Knudsen Layer Characteristics for a Highly Cooled Blunt Body in Hypersonic Rarefied Flow

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Abstract

RESULTS are presented summarizing the first detailed Knudsen-layer characteristics at $\lambda_\infty/R_N=0.75$ (freestream mean free path normalized by the spherical nose radius, R_N) for a cold wall ($T_W/T_\infty=2$) at Mach 26 using a Monte Carlo (MC) code developed for a virtual memory minicomputer. Flow profiles are in reasonable agreement with previous Monte Carlo results outside the Knudsen layer, but differ appreciably from continuum predictions with boundary conditions simulating rarefied flow effects of shock slip and body slip. MC results for slip velocity and temperature jump at the wall are considerably lower than predicted by slip models used in the continuum codes. Breakdown of the continuum description for heat transfer and shear stress in the Knudsen layer is documented at the rarefied flow conditions corresponding to a Reynolds number $Re_\infty=65$, based on R_N.

Contents

Previous studies[1] of this flowfield using a kinetic theory MC code have shown large differences in the near-surface flow profiles and surface measurable quantities compared to continuum calculations for conditions including no-slip and various slip boundary assumptions. Resolution of the flow in the Knudsen layer with the MC code operating on a large mainframe computer was not feasible; consequently the basis for the discrepancies between the theoretical approaches could not be isolated.

A new kinetic theory MC flow code was developed for application to blunted shapes by McGregor[2] in conjunction with Bird[3]; this code used to advantage the virtual memory capability and cost effectiveness of the Digital Equipment Corporation VAX minicomputer to allow substantial increases in the number of computational cells for improved flowfield resolution. The radial cell spacing was selected to provide an average of 15 cells in the Knudsen layer; 13 cells were located in the stagnation region, increasing to 21 near the aft portion of the spherical nose. A variable cell size distribution and modified weighting factor option[3] were specified to provide high resolution of the flow within the Knudsen layer, together with gradients in the shock layer and outer disturbance layer. A relatively small time step was determined to satisfy the requirement that the molecules move less than the minimum cell dimension between collisions. A relatively uniform number of simulated molecules per cell (12) was obtained; minimums of five simulated molecules were obtained in the outer flow region. These numbers were sufficient to provide a realistic collision frequency, and a practical, albeit long, computer run time. Results obtained in this study were for hard sphere modeling for a perfect diatomic gas; the two degrees of freedom associated with internal energy are represented by the rotational mode (vibration neglected); diffuse reflection with full thermal accommodation for molecules striking the body surface; axisymmetric flow.

Continuum solutions of the parabolized Navier-Stokes equations, using the VSL3D flow code, were obtained[1] for boundary conditions simulating rarefied flow effects of a viscous shock ("shock slip"), surface temperature jump, and velocity slip ("body slip"). VSL3D predictions were compared with MC results and an evaluation of the Chapman-Enskog formulation[4] for heat transfer and shear stress (neglecting bulk viscosity and other higher order terms) using the MC data and assuming a Prandtl number of 0.71.

Results

Temperature ($\bar{T}=T_{av}/T_{0\infty}$, MC average temperature over five degrees of freedom normalized by freestream stagnation temperature) profiles normal to the surface (Y/R_N) at $s/R_N=1.4$ (s is surface distance from the stagnation point) near the aft of the nose from the present study are compared to previous MC and VSL3D results[1] for the same flow conditions in Fig. 1. Reasonable agreement within the high compression region near the body is indicated between the MC solutions; VSL3D predictions using the two slip conditions differ substantially in both trend and magnitude with the MC data in the Knudsen layer. Temperature jump is indicated by the difference in the wall value $\bar{T}_w=0.015$ and the mean of the MC data near the surface $\bar{T}=0.105$, shown in Fig. 1a.

The tangential velocity ($\bar{U}=u/U_\infty\cos\theta$, MC mean tangential velocity normalized by freestream velocity tangent to the surface) profile at $s/R_N=1.4$ is compared to the previous study results in Fig. 1b. Comparisons are similar to the $\bar{T}$ profiles; a slip velocity $\bar{U}_{slip}=0.070$ is apparent as the mean of the data near the surface. VSL3D results for shock combined with body slip considerably overpredict the MC slip velocity and temperature jump, demonstrating the failure of present slip modeling, which is based on assumptions of small departure from thermodynamic equilibrium.

Heat transfer defined as the Stanton number (S_t) and skin-friction coefficient (C_f) distributions are compared with previous results[1] in Fig. 2. Reasonable correlation of the MC data is shown for $s/R_N>0.6$; the present MC results provide somewhat larger mean values (about the scatter) of S_t and C_f over the aft half of the spherical nose. This difference is attributed to the larger nonequilibrium influence on the energy and momentum fluxes in this region obtained with the Larson-Borgnakke collision model used in the present code. VSL3D predictions with shock slip are in agreement with the present

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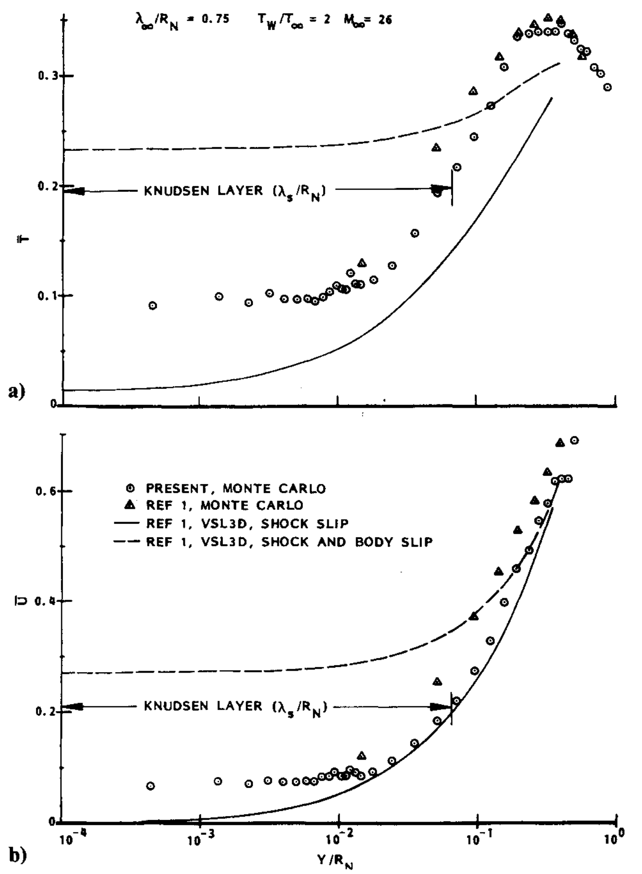

Fig. 1 **Flow profiles at $s/R_N = 1.4$; a) temperature and b) tangential velocity.**

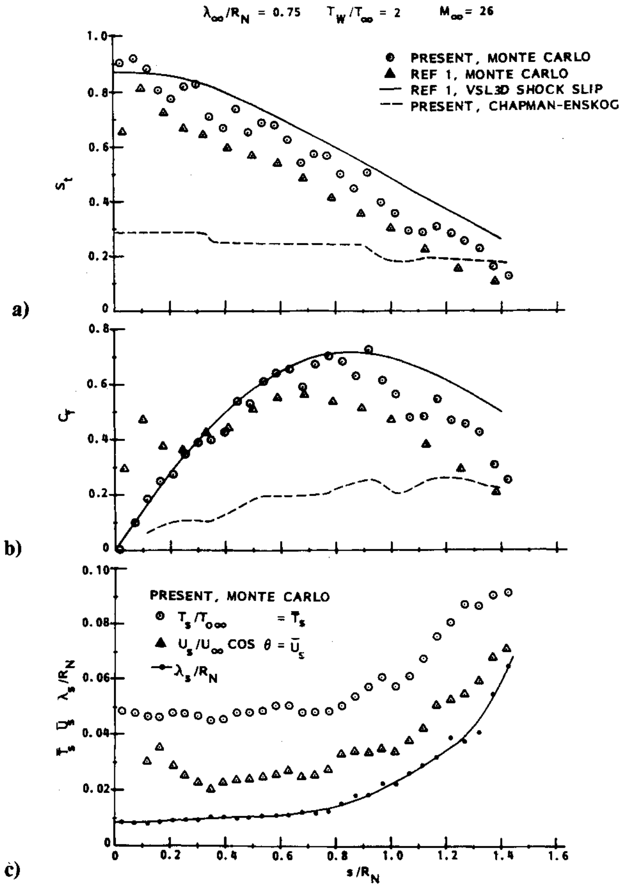

Fig. 2 Distributions of a) surface heat transfer, b) surface skin friction, and c) near-surface gas properties.

results; in contrast to the poor agreement of profiles in the Knudsen layer. The apparent disparity between continuum predictions and MC results can be reconciled by evaluating S_t and C_f from the Chapman-Enskog theory using smoothed MC profiles and the variable hard sphere (VHS) molecular model[5] for transport properties of the gas, assumed in thermodynamic equilibrium. MC $\bar{T}$ profiles for $s/R_N < 1.1$ were relatively smooth throughout the Knudsen and shock layers, thereby providing excellent resolution for the heat-transfer coefficient from the continuum theory, labeled "Chapman-Enskog" in Figs. 2a and 2b. MC $\bar{U}$ profiles were not defined as well for $s/R_N < 0.3$ because of the scatter in the relatively small component of total velocity in the Knudsen layer; consequently, C_f evaluation from the continuum theory (Fig. 2b) is subject to more uncertainty than for S_t. Significant underprediction of S_t and C_f is shown over the nose, demonstrating the breakdown of continuum theory in the Knudsen layer for rarefied transitional flow.

Gas properties in the Knudsen layer extrapolated to the wall (designated with subscript s) from the present MC results are presented in Fig. 2c. The $\bar{T}_s$ and $\bar{U}_s$ distributions along the surface are correlated with the variation of mean free path λ_s determined for an equilibrium gas from the VHS model [5]

$$\lambda_s = 1/(\sqrt{2}(\rho_s/\rho_\infty)\eta_\infty \pi d_{\text{eff}}^2) \tag{1}$$

where ρ is the gas mass density, η the number density, d_{eff} the effective molecular diameter based on the measured coefficient of viscosity of the gas, and subscript ∞ denotes freestream value.

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