Three-Dimensional Nonequilibrium Viscous Shock-Layer Flows over Complex Geometries

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Abstract

RESULTS of numerical analyses of three-dimensional, nonequilibrium, viscous shock-layer flows over complex geometries are presented in this paper.[1] The viscous shock-layer code (VSLNEQ)[2] for analyzing nonequilibrium, multicomponent, ionizing airflow over sphere-cones has been extended to analyze multiconic geometries. The geometries considered for the analysis include straight and bent biconics and a sphere-cone-cylinder-flare with a moderate flare angle. This code is capable of analyzing shock-slip or no-shock-slip boundary conditions and fully catalytic or noncatalytic wall boundary conditions. The results from the nonequilibrium code have been compared with perfect gas and equilibrium air results. In general, the surface pressure distributions are in good agreement, whereas the nonequilibrium heat transfer is about 15% higher than the perfect-gas results. The aerodynamic forces and moments at the base of the bent biconic for various flow conditions are presented and they agree reasonably well with each other.

Contents

The viscous shock-layer method has been used by many previous investigators to solve practical engineering problems. The three-dimensional viscous shock-layer perfect-gas flows over blunt sphere-cones have been analyzed by Murray and Lewis[3] and their method has been extended to equilibrium air by Thareja et al.[4] The three-dimensional hypersonic laminar, transitional and/or turbulent shock-layer flows have been analyzed by Szema and Lewis.[5] Thareja et al,[6] extended the above method to analyze hypersonic laminar or turbulent flows in chemical equilbrium over the windward surface of a shuttle-like vehicle. The axisymmetric, nonequilibrium flows over blunt sphere-cones have been analyzed by Miner and Lewis[7] and the three-dimensional nonequilibrium flows over blunt sphere-cones have been analyzed by Swaminathan et al.[2] Kim et al.[8] extended the above method to analyze general bodies such as the Space Shuttle and the results agree very well with the flight data. The present paper extends the work of Swaminathan et al.[2] to analyze multiconics and bent biconics.

Since this code uses a body-oriented orthogonal coordinate system, the solution procedure[2] was modified to treat the geometrical discontinuities. The forecone is treated as a sphere-cone, and the aft cone is treated separately with the initial data plane profiles obtained from the forecone flowfield. At the expansion corners, the solution procedure is marched over an extension of the upstream geometry past the discontinuity for a streamwise length of 0.6 nose radii. Then the profiles at two computational stations are interpolated to obtain the initial data plane profiles for the aft cone. The velocity components are then transformed to the aft-cone coordinate system. At the compression corners, the solution procedure is marched up to the discontinuity, and the profiles at the last two computational stations on the forecone are used to obtain the initial data plane profiles for the aft cone.

For the bent biconic (Fig. 1), since the aft-cone axis is bent with respect to the forecone axis, the treatment is slightly different. Initially, the discontinuity is treated as a straight biconic and the initial data plane profiles for the aft cone are obtained by the procedures used for the expansion corners. Subsequently, the velocity components are transformed to the aft-cone coordinate system.

At the body surface, the no-slip and no-temperature-jump boundary conditions were imposed. Although the code has the capability of analyzing the adiabatic wall boundary condition, only the constant wall temperature option is excercised in the present paper. The wall can be fully catalytic or noncatalytic. The shock boundary conditions with slip are the modified Rankine-Hugoniot equations and are given in Ref. 2.

The multicomponent gas mixture was considered to be one of thermally perfect gases, and the thermodynamic and transport properties of each species were calculated using the local temperature. The properties for the gas mixture were then determined in terms of those of the individual species. In this study, the diffusion model is limited to binary diffusion. A multicomponent ionizing air mixture consisting of N, O, N_2, O_2, NO, NO+, and $e-$ is assumed to be the medium. It is asumed that the chemical reactions proceed at a finite rate,

Table 1 Force and moment coefficients for bent biconic

	α^a	CA	CN	CM^b	ZCP/L^b
PG	0	0.24316	0.15179	−0.06843	0.4508
PG	10	0.33425	0.39959	−0.18266	0.4571
NEQ	0	0.27199	0.13590	−0.06516	0.4793
NEQ	10	0.34733	0.38397	−0.17680	0.4605
NEQ	20	0.44640	0.69780	−0.30881	0.4425
EQBM	0	0.26910	0.14155	−0.06766	0.4779

[a]Measured from the aft-cone axis. [b]Measured from base of the body.

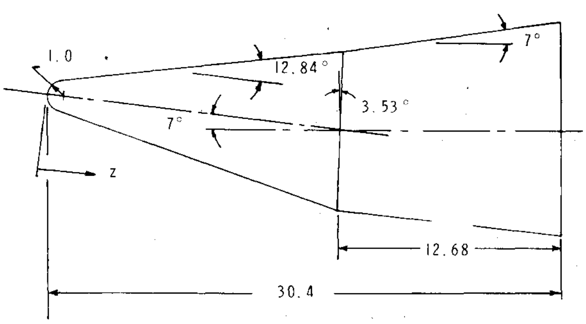

Fig. 1 Schematic of bent biconic.

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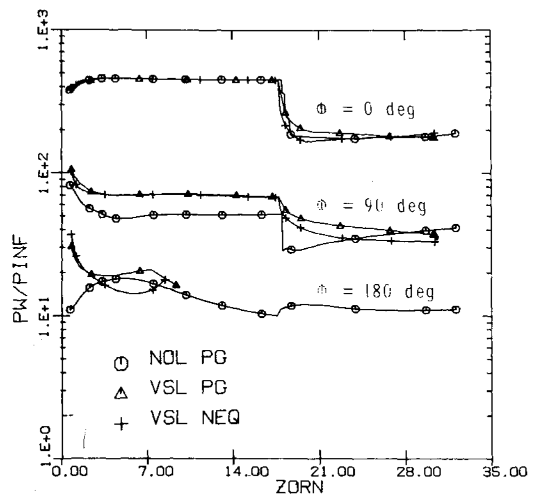

Fig. 2 Surface pressure distribution for bent biconic at $\alpha = 20$ deg.

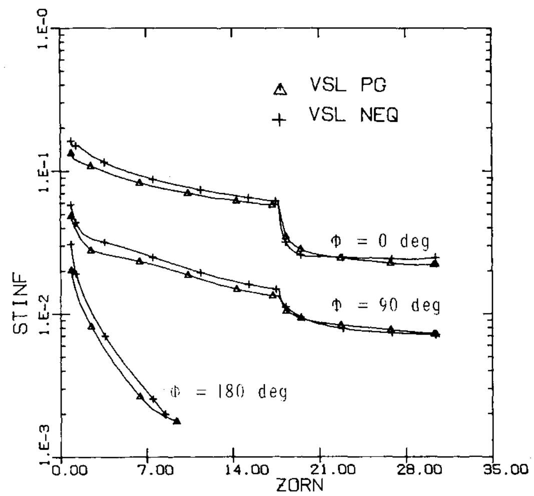

Fig. 3 Surface heat-transfer distribution for bent biconic for $\alpha = 20$ deg.

and the number of reactions and the reaction rate constants are based on Blottner's study.[9]

Sample results for the bent biconic are presented in this paper. The surface pressure distribution for the bent biconic is compared with those from the perfect-gas code[4] and from an inviscid code.[10,11] The surface heat-transfer distribution is compared with predictions from the perfect-gas code.[4] The surface pressure distribution for $\alpha = 20$ deg for various ϕ planes is presented in Fig. 2. In general, the surface pressure predictions by various codes are in good agreement. The viscous shock-layer method is parabolic in the cross-flow direction as well as the streamwise marching direction, and hence the VSL3D method cannot treat cross-flow separation. This VSLNEQ code has been written in such a way that the separated flowfield is not analyzed.

Figure 3 shows the surface heat-transfer distribution for $\alpha = 20$ deg for various ϕ planes. The nonequilibrium calculations have been performed assuming fully catalytic wall boundary conditions. The nonequilibrium heat-transfer rate is higher on the forecone, whereas on the aft cone the agreement is better. Table 1 shows the force and the moment coefficients for the bent biconic. The computing time required to solve the bent biconic was about 3 min for perfect-gas flow and about 16 min for nonequilbrium flow using an IBM 3081, H = OPT2 compiler.

In conclusion, a code for analyzing three-dimensional nonequilibrium flows over straight multiconics and bent biconics has been developed. The surface pressure distributions over the bent biconic agree well and the heat-transfer rates are about 15% above those predicted by other perfect-gas codes. The aerodynamic force and moment coefficients at the end of the body for the bent biconic have been computed.

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