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Investigation of thermal protection system by forward-facing cavity and opposing jet combinatorial configuration

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Abstract This paper focuses on the usage of the forward-facing cavity and opposing jet combinatorial configuration as the thermal protection system (TPS) for hypersonic vehicles. A hemisphere-cone nose-tip with the combinatorial configuration is investigated numerically in hypersonic free stream. Some numerical results are validated by experiments. The flow field parameters, aerodynamic force and surface heat flux distribution are obtained. The influence of the opposing jet stagnation pressure on cooling efficiency of the combinatorial TPS is discussed. The detailed numerical results show that the aerodynamic heating is reduced remarkably by the combinatorial system. The recirculation region plays a pivotal role for the reduction of heat flux. The larger the stagnation pressure of opposing jet is, the more the heating reduction is. This kind of combinatorial system is suitable to be the TPS for the high-speed vehicles which need long-range and long time flight.

1. Introduction

Hypersonic vehicles such as interceptor missiles, re-entry vehicles, hypervelocity projectiles and hypersonic aircraft are designed to withstand severe heat loads. The scholars in thermal protection fields are always keeping their eyes on the design of high speed vehicles' thermal protection system. With the development of the spacecraft, new function requirements, such as reusable, are desired. Some traditional thermal protection techniques, for example, the ablation technique,[1] are difficult to satisfy these requirements. New techniques such as platelet transpiration,[2] heat-pipe,[3] thermal photovoltaic (TPV)[4] were used to the thermal protection system.

In 1921, a body containing a forward-facing cavity under a supersonic flow was introduced first by Hartmann.[5] It was used as a new technique for producing sound of high intensity and discrete frequency at that time, which was known as the "Hartmann whistle". Research efforts related to these ideas have been done by a number of researchers.[6] In 1959, Burbank and Stallings[7] reported this idea as a thermal protection technique for the nose-tip of hypersonic vehicles firstly. In recent years, attracted by its simple structure and excellent thermal

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protection effect, many studies have done on it. Preliminary experiments, using an infrared (IR) camera, by Yuceil et al.[8] indicated that large diameter, shallow cavities (length-to-diameter ratio L/D between 0.15 and 0.35) created a stable "cool ring" in the vicinity of the sharp cavity lip, which means that the local temperature was lower than that of a simple spherical nose. Seiler et al.[9] researched on the thermal protection efficiency of forward-facing cavity at Mach number $Ma = 4.5$. An important result of their study is that the deepest cavity has the smallest heat flux. Saravanan et al.[10,11] investigated the effects of a forward-facing cavity on heat transfer and aerodynamic coefficients. Numerical simulation was carried out with steady-state flow assumption and had a good agreement with their tests in hypersonic shock tunnel HST2, at a hypersonic Mach number of 8.

In the early 1960s, opposing jet was reported as a thermal protection technique for the nose-tip of hypersonic vehicles and validating experiments were conducted.[12] More studies on opposing jet flow have been conducted in the 21st century. Aerodynamic heating reduction[13] due to opposing jet from the top of blunt body is experimentally and numerically investigated. Aerodynamic heating reduction due to opposing jet is proved to be quite effective at the nose of the blunt body by experiment. Detailed numerical investigation of the flow field indicates that the recirculation region plays an important role in reduction of aerodynamic heating. The effect of the ratio of stagnation pressure of opposing jet to free stream on the reduction of aerodynamic heating is investigated by Hayashi et al.[14,15] The experimental and numerical results showed that as the pressure ratio increased, the heat flux decreased at each point of the nose surface. The detailed influences of the free Mach number, jet Mach number and attack angle on the reduction of drag coefficient were studied by high precise simulation of Navier–Stokes equations.[16]

In the present study, the forward-facing cavity and opposing jet combinatorial TPS is investigated numerically. Some numerical results are validated by experiments. Remarkable aerodynamic heating reduction due to the combinatorial TPS in hypersonic flow field is revealed by detailed numerical simulation. Furthermore, the influence of the opposing jet stagnation pressure on thermal protection efficiency of the TPS is discussed.

2. Configuration of combinatorial TPS

The configuration of the forward-facing cavity and opposing jet thermal protection system is shown in Fig. 1. The nozzle exit of the opposing jet is located at the center of the base wall of the cavity and the diameter is 4 mm. The fluid medium for opposing jet is assumed as compression air. In order to compare with the results of experiment, the geometric configuration of the nose-tip is the same as that in Ref.[11] The depth of the cavity L is 24 mm and the diameter D is 12 mm, the diameter of the nose-tip bottom surface D_n is 51 mm.

3. Computation scheme

3.1. Governing equation

The 3-D Navier–Stokes equations is given by[17]

$$\frac{\partial U}{\partial t}+\frac{\partial E}{\partial x}+\frac{\partial F}{\partial y}+\frac{\partial G}{\partial z}=\frac{\partial E_v}{\partial x}+\frac{\partial F_v}{\partial y}+\frac{\partial G_v}{\partial z} \tag{1}$$

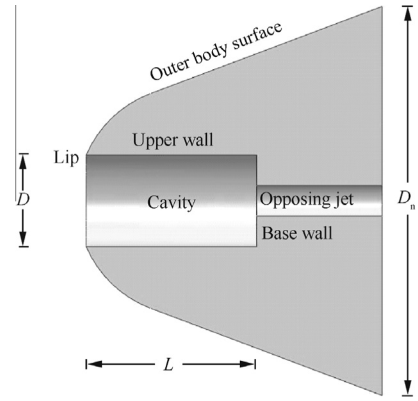

Fig. 1 Schematic of combinatorial TPS.

where (x, y, z) is the coordinate of the physical space, U the conservation variable, E, F and G are the inviscid terms, and E_v, F_v and G_v are the viscous terms. The k-ε turbulence model[18] is used in the simulation.

The convective terms are approximated using the advection upstream splitting method-DV (AUSM-DV) splitting method[19] and central difference method for the viscous terms. The lower–upper symmetric successive over relaxation (LU-SSOR) scheme[20] is used for the time integration.

3.2. Generation of grids

The three-dimensional boundary-fitted grids for the nose-tip with three kinds of TPS are generated by the Poisson equation.[21]

$$\begin{cases}\nabla^2_{(x,y,z)}\xi = P\\ \nabla^2_{(x,y,z)}\eta = Q\\ \nabla^2_{(x,y,z)}\varsigma = R\end{cases} \tag{2}$$

where (ξ, η, ζ) is the coordinate of the calculation space, and P, Q, R are the source items which control and regulate the refinement of the grid.[22,23]

The grid of simulation model (nose-tip with combinatorial TPS) on the symmetry plane and on the wall of the nose-tip is shown in Figs. 2 and 3.

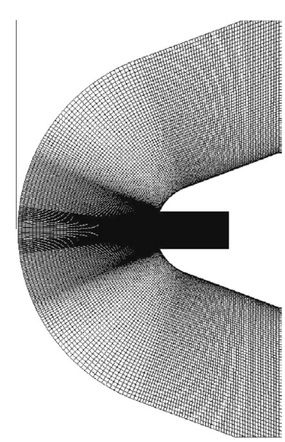

Fig. 2 Grid on symmetry plane.