Viscous Hypersonic Flow Past Blunted Cones at Small Angles of Attack

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Theme

VISCOUS hypersonic flow over spherically blunted cones of large half angles is calculated at small angles of attack in the plane of symmetry of the flowfield. Time-dependent viscous shock-layer equations in body-oriented coordinates are used to describe the flowfield. The shock wave is treated as a discontinuity, across which the shock relations are used to compute the flow conditions behind the shock. A time-dependent second-order finite-difference method is used to solve the equations for a perfect gas. The local Courant-Friedrich-Lewy time increment is used to advance the solution in time at each grid point. A fourth-order damping is used to damp the oscillations in the flow quantities. The numerical results of the present analysis for quantities such as shock standoff distance, surface pressure distribution, and heating rates compare well with the existing theoretical and experimental results.

Contents

The flow over blunted cones has been the subject of numerous studies due to its importance in planetary entry technology. The effect of angle of attack on detailed flow structure, heat transfer, and surface pressure distribution has been investigated at high speeds. However, these investigations generally are limited to cone half angles of 15° or less,[1,2] and for cones with large half angles, the studies are limited mostly to zero angle of attack. The purpose of the present investigation is to study the viscous flow over spherically blunted cones of large half angles at small angles of attack.

Time-dependent viscous shock-layer equations in body-oriented coordinates are used to describe the flowfield. Solutions are obtained for a perfect gas in the plane of symmetry of the flowfield. The crossflow momentum equation is used and crossflow terms are retained in all of the flow equations. Since the crossflow velocity is identically zero in the symmetry planes, the crossflow momentum equation cannot be used directly; however, the required equation is obtained by differentiating the momentum equation with respect to the crossflow direction. The crossflow velocity gradient then is used as the new dependent variable.

Two independent-variable transformations are applied to the governing equations. The first transformation maps the computational domain into a rectangular region in which both the shock and the body are made boundary mesh lines. The second transformation further maps the rectangular region into another plane to allow higher resolution near the body surface. This is desirable for the accurate calculation of skin-friction and heating rates without too many points in the normal direction.

A time-dependent finite-difference method of MacCormack[3] is used to solve the equations. This explicit two-step method has second-order accuracy in both space and time. Since the transient solution of the problem is of no interest in the present analysis, the Courant-Friedrich-Lewy (CFL) stability condition, which provides the largest possible time step for all of the grid points in the computational region for the transient problems, is not followed strictly. Rather, the solution is marched in time at each grid point according to its largest possible CFL time step. This results in faster convergence of the solution. It is found in the present analysis that the solution exhibited large oscillations across the shock layer. These oscillations are also present in the results given by Li[4] for zero angle of attack. The undamped solution could not be run for a large number of time steps because of the oscillations which grew with increasing time and resulted in the solution blowing up. A fourth-order damping technique is used to damp these oscillations in the flow quantities.

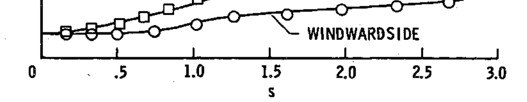

Fig. 1 Shock standoff distance for a 30° half-angle cone at 10° angle of attack.

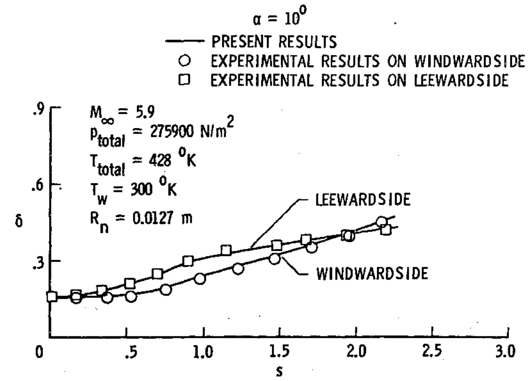

Fig. 2 Shock standoff distance for a 45° half-angle cone at 10° angle of attack.

Received Jan. 17, 1977; presented as Paper 77-172 at the AIAA 15th Aerospace Sciences Meeting, Los Angeles, Calif., Jan. 24-26, 1977; synoptic received March 14, 1977; revision received April 29, 1977. Full paper available from AIAA Library, 750 Third Avenue, New York, N.Y. 10017. Price: Microfiche, $2.00; hard copy, $5.00. **Order must be accompanied by remittance.**

Index categories: Supersonic and Hypersonic Flow; Viscous Nonboundary-Layer Flows.

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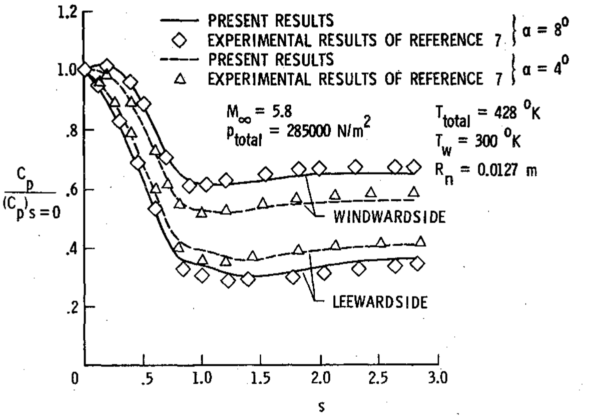

Fig. 3 Surface pressure distribution for a 40° half-angle cone at 4 and 8° angles of attack.

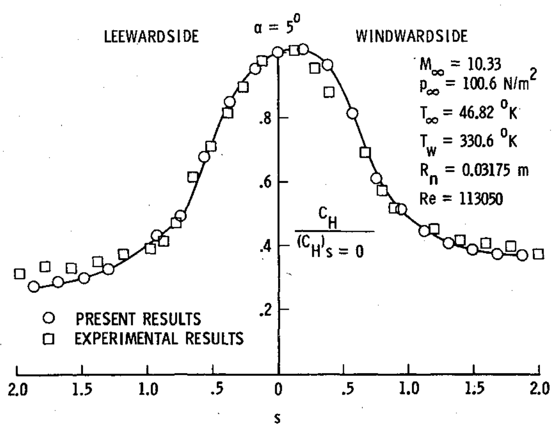

Fig. 4 Heating rate distribution for a 45° half-angle cone at 5° angle of attack.

Removal of these oscillations allowed the solution to reach steady state. The details of the formulation and method of solution are given in Ref. 5.

It is found in the present analysis that the quantities such as shock standoff distance and surface pressure are converged fairly well in less than a thousand time steps, but the heating rate requires a much larger number of time steps to reach the steady-state value. This is because the time increment for the grid points near the body surface is much smaller as compared to the time increment for the grid points near the shock wave.

Figures 1 and 2 show the distribution of shock standoff distances δ against the distance along the body s for 30° and 45° half-angle cones at 10° angle of attack. s and δ are nondimensionalized with respect to the nose radius R_n. The experimental results of Calloway[6] also are plotted. It is seen that the present results are within 5% of the experimental results. For a blunt body at angle of attack, the shock standoff distance on the leeward side is expected to be larger than on the windward side. This is seen to be true in Fig. 1 for a 30° half-angle cone; but, for a 45° half-angle cone, Fig. 2 shows that at the downstream portion of the body, the shock standoff distance on the windward side becomes larger than on the leeward side. Experimental results also exhibit the same behavior.

In Fig. 3, surface pressure distributions are compared with the experimental results of Ref. 7 for a 40° half-angle cone at 4 and 8° angles of attack. The results of the present analysis are within 5% of the experimental values.

Figure 4 shows the comparison of heating rate for a 45° half-angle cone at 5° angle of attack with the preliminary data of experiments conducted by Throckmorton.[8] The maximum difference is seen to be about 10% at the downstream points of the body.

The results of this investigation were obtained on a Cyber 175 computer. About 15 min are needed for a zero-angle-of-attack case, and about 40 min are needed for an angle-of-attack case. The program has been rewritten for a CDC-STAR-100 computer and an angle-of-attack case now requires about 4 min. The present analysis can be applied for computing the flowfield past other axisymmetric bodies like hyperboloids and paraboloids at angle of attack.

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