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Experimental and numerical study on the aero-heating characteristics of blunted waverider

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HIGHLIGHTS

► Aero-heating Characteristics are studied based on numerical and experiment methods.
► The effects of attack angle and sideslip angle are studied in the present paper.
► The influence of attack angle on the aero-heating of nose region can be neglected.
► High heat flux is limited in a small region around the stagnation point.
► Zero degree sideslip angle is suggested in this paper.

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ABSTRACT

Aero-heating analysis is very important for the thermal protection system design of blunted waverider. In this paper, the heat flux distributions on the nose region and leading edge, the upper surface and the lower surface are studied with numerical and experiment methods, including the effects of attack angle and sideslip angle. The results show that high heat flux is limited in a small region around the stagnation point, and the influence of attack angle on the aero-heating of nose region can be neglected. Because even small sideslip angle may induce great enhanced aero-heating on the windward side of blunted waverider, zero degree sideslip angle is suggested in the present paper. With this assumption, the thermal materials of nose region, leading edge and upper surface can be chosen based on their aero-heating under on-design condition; while for the lower surface, the thermal materials should be determined by the aero-heating under maximum angle of attack.

1. Introduction

Waverider, first proposed by Professor Nonweiler [1], is a lifting body derived from a known analytical flow field such as flow over a two dimensional wedge or flow around a cone [2]. This configuration is designed with infinitely sharp leading edges for shock wave attachment. By confining the high pressure under vehicle, the waverider effectively rides on the shock wave, thus making its lift-to-drag ratio higher than the conventional vehicles [3]. The simulation results showed that the aerodynamic performance of viscous optimized waverider configuration can break the "lift-to-drag ratio barrier" which is proposed by Kuchemann [4] for hypersonic aircrafts, and waverider is a good candidate for hypersonic flights [5–18]. However, for the practical hypersonic configuration, Santos [2] pointed out that the sharp leading edge of ideal waverider should be blunted due to manufacturing, handling concerns and serious aero-heating.

Recently, lots of attention has been paid to the influence of bluntness on the aerodynamic performance of waverider. Silvester [19] concluded that rounding the leading edges significantly degrades the aerodynamic performance of caret waverider. In addition, the simulation results of Cao [20] showed that the lift-to-drag ratio would decrease 7.21% if blunt radius is 0.01 m for the studied waverider. Furthermore, Santos [2] investigated the bluntness impact on the aerodynamic surface quantities of hypersonic wedge flow by employing Direct Simulation Monte Carlo Method, and he found that even small leading edge bluntness resulted in significant reduction on the performance; the heat transfer coefficient, drag coefficient and lift coefficient are highly sensitive to the bluntness. An original aerodynamic study of AEDC waverider model by Gillum [21] showed that the peak lift-to-drag ratio reduces 19.74% with the addition of blunt leading edges. Afterwards, Chen [3] studied the performances for waveriders with blunt radius of 0.01 m, 0.02 m and 0.03 m based on CFD techniques. He pointed out

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Nomenclature

t	time component
u, v, w	velocity components in the x, y, z directions, respectively
x, y, z	rectangular axis
ρ	density
P	pressure
T	temperature
e	internal energy
e_t	total energy
q	heat flux
μ	viscosity coefficient
C_P	constant-pressure specific heat
k	thermal conductivity
α	angle of attack
AOA	angle of attack
β	angle of sideslip
R	blunt radius
η	three dimensional correction factor at the stagnation point
γ	specific heat ratio
Ma	Mach number
P	Prandtl number
Re	Reynolds number
L	length of computational model
b	half span length

Subscript

i	relative terms for inviscid flow
v	relative terms for viscous flow
o	stagnation properties
w	wall values
∞	free-stream conditions

that blunting leading edge could reduce the maximum heat flux effectively, but it also degrades the aerodynamic performance. As the blunt radius increases, the lift-to-drag ratio degrades significantly, while the heat flux wears off. Therefore, the impact of bluntness on aerodynamic performance and heat flux should be taken into account synthetically during the designing of hypersonic waverider vehicle. Though the influence of bluntness on the performance of waverider configuration has been studied deeply, especially the aerodynamic coefficients, less attention is paid to the impact of flight attitude on the blunted waverider. As a further study of Chen, this paper aims to study the aero-heating characteristics of blunted waverider. Based on numerical and experiment methods, the heat flux distribution on the nose region and leading edge, the upper surface and the lower surface are investigated under different attack angles and sideslip angles. The paper is organized as follows: Section 2 introduces the computational model and numerical methods as well as two test cases; Section 3 presents the experiment facilities and experiment model; Section 4 discusses the results of computation and experiment.

2. Computational model and method

2.1. Computational model

The computational model of this paper is designed with the similar method of Ref. [3] shown in Fig. 1(1). Firstly, an ideal waverider is constructed according to the known hypersonic cone flow with the Mach number of 10 and the cone angle of 12°. A baseline is conceived on a cross section of the flow field. The upper surface is obtained by the rules of being parallel to the free stream. And then the leading edge can be defined on the shock wave induced by the cone. Afterwards, the lower surface would be designed by tracing the streamlines. In this paper, the sharp leading edge of ideal waverider is modified with the blunt radius of 0.03 m, and the computational model of blunted waverider is shown in Fig. 1(2).

2.2. Computational method

Without consideration of volume force and outer heat source, the three-dimensional compressible Navier–Stokes equations in Cartesian coordinate system can be expressed as [3]:

$$\frac{\partial Q}{\partial t}+\frac{\partial(F_i-F_v)}{\partial x}+\frac{\partial(G_i-G_v)}{\partial y}+\frac{\partial(H_i-H_v)}{\partial z}=0 \quad (1)$$

In the formula, Q is the conservation vector flux; and F, G, H is the flux of x, y, z directions, respectively. The subscript i means the relative inviscid term, and the subscript v means the relative viscous term. Furthermore, if the governing equations are written into vector form, the expression would be:

$$Q=[\rho,\rho u,\rho v,\rho w,\rho e]^T,\quad F_i=\begin{bmatrix}\rho u\\ \rho u^2+p\\ \rho uv\\ \rho uw\\ (\rho e_t+p)u\end{bmatrix},$$

$$F_v=\begin{bmatrix}0\\ \tau_{xx}\\ \tau_{xy}\\ \tau_{xz}\\ u\tau_{xx}+v\tau_{xy}+w\tau_{xz}+q_x\end{bmatrix},\quad G_i=\begin{bmatrix}\rho v\\ \rho uv\\ \rho v^2+p\\ \rho vw\\ (\rho e_t+p)v\end{bmatrix},$$

$$G_v=\begin{bmatrix}0\\ \tau_{xy}\\ \tau_{yy}\\ \tau_{yz}\\ u\tau_{yx}+v\tau_{yy}+w\tau_{yz}+q_y\end{bmatrix},\quad H_i=\begin{bmatrix}\rho w\\ \rho uw\\ \rho vw\\ \rho w^2+p\\ (\rho e_t+p)w\end{bmatrix},$$

$$H_v=\begin{bmatrix}0\\ \tau_{xz}\\ \tau_{yz}\\ \tau_{zz}\\ u\tau_{zx}+v\tau_{zy}+w\tau_{zz}+q_z\end{bmatrix},$$

in which

$$\tau_{xx}=2\mu\frac{\partial u}{\partial x}-\frac{2}{3}\mu\nabla\cdot\vec{V},\quad \tau_{yy}=2\mu\frac{\partial v}{\partial y}-\frac{2}{3}\mu\nabla\cdot\vec{V},$$

$$\tau_{zz}=2\mu\frac{\partial w}{\partial z}-\frac{2}{3}\mu\nabla\cdot\vec{V},\quad \tau_{xy}=\tau_{yx}=\mu\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right),$$

$$\tau_{zx}=\tau_{xz}=\mu\left(\frac{\partial u}{\partial z}+\frac{\partial w}{\partial x}\right),\quad \tau_{yz}=\tau_{zy}=\mu\left(\frac{\partial v}{\partial z}+\frac{\partial w}{\partial y}\right),$$

$$q_x=k\frac{\partial T}{\partial x},\quad q_y=k\frac{\partial T}{\partial y},\quad q_z=k\frac{\partial T}{\partial z},$$

$$e_t=\frac{p}{(\gamma+1)\rho}+\frac{1}{2}\left(u^2+v^2+w^2\right).$$

The viscosity coefficient μ can be calculated by Sutherland law, and the thermal conductivity k can be determined by Prandtl number: