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High-temperature gas effects on aerodynamic characteristics of waverider

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Abstract This paper focuses on the analysis of high-temperature effect on a conical waverider and it is a typical configuration of near space vehicles. Two different gas models are used in the numerical simulations, namely the thermochemical non-equilibrium and perfect gas models. The non-equilibrium flow simulations are conducted with the usage of the parallel non-equilibrium program developed by the authors while the perfect gas flow simulations are carried out with the commercial software Fluent. The non-equilibrium code is validated with experimental results and grid sensitivity analysis is performed as well. Then, numerical simulations of the flow around the conical waverider with the two gas models are conducted. In the results, differences in the flow structures as well as aerodynamic performances of the conical waverider are compared. It is found that the thermochemical non-equilibrium effect is significant mainly near the windward boundary layer at the tail of the waverider, and the non-equilibrium influence makes the pressure center move forward to about 0.57% of the whole craft's length at the altitude of 60 km.

1. Introduction

Global strike and persistent attack have attracted an increasing attention worldwide since human started the space era.[1] With respect to subsonic and supersonic vehicles, the near-space hypersonic vehicles have so many advantages, such as fast arrival within the global and exceptional ability of anti-defense, thus much attention has been drawn to its research.[2,3]

A series of near space hypersonic vehicles has been investigated, such as HTV-2,[4] X-37B[5,6] and EXPERT[7] in recent years. It has already been proved in the flight practice of conventional reentry vehicles such as space shuttle orbiters and capsules that high-temperature effect, especially non-equilibrium effect has a significant influence on the aerodynamic performances of these blunt crafts. In view of the great differences in the flying track and configuration between the high lift to drag ratio (L/D) near-space vehicles and the conventional blunt reentry vehicles, high-temperature effect on these near space vehicles needs further investigation.

Nowadays, computational fluid dynamics has grown mature to a point where it is widely accepted as an essential, complementary analysis tool to wind tunnel experiments and flight tests.[8] In the research process of high-temperature effect, numerical simulation is particularly important in respect that

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the flight tests cost too much and the wind tunnel experiments cannot entirely simulate the real flight condition. The high-temperature effect on the flow structure and aerodynamic performances is apparent. It changes not only the position and shape of shock waves, but also the characteristics of boundary layer, which ultimately results in the variations in the aerodynamic performance of the vehicles. High-temperature effect on the aerodynamics is mainly embodied in the variations of the pitching moment and pressure center location. During the flight test of STS-1, because of disregarding the high-temperature effect the flap deflection angle was more than twice of the value predicted in the wind tunnel to balance the angle of attack. Some scientists, like Park and Yoon,[9] have been studying the high-temperature effect long before, but most of the subjects investigated are space shuttle orbiters and reentry capsules. Park's research shows that the pressure center location may move forward by as much as 1% of the whole craft for hypersonic vehicles with similar configuration as space shuttle orbiter when the airvanes are totally deflected.

The research on high-temperature effect over the aerodynamics of waverider vehicles has begun since a short time ago and most of the study is about equilibrium effect. Anderson et al.[10] developed a few conical waveriders by using the equilibrium conical flow as the basic flow field, and compared their aerodynamic performance with those derived from perfect conical flow. Anderson's result shows that these two kinds of waveriders nearly have the same L/D ratio in the inviscid flow or when the Mach number is lower than 50. Zeng et al.[11] from the Institute of Mechanics, Chinese Academy of Science, studied the equilibrium effect in the viscous condition over the aerodynamic performance of the conical waverider. The results show that unlike the reentry shuttle orbiters, the equilibrium effect makes the pressure center move backward for the conical waverider.

High-temperature effect on the aerodynamic performance of the waverider vehicles contains not only the equilibrium effect but also the non-equilibrium effect in the near-space region. Against such background, this paper will analyze the high temperature effect on the aerodynamic performance of the conical waverider by using a non-equilibrium numerical simulation program TCNEQ3DP developed by the authors before. Differences in the flow structure and some aerodynamic parameters between the non-equilibrium and perfect gas models will be presented.

2. Numerical methods and physiochemical models

While the hypersonic vehicles travel at an altitude of 40–80 km, the high temperature effect mainly acts as thermochemical non-equilibrium effect because the characteristic time of the flowfield has nearly the same magnitude with the molecule vibration relaxation time and the chemical reaction time. Even though there are a few non-equilibrium flow field solver programs such as LAURA[12], GASP[13] and FLOWer,[14] etc. many unfathomed problems still exist in the non-equilibrium numerical study. Dong et al.[15] and Li[16] from China Aerodynamics Research and Development Center, Ma et al.[17] from Beihang University as well as Yu et al.[18] from Nanjing University of Aeronautics and Astronautics have done a lot of researches on the non-equilibrium flow. However, researches of the non-equilibrium effect upon the waveriders can still not be found in the literature. Therefore, a parallel non-equilibrium program has been developed by the authors and used in the analysis of high temperature effect in the current study.

The parallel non-equilibrium program used in this paper is derived from TCNEQ3D[19] by using MPI systems, called TCNEQ3DP. This program is based on the structured multiblock mesh and finite difference method (FDM). The AUSMPW second order upwind scheme with MUSCL reconstruction is used for the inviscid fluxes, and the center difference scheme is used for the viscous fluxes. For time discretization, an approximately factored LU-SGS scheme has been used. The total implicit time preconditioning method is employed to eliminate the rigid problem.

Gupta's eleven species model is utilized to describe the non-equilibrium gas mixture as well as a series of models, such as Park's T-TV model[20] for vibration–dissociation coupling, the Landau–Teller model with Millikan and White's rates plus Park's modifying formula[21] for energy relaxation, Gupta's fit formula[22] for single species' transportation coefficients and Wilke's half experiential formula for the mixture's.

3. Waverider configuration and mesh

The high temperature effect upon the blunt reentry vehicles has been investigated early and a generally accepted view shows that the high-temperature effect makes the pressure center move forward with respect to the perfect gas expected results. However, as for the hypersonic vehicles with slender configuration, such as the high L/D ratio vehicle, namely the HTV-2 and the waverider, that the high-temperature effect makes the pressure center move forward or backward still needs further investigations.

The design methods of the waveriders are still quite hot in recent years and new design methods appear consecutively.[23–25] The design sketch of the conical waverider used for the geometric model in current research is shown in Fig. 1. The values of the design parameters are given in Table 1, where ϕ_{max}, R_s and R_0 stand for the max anhedral angle, the shock radius at the base plane and the distance between the midpoint of the trailing edge and the axis of the base cone respectively. This waverider is about 4 m in length, 2.2 m in width and 1.6 m in height, as is nearly the same size with HTV-2.

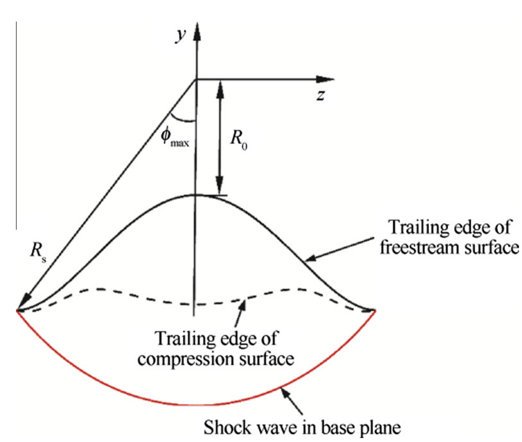

Fig. 1 Design sketch of the waverider.