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A numerical model for the platelet heat-pipe-cooled leading edge of hypersonic vehicle

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ABSTRACT

A new design, the platelet heat-pipe-cooled leading edge, is discussed for the thermal management to prevent damage to hypersonic vehicle leading edge component. For calculating the steady state behavior of platelet heat-pipe-cooled leading edge, a numerical model based on the principles of evaporation, convection, and condensation of a working fluid is presented. And then its effectiveness is validated by comparing the wall and vapor temperature against experimental data for a conventional heat pipe. Further investigations indicate that alloy IN718, with sodium as the working fluid is a feasible combination for Mach 8 flight with a 15 mm leading edge radius.

1. Introduction

Severe aerodynamic heating to which the hypersonic leading edge are subjected during flight imposes serious harm for flight safety [1–4]: the elevated temperature reduces material's ability to withstand design loads, the thermal stress causes excessive deformation and so on. The heat-pipe-cooled thermal protection system, based on the evaporation, vapor flow, and condensation of the working fluid in heat pipes coupled to the leading edge, can effectively isothermalizes the leading edge structure and reduce the peak temperature and thermal gradient. The concept, which was proposed in early 1970s [5], attracts more researcher's attention and studies with the continuous development of space industry. In more recent studies, Steeves et al. [6] analytically predicted the thermostructural performance of metallic structural heat pipe cooled sharp leading edges. Guangming et al. [7] proposed a coupled heat transfer analytical methods for the heat pipe cooled thermal protection structure considering the sonic limit of heat pipe. Experimental investigations of Jian and Wei-Qiang [8] showed that the working fluid of heat pipe played a key role in the application range for the thermal protection effect.

However, there are some drawbacks to the concept of conventional heat-pipe cooled leading edges. First, the joining of heat pipes to an exterior face sheet increases the solid wall thickness, which is disadvantageous to keep this wall thickness as small as possible in order to maximize the heat flux that enters the heat pipes and to minimize high temperatures and thermal stresses. Second, the thermal contact resistance between heat pipes and high temperature composite materials strongly influences the system's thermal protection performance.

In this paper, a new platelet heat-pipe-cooled thermal protection structure that intend to overcome the aforementioned drawbacks is discussed. And a numerical method considering the flow and heat transfer properties with the vapor-phase and liquid-phase coexistence inside, which is seldom analyzed but helpful to predict dry-out, are established to study the steady state behavior of the structure.

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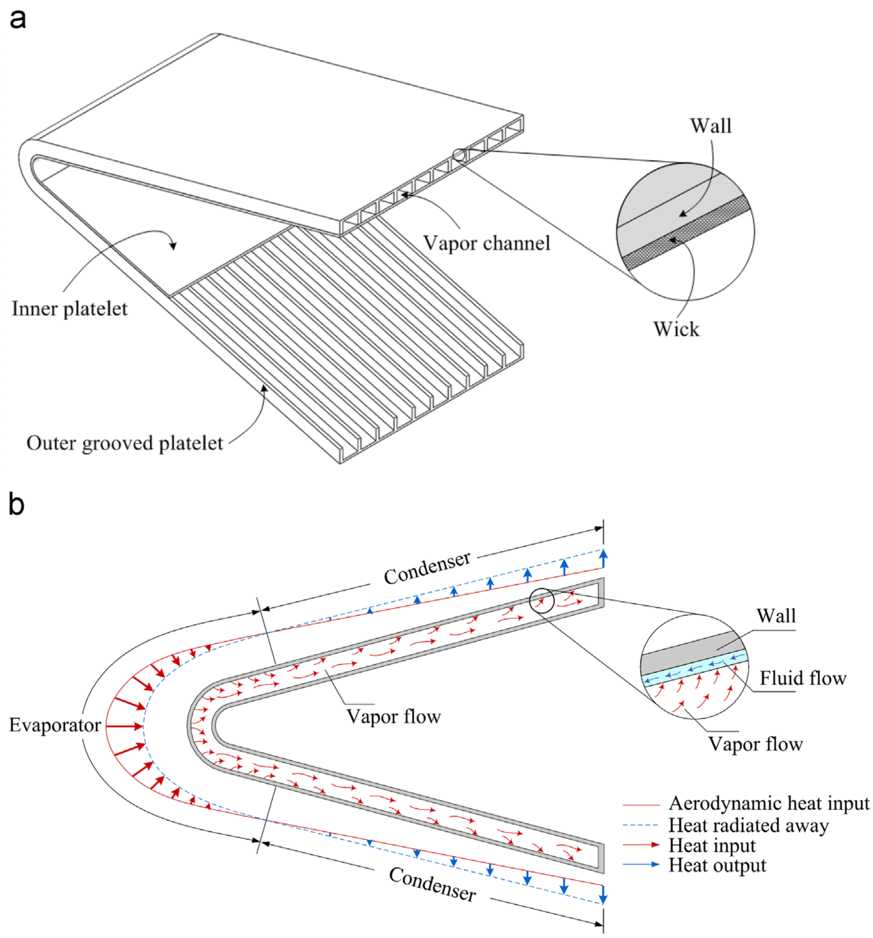

Fig. 1. Structure and operation of a platelet heat-pipe-cooled leading edge. (a) Schematic drawing of a platelet heat-pipe-cooled leading edge structure (b) schematic diagram of the operation of a platelet heat-pipe-cooled leading edge.

2. Structure of platelet heat-pipe-cooled leading edge

The platelet heat-pipe-cooled leading edge structure consists of outer grooved platelet and inner platelet, resulting in rectangular channels situated in the forward-aft direction as vapor core of heat pipes, as shown in Fig. 1(a). Because high thermal flux conducted through the tip's wall would bring greater thermal stresses at the stagnation region, the outer face plate is designed to be an integrally machined grooved-shaped panel to avoid drop of yield strength caused by weld. Ni-based IN 718 is chosen as the wall material due to its oxidation resistance, good weldability and high strength at elevated temperatures. Sodium is chosen as the working fluid for its high latent heat of vaporization and chemical compatibility with IN718. Contiguous nickel foam wicks, with pore radius of 10 μm and permeability of 7.74×10^{-9} m^2, are set onto the interior surface to pump the working fluid from the condenser to the evaporator region.

As schematically shown in Fig. 1(b), the platelet heat-pipe-cooled leading edge is based on the evaporation of the fluid near the stagnation region that sets up a region of elevated vapor pressure inside the sealed pipe. The vapor is driven by the resulting internal pressure gradient in opposing directions aft of the tip where it condenses. And thus its latent heat is released and conducted through the heat pipe wick and wall to the skin of leading edge and finally radiated into space. Replenishment of the condensed working fluid to the evaporator is completed through the capillary action of a wick which lines the interior surface of the pipe. The use of heat pipes results in thermal redistribution from the smaller stagnation region to the larger radiating surface, thereby results in a nearly isothermal leading edge that would reduce the temperatures and thermal stress in the stagnation region.

3. Aerothermal environment of leading edge

The geometry for the calculation of the aerodynamic heat flux incident upon the leading edge is shown in Fig. 2.

The aerodynamic heat flux at the stagnation point can be approximated from Eq. (1) [9].

$$q_{st}=0.57\mathrm{Pr}^{-0.6}(\rho_{st}\mu_{st})^{1/2}\sqrt{\frac{du_{st}}{dx}}(H_{aw}-H_w) \tag{1}$$

where Pr is 0.715. The remaining fluid properties are the density, ρ_{st}, viscosity coefficients, μ_{st}, and velocity u_{st},