be noted that Fig. 4 shows preliminary TPSs, while Fig. 5 is a further refined one for the case of h_{eff} = 10 W/(m^2·K). One can observe some difference between them.

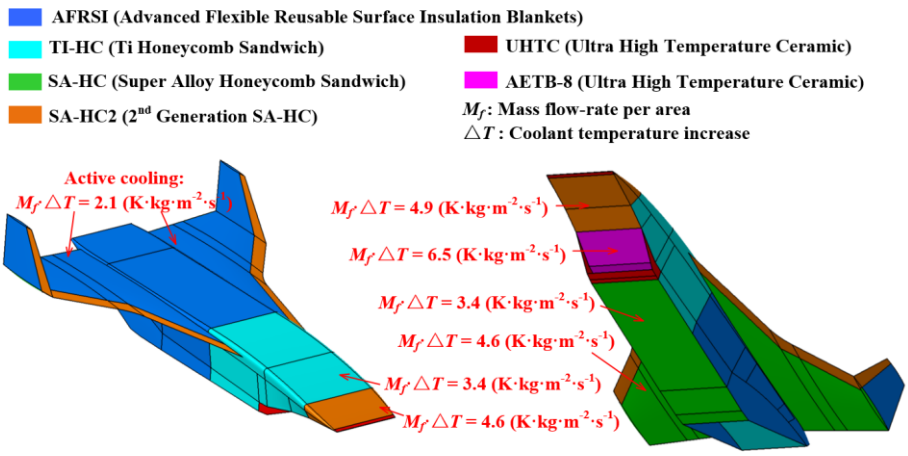

Fig. 5 The active/passive TPS (h_{eff} = 10 W/(m^2·K))

5. Conclusions

In this paper, a TPS design method considering active cooling is developed. The method can be used to design large-area region TPS for a reusable launch vehicle. A parameter, i.e., effective heat transfer coefficient h_{eff} is used to evaluate the heat that transferred by active cooling. The active cooling system can reduce the weight of passive TPS by 33% with h_{eff} increases from 0 to 10 W/(m^2·K). Such a system needs a product of coolant mass flow-rate per area and temperature increase between 2.1 and 4.9 (K·kg·m^{-2}·s^{-1}).

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