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Research Paper

Study on helium impingement cooling for a sharp leading edge subject to aerodynamic heating

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HIGHLIGHTS

- The model couples outer aerodynamic heating and inner impingement cooling together.
- Cooling effectiveness of helium impingement-cooled TPS is significant.
- Thermal and mechanical performances of the TPS with different materials are tested.
- Operating requirements and limitations for the actively-cooled TPS are probed.

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ABSTRACT

This paper presents numerical studies on a typical actively-cooled thermal protection system (TPS) which turns out to be a potential candidate for the leading edge thermal management. The leading edge is cooled by the impingement jet of gaseous helium. The external aerodynamic heating and radiation, the heat conduction in solid wall, and the internal impingement cooling are coupled in a unified computational fluid dynamics system by using a quasi-coupling method. The thermal-hydraulic performance of internal impingement cooling is particularly highlighted. Four metal alloys are tested in order to find out the impact of the material property on the TPS's cooling performance. Results show that the reduction of leading edge temperature is remarkable with the impingement cooling scheme and the maximum temperature can be controlled far below the materials' melting point. However, the thermal stress does not significant decrease and is still a barrier for the application of the actively-cooled TPS. The operation limits of various materials are demonstrated, which may benefit to the future material selection work. Besides, the coolant flow rate requirements for safely operating the TPS under various flight conditions are ascertained.

1. Introduction

Hypersonic vehicles typically wear wings with sharp leading edge to facilitate their maneuverability. Rapid stagnation of high enthalpy airflow over the vehicle's leading edge induces elevated temperature around the stagnation region, which may cause the material failure and bring risk to the vehicle. Therefore, robust TPSs are needed to retain the structural integrity of leading edge during hypersonic flight.

According to the operation feature, TPSs can be divided into three categories: passive, semi-passive, and actively-cooled [1]. Passive TPS is the most commonly used TPS for hypersonic vehicles, which uses the insulation material to block the aerodynamic heat. For example, the U.S. space shuttle orbiter applied reinforced carbon-carbon material on the leading edge to withstand the temporary heating during atmosphere exit and re-entry. Generally, these TPS materials are vulnerable to damage due to their inherent brittleness [2]. In addition, passive TPSs vitally rely on the development of ultra-high-temperature material technology and are infeasible for long time operation. Semi-passive TPS intends to use high efficient heat transfer approaches to move the heat from a high-temperature region to a relatively cold region. For instance, the heat-pipe-cooled leading edge is a typical semi-passive TPS, which is supposed to be a competitive candidate for hypersonic vehicle leading edge thermal management. Despite its advantages, heat-pipe-cooled TPS for leading edge is still full of complexity in design, manufacture and operation process, which delay its extensive implementation [3]. Besides, ablative TPS also can be classified as semi-passive TPS [1], which is nowadays a relatively mature technology. However, it is impractical for leading edge thermal management due to its evolving shape during

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Nomenclature

Alt	altitude, km
B_H	height of the flow channel, m
b_w	wall thickness, m
C_f	local skin-friction coefficient
c	specific heat of solid material, J kg^{-1} K^{-1}
cp	specific heat at constant pressure, J kg^{-1} K^{-1}
D_h	hydraulic diameter, $D_h = 2B_H$, m
E	Young's modulus, GPa
f	friction factor
H	enthalpy, J kg^{-1}
I	turbulent intensity
k	turbulent kinetic energy, m^2 s^{-2}
L	lateral distance from the stagnation point, m
L_{FP}	length of the flat panel, m
Ma	Mach number
Nu	Nusselt number
Pr	Prandtl number
p	pressure, Pa
q	heat flux, W m^{-2}
Re	Reynolds number
R_L	radius of the leading edge, m
R_g	gas constant, air, J kg^{-1} K^{-1}
St	Stanton number
T	temperature, K
u	velocity, m s^{-1}
X	x distance, m

Greek symbols

α	thermal expansion coefficient, K^{-1}
β	oblique shock angle relative to freestream
γ	ratio of specific heats, air
Δ	gradient
ε	turbulent energy dissipation rate, m^2 s^{-3}
ϵ	strain
θ	shift angle of tip curve
λ	thermal conductivity, W m^{-1} K^{-1}
μ	viscosity, kg m^{-1} s^{-1}
v	Poisson's ratio
ρ	density, kg m^{-3}
σ	stress, Pa
σ_Y	yield strength, Pa
ς	shear strain
τ	shear stress
φ	half-angle of the leading edge

Subscripts

0	total
∞	freestream condition
$aero$	aerodynamic heating
aw	adiabatic wall
e	edge of the boundary layer
in	coolant inlet
net	net heat flux
rad	radiation
st	stagnation point
sp	straight passage
tc	tip curve
w	wall

ablation. The actively-cooled TPS is an alternate approach to manage the aerodynamic heat on the leading edge, especially appropriate for air-breathing or single-stage-to-orbit vehicles, which are required for longer duration hypersonic flight, under which conditions the maximum heating or the total heat load exceeds the operating limit of passive or semi-passive TPS.

Recently, Schwanekamp et al. [4] presented a review paper to emphasize the potentiality of applying active TPS on future hypersonic crew-vehicle. Various layouts of actively-cooled TPS were presented. Future hypersonic vehicles are supposed to be much faster and are required for longer duration cruise in atmospheric environment. The TPS is going to meet much more challenges in the future. Therefore, actively-cooled TPS, as one of the most efficient scheme, should be further explored.

The actively-cooled TPS for the leading edge can be implemented in a variety of ways, such as film cooling [5], transpiration cooling [6] and convective/impingement cooling [4]. Compared to the former two cooling schemes, the convective/impingement cooling TPS seems to be simpler and more feasible. This cooling scheme has been widely employed to manage the high flux on the airfoil leading edge of engine turbines [7–10]. Within our knowledge, there only exist a few research works focusing on the application of the impingement cooling scheme for the leading edge of hypersonic vehicle wing. Dechaumphai et al. [11] numerically studied a hydrogen impingement-cooled leading edge subjected to shock wave interference heating. They focused on solving the aerodynamic heating over the leading edge, while the internal cooling was modeled by just setting a constant heat transfer coefficient of 49,800 W m^{-2} K^{-1}. They concluded that their model was very much time-consuming because the governing equations for external flow must be solved to evaluate the aerodynamic heating. Gladden et al. [12] investigated a hydrogen impingement-cooled leading edge that was similar to Dechaumphai's. They promoted the cooling model by employing some empirical correlations to weigh the heat transfer coefficient of the impingement cooling. Overall, both Dechaumphai and Gladden found great reduction in the peak-temperature of the leading edge. The recent research of Brown et al. [13] related to the actively-cooled TPS mainly concentrated on the accurately modeling of heat load on external surface while the internal cooling was simply treated. The calculation of aerodynamic heating is, of course, essential to the design of actively-cooled TPS, but the accurate prediction of internal cooling effect is also very important [14].

The cooling effectiveness of impingement jet is greatly dependent on the configuration, structure material, coolant flow characteristic and the external thermal conditions. Previous models [11–14] for actively-cooled TPS, which simply utilized idealized cooling flux to evaluate the cooling capacity seems insufficient. In terms of the impingement-cooled leading edge, the internal flow and heat transfer over concave surface are very complex, and the local heat transfer coefficient alters greatly along the streamwise [15–20]. So the accurate prediction of internal impingement cooling is critical for modeling such actively-cooled TPS. In addition, the external aerodynamic heating and radiation strongly depend on the wall temperature, which is influenced by the internal cooling. So it is necessary to couple the aerodynamic heating and impingement cooling in an integrate model.

The purpose of this paper is to give particular insight into the internal cooling performance of the impingement jet for a sharp leading edge under aerodynamic heating. The gaseous helium is selected as the working fluid. The impingement-cooled leading edge is modeled by using Computational Fluid Dynamics (CFD)