Complete Supersonic Flowfields over Blunt Bodies in a Generalized Orthogonal Coordinate System

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Abstract

THE material presented herein is a continuation of a research effort[1] which is directed toward developing a computer code which can compute full Navier-Stokes solutions around complete probelike configurations for a wide range of supersonic Mach numbers and Reynolds numbers. A key feature of this code is that it is programmed in a general orthogonal coordinate system[2] which can be used to describe many different axisymmetric and two-dimensional shapes and can closely approximate planetary probe configurations. The advantage of such an approach is that it allows one to study realistic configurations in a computational field with easily implemented boundary conditions and a relatively simple coding effort. The governing equations for the laminar flow of a perfect gas are discretized using Cheng and Allen's[3] method. The code is equipped to capture the bow shock or to treat it as a discontinuity which floats in the computational field. Both body and shock slip boundary conditions can be implemented.

Good comparisons with experimental data and with other numerical methods have been achieved with this program using a grid of 51×50, some examples of which follow. Results on this grid remain consistently good for an approximate Reynolds number range $Re_\infty \leq 0(10^4)$. As this limit is exceeded, some unexpected problem areas are encountered. Some of these problem areas are also discussed and possible causes and remedies are suggested. On the basis of this "total picture," the present code is considered a final product for the indicated Reynolds number range. For larger Reynolds numbers, these results suggest that the complexities associated with a nonorthogonal, nonanalytic coordinate system may be offset by the benefits of being able to make the computational mesh coarse or fine where needed.

Contents

Comparisons between the present method and experimental results of Tewfik and Giedt[4] for pressure distribution and heat transfer on a cylinder are presented in Figs. 1 and 2. Shock and body slip conditions were used although the calculated effects of shock slip were negligible. The static pressure distribution along the wake centerline of a cylinder is compared to experimental data of McCarthy and Kubota[5] in Fig. 3. The distributions near peak centerline pressure are also plotted for the previous cases and for a sphere to illustrate the effect of Reynolds number and shape. The overprediction of pressure downstream is most likely due to a lack of resolution in the numerical technique in that region because experimental data for a laminar wake show a dip in the transverse pressure distribution which cannot be resolved in the present computational grid.

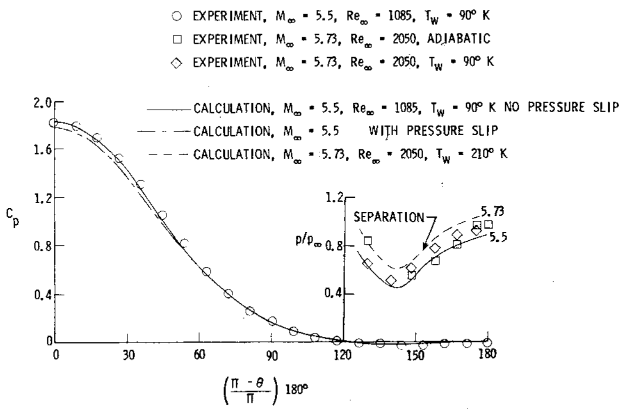

Fig. 1 Distribution of C_p and p/p_∞ over cylinder, $T_0 = 300$ K.

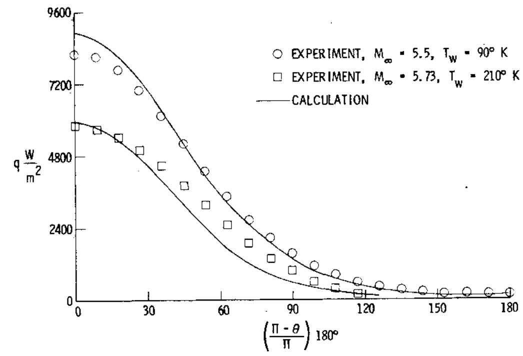

Fig. 2 Distribution of q over cylinder: $M=5.5$, $Re=1085$, $T_w/T_0=0.3$, $T_0=300$ K; $M=5.73$, $Re=2050$, $T_w/T_0=0.68$, $T_0=300$ K.

Calculations have been made for supersonic flow over an approximation to the Viking Aeroshell ($\gamma=1.285$, $Pr=0.685$). The recirculation pattern from one of these calculations is presented in Fig. 4. Supersonic recirculation velocities on the axis of symmetry were calculated for $M_\infty=2$, $Re_\infty=1000$, 5000, 30,000, and $M_\infty=5$, $Re_\infty=5000$. For $M_\infty=2$, $Re_\infty=1000$, sonic velocity was just achieved in the recirculation region, and as the Reynolds number was increased, a Mach number of approximately 1.4 was attained and a small shock formed 0.4 nose radii away from the base, with a radius of approximately 0.25 nose radii. The recirculation shock strengths for $M_\infty=5$, $Re_\infty=5000$, and $M_\infty=2$, $Re_\infty=1000$ are almost equal, suggesting that such phenomena are a function of $M_\infty/\sqrt{Re}$, although more calculations are needed to confirm the relation. A calculation by Erdos and Zakkay[6] for supersonic flow over a wedge in which nearly supersonic recirculating velocity was reported is the only other mention of large recirculating velocity that was found in the literature. They conclude that the recirculation velocity varies directly with the vorticity entering the region up to some choking condition in the flow. Still, the calculation

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Index categories: Computational Methods; Jets, Wakes, and Viscid-Inviscid Flow Interactions; Viscous Nonboundary-Layer Flows.

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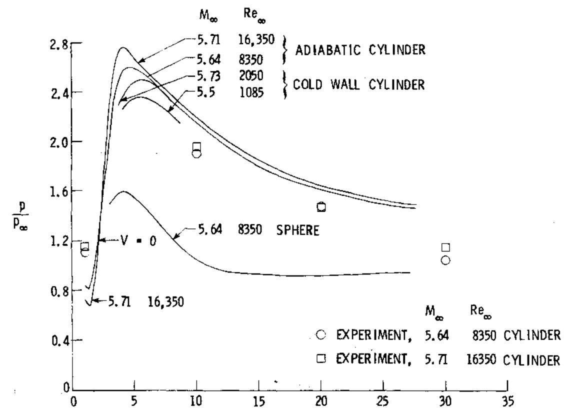

Fig. 3 Static pressure distribution on wake centerline.

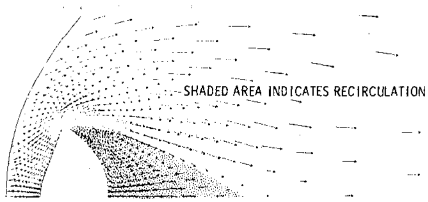

Fig. 4 Velocity vectors over Viking Aeroshell, $M_\infty = 2$, $Re_\infty = 5000$.

of this "recirculation shock" is a disturbing development, even though the magnitudes of pressure and density are small in its vicinity. It is suspected that the given grid is too coarse to properly resolve the free shear layer over its entire length, bringing in more momentum from the outer flow and raising the stagnation pressure on the line of symmetry. Such a numerical phenomenon is consistent with the results of Fig. 3 and could drive the recirculating velocities up, though clearly more investigation is needed in this area.

A calculation was attempted for $M_\infty = 5$, $Re_\infty = 30{,}000$. This case could not be run to convergence because negative densities and enthalpies were calculated near the wall just below the corner of the probe. The expansion around the corner was extremely severe. Even a half cell away from the body, the velocity was supersonic. Increased resolution near the body made this problem worse. A mesh spacing that was just fine enough to resolve the boundary layer in the forebody was less than the mean-free path immediately behind the expansion corner. There is a rapid compression at the wall following the expansion, the flow becomes subsonic, and then separates. This behavior may be due to the formation of a lip shock, normal to the body, immediately below the expansion corner. This shock could not be captured with the present distribution of node points in a tangential direction and with the present formulation of the boundary conditions. The numerical undershoot of properties on the low-pressure side of a shock that occurs with shock capturing would then explain the calculation of negative enthalpies, in which case it would become necessary to "float" the lip shock rather than smear it over several mesh points and thus destroy the detail of the flow in this region. There is also some evidence[7] that when one goes below a certain critical mesh Reynolds number, the computed results can be distorted as in this expansion region, in which case some readjustment of the coordinate system would be required locally. As indicated earlier, it appears that the best approach for resolving these problem areas for the large Reynolds number calculations is to implement a more versatile, nonorthogonal grid structure. The present formulation should be used for the lower Reynolds number cases [$Re_\infty \lesssim 0(10^4)$] for initializing the high Reynolds number cases and for giving a first approximation of where fine or coarse grids are needed in those situations.

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