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Three-Dimensional Hypersonic Laminar, Transitional, and/or Turbulent Shock-Layer Flows

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Introduction

HYPERSONIC flow past a blunt body has been the subject of numerous studies due to the importance in planetary entry technology. Numerical solutions to this problem have been either inviscid plus boundary-layer solutions,[1] viscous shock-layer solutions,[2] or full Navier-Stokes solutions.[3] It is shown in Ref. 3 that full Navier-Stokes equations are not necessary until the Reynolds number becomes very small. The shock-layer equations treat the entire flowfield from the body to the shock with a uniform set of equations. The problem associated with displacement thickness interaction and edge conditions, present in the inviscid plus boundary-layer approach, are thus eliminated. Consequently, the viscous shock-layer method treats all higher-order boundary-layer effects (displacement, vorticity interaction, longitudinal and transverse curvature, including proper matching conditions) in a straightforward and consistent manner.

Recently a numerical method for three-dimensional hypersonic flow over a blunt body was developed by Murray and Lewis.[2] The solutions were determined by using an implicit finite-difference scheme for solving the viscous shock-layer equations. However, this analysis is valid for laminar flow only. The main purpose of this study is to extend the development of the viscous shock-layer analysis applicable to predict laminar, transitional, and/or turbulent hypersonic flows of a perfect gas over a blunt body at angle of attack. The two-layer eddy-viscosity model proposed by Cebeci[4] and the transitional model developed by Dhawan and Narasimha[5] are used in this study. Comparisons are made with existing boundary-layer results and experimental data, and the agreement is good in all cases.

Basic Formulation

The basic equations are derived from the steady Navier-Stokes equations. The normal velocity v and normal coordinate η are assumed to be of order ϵ, and all terms which are of higher order than ϵ are neglected. The nondimensional turbulent governing equations of the body-oriented coordinate system are given in Ref. 6.

In order to solve the governing equations, it is essential to specify appropriate boundary conditions at the body surface and the shock. At the body surface (wall), no-slip and no-temperature-jump conditions were used. The conditions immediately behind the shock were obtained by using the Rankine-Hugoniot relations. The finite-difference method used to solve these equations is discussed in Ref. 2.

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Eddy-Viscosity and Transition Model

In turbulent flow, Reynolds stress is related to mean properties. A two-layer eddy-viscosity model consisting of an inner law based upon Prandtl's mixing-length concept and the Klebanoff expression for the outer law is used in the present investigation. This model assumes that the inner law is applicable for the flow from the wall outward to the location where the eddy viscosity given by the inner law is equal to that of outer law. The outer law is then assumed applicable for the remainder of the viscous layer. Reference 6 gives a more detailed description of the turbulent expressions used in the present study.

The distance between transition onset at x_{tr} and the beginning of fully turbulent flow further downstream at x_t is called the transition zone. Continuous transition is effected by a streamwise transition intermittency factor $\gamma_{i,\xi}$ which modifies the composite eddy viscosity ϵ^+ over an interval $\bar{x}$. The factor $\gamma_{i,\xi}$ is initially set to zero and is evaluated when the vorticity Reynolds number $\chi = n^2\rho/(\epsilon^2\mu)\partial u/\partial n$ exceeds a critical value χ_c. For the evaluation of $\gamma_{i,\xi}$ the relations $\gamma_{i,\xi} = 1 - \exp\ (-0.412\bar{s}^2)$, $\bar{s} = 2.96(s-s_0)/[s_0(\bar{x}-1)]$ are used. The approximate values of χ_c and $\bar{x}$ are strongly dependent upon the body slope and flow conditions being considered and are more appropriately defined by comparison with experimental data. A detailed discussion of these parameters is given in Ref. 6.

Results and Discussion

The governing equations and the implicit finite-difference scheme mentioned in the previous sections and developed in Ref. 2 have been applied to obtain solutions of laminar, transitional, and/or turbulent flows of perfect gases over a spherically blunted cone and a spike inlet diffuser at different angles of attack. Figures 1 and 2 present the convective heating rate along the body of a sphere-cone. Since experimental data are not available for this case, the present results are compared with a previous boundary-layer solution given by Anderson and Lewis.[1] The comparisons are in good agreement, and the results clearly show the higher-order boundary-layer effects (entropy-layer swallowing), especially for the turbulent calculation.

The convective heating rate results for case 2 (Fig. 2) are compared with experimental data given by Holden.[7] The

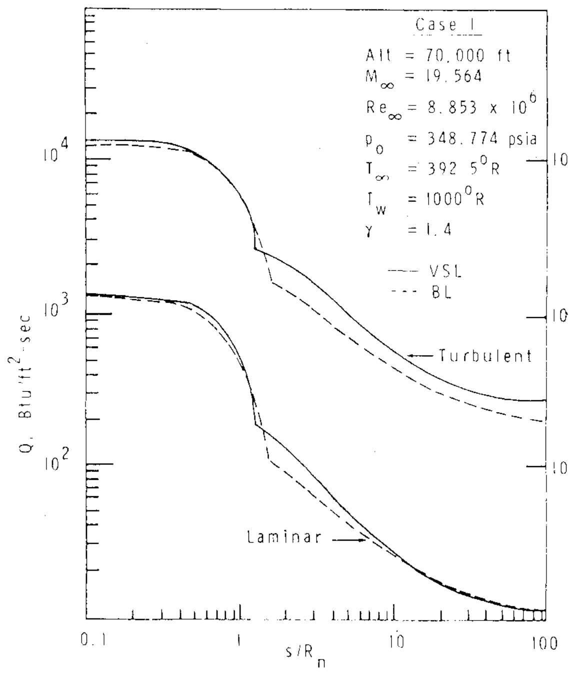

Fig. 1 Surface heat-transfer distribution ($\alpha = 0$ deg).

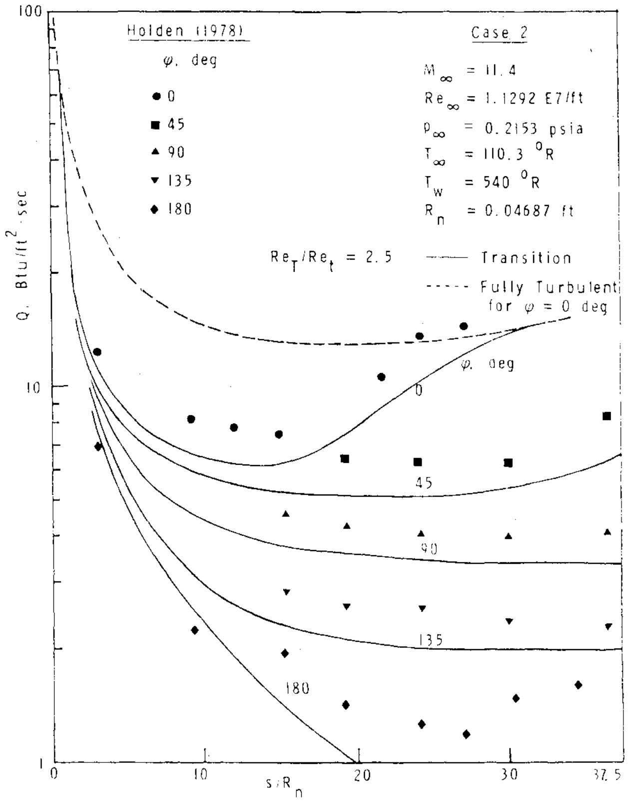

Fig. 2 Surface heat-transfer distribution ($\alpha = 2.93$ deg).

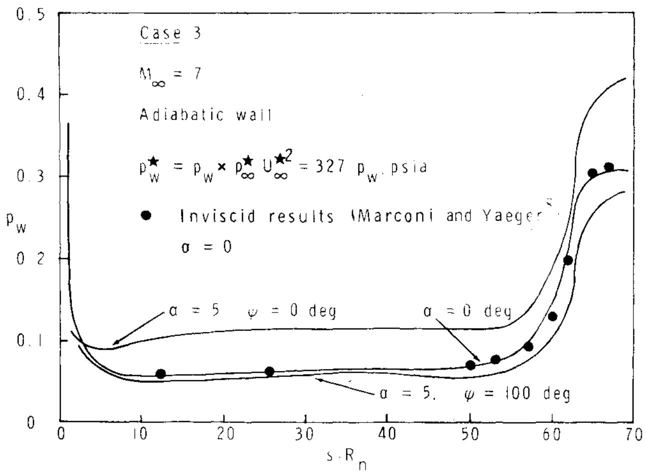

Fig. 3 Spike inlet surface pressure distribution ($\alpha = 0$ and 5 deg).

ratio ($\bar{x}$) of transition end-to-onset boundary-layer-edge Reynolds number is assumed to be 2.5. It is noted that the comparison is in reasonably good agreement, within 15% difference for all the planes (from windward side $\phi = 0$ to leeward side $\phi = 180$).

Figure 3 shows the surface pressure distribution from part of a spike inlet diffuser which is a spherically blunted cone with three different isentropic compression sections downstream of the cone at different Mach numbers and angles of attack. For the axisymmetric solutions ($\alpha = 0$ deg), the surface pressure increased from 19.63 psia in the cone region to 91.60 psia at the end of the compression region. For the angle-of-attack case in the windward plane ($\phi = 0$ deg), the surface pressure increased to 137.40 psia at the end of compression. The inviscid solutions from Marconi and Yaeger[8] are also presented and are in very good agreement with the viscous shock-layer calculations.

Conclusion

Numerical solutions for the three-dimensional viscous shock-layer equations for laminar, transitional, and/or turbulent flows are presented. The present solutions for both laminar and turbulent flows are in good agreement with boundary-layer solutions. The results clearly show the higher-order boundary-layer effects. The heating rate is approximately 15% lower than the experimental data. It is not clear why the experimental data are higher than the prediction. Equilibrium real-gas effects do not appear to be the cause, since the wind-tunnel conditions are essentially perfect gas.

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Effect of Radial Fins on Base Drag of an Axisymmetric Body at Low Speeds

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Introduction

It is well known that the total drag of an axisymmetric blunt based body of revolution, in general, consists of friction, wave, and base drag. It is the aim of the designer to eliminate or as far as possible minimize these retarding forces. Whereas the friction drag is essentially a function of the wetted area and the local Reynolds number, wave drag and base drag are strongly dependent on the shape of the vehicle. It is usually not possible to completely eliminate the base area on a missile/rocket or any other streamlined vehicle because of the necessity to accommodate the propulsion system and other related equipment in the base region. At low speeds, the base drag forms a major part of the total drag.

The axisymmetric base flow problem at low speeds has been a subject of study in recent years. References 1-6 represent

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