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Research Paper

Numerical investigation on the performances of porous matrix with transpiration and film cooling

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HIGHLIGHTS

- A coupled method is established to simulate transpiration cooling under hypersonic condition.
- The downstream film cooling effect derived by transpiration cooling is systematically analyzed.
- An innovative composite cooling concept combining transpiration and film cooling is proposed.
- A single channel coolant supply scheme to realize non-uniform coolant allocation is exhibited.

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ABSTRACT

Aimed at solving the thermal protection problems of the leading edge and entire structure of hypersonic vehicles synchronously, this paper presents an innovative conception of active thermal protection, which combines transpiration and film cooling within separate porous matrixes, and a coupled numerical method to simulate the combined cooling effect of the entire field. The numerical method is validated by experimental data obtained at Ma = 4.2 in an arc-heated wind tunnel. Using gaseous Nitrogen as coolant: (1) the downstream film cooling effect derived by upstream transpiration cooling is systematically investigated; (2) the comprehensive cooling effects of two layouts of porous matrix, single porous matrix (SPM) and binary porous matrixes (BPM), are compared in detail; (3) a single channel coolant supply scheme is designed to realize desired non-uniform coolant allocation for BPM. These discussions and results are valuable for the designers searching for large area thermal protection and light weight systems.

1. Introduction

To increase the lift-to-drag ratio, hypersonic vehicles are usually designed with sharp leading edges, however, the aerodynamic gains obtained are at the cost of extreme localized thermal loads, which may far exceed the capabilities of current material limits [1]. In the development process of more efficient active thermal protection systems (TPS), coolant consumption is an important consideration to decrease takeoff weight and prolong flight duration. Eckert et al. [2] compared three active TPSs, and concluded that transpiration cooling requires much less coolant amount at the same temperature-difference ratio than film cooling and convective cooling.

There have been a large number of numerical and experimental investigations on the mechanism and application of transpiration cooling. Dong et al., Andoh et al., and Jiang et al. [3–5] studied the heat and mass transfer characteristics within porous matrixes, Dahmen et al., Frank et al. and Keller et al. [6–8] investigated the heat transfer, chemical reaction and skin friction performances in the boundary layer outside the porous matrixes. Liu et al., Huang et al. and Xiao et al. [9–11] focused on the mixing effects of coolant passing through the micro pores with mainstream blowing on the outside wall. It is accepted that all active TPSs need to take along additional coolant and injection systems, and therefore it is valuable to optimize the cooling system to minimize the coolant weight and associated costs, under the conditions to satisfy the mission requirements [12], especially for long duration flights. To optimize designs of transpiration cooling, Zhao et al. and Jiang et al. [13,14] focused on the structures of leading edges, Herbertz et al. and Wang et al. [15,16] discussed porous material properties and selection, and Wu et al. [17] studied a coating material on porous matrix as sublimation switch to activate transpiration cooling.

However, most of the previous investigations focused on the effective cooling of the stagnation region, but did not consider the tough

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Nomenclature

SPM	single porous matrix
BPM	binary porous matrixes
TPS	thermal protection system
Ma	Mach number
T	temperature, K
p	pressure, Pa
U	velocity, m/s
Y	species mass fraction
F	coolant injection ratio
x, y	Cartesian coordinate, m
M	mass flow rate, g/s
L	porous matrix length, mm
L_{eff}	effective film length, mm
ε	porosity
D_p	average pore diameter, m
ρ	density, kg/m^3
μ	dynamic viscosity, Pa·s
k	thermal conductivity, W/(m·K)
J	mass diffusion flux, kg/(s·m^2)
R_g	gas constant, J/(kg·K)
Δ	shock wave stand-off distance, mm
c	coolant chamber
p1, p2	the first/second porous matrix
w1, w2	the first/second impermeable wall
f	free flow

Subscripts

0	stagnation
1	of the first porous matrix
2	of the second porous matrix
c	coolant
f	fluid
s	solid

issue of effective large-area cooling, which is also necessary in future hypersonic vehicles with higher flight duration and frequency. Recently, Shen et al., and Huang et al. [18,19] revealed that the downstream film cooling effect derived from upstream transpiration cooling is observed, and should be further considered and applied. Ostu et al. [20] also indicated that more heat sink of the gaseous coolant is wasted when the ejection rate rises higher in transpiration cooling. It is clear that the derived film cooling can make full use of the coolant, and enlarge the effective cooling area. But up to now, systematical investigation and quantitative evaluation on the derived film cooling are insufficient, and in the designing of transpiration cooling system, such coverage cooling effect has not yet been utilized.

Therefore, this paper presents a numerical method to simulate the coupled cooling effect of the entire field. Firstly, a systematical investigation on the film cooling performances originated from transpiration cooling within single porous matrix (SPM) is conducted. After that, to deal with the limitations of SPM, a new layout of transpiration cooling within binary porous matrixes (BPM) is promoted and studied. Finally, to realize the desired non-uniform coolant allocation for BPM, a single channel coolant supply scheme is specially designed and tested. The aim of this work is to provide designers of future hypersonic vehicles with a relatively comprehensive reference for optimal design of TPSs with functions of large area and light weight.

2. Simulation method

2.1. Geometry and physical model

As shown in Fig. 1, the geometry model of the leading wedge has a radius of 3 mm, a wedge angle of 14 degree and a wall thickness of 2 mm. To observe the derived film cooling effect adequately, the length is selected as 114 mm. During transpiration cooling, a uniform free flow blows from far-field region and impinges on the sharp leading edge. The coolant is injected from the coolant chamber through interface I into the porous matrixes, exchanges heat with the solid structures in the inner micro channels, and forms a covered film after ejecting out from interface II to further resist the high temperature invasion.

2.2. Mathematical model and boundary conditions

To quantitatively describe the physical procedures, the entire computational domain is divided into six parts, as shown in Fig. 2, coolant chamber (c), two porous matrixes (p1, p2), two impermeable walls (w1, w2), and free flow (f). The corresponding mathematical model includes the following equations as listed in Table 1:

(1) In the coolant chamber (c), gaseous Nitrogen is supplied at a constant mass flow rate M_c = 50 g/s. The Reynolds number of the Nitrogen flow is 1495.4, which is lower than the critical Reynolds number 2220 provided by Sarpkaya [21], hence the flow in the

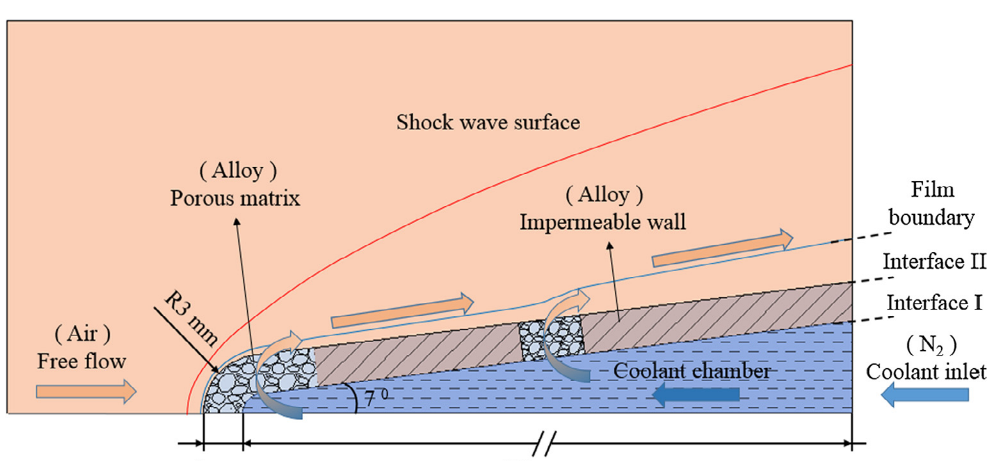

Fig. 1. Geometry and physical model.