Rarefaction Effects for Hypersonic Re-Entry Flow

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The direct simulation Monte Carlo (DSMC) method is applied to simulate one-dimensional flow along the stagnation streamline. The freestream conditions considered are those encountered by the nose region of the Space Shuttle Orbiter during the hypersonic re-entry. The range of altitudes considered in the present calculations covers continuum to the less rarefied portion of the transition flow regime. The calculations account for thermal as well as chemical nonequilibrium effects. The effect of shock location on the flow structure and stagnation point heat transfer is analyzed for specific altitude; consequently, these results are appropriate for hemispherical bodies with different nose radii.

Contents

THE DSMC method models the real gas by some thousands of simulated molecules in a computer. The position coordinates, velocity components, and internal state of each molecule are stored in the computer and are modified with time as the molecules are simultaneously followed through representative collisions and boundary interactions in simulated physical space. The time parameter in the simulation may be identified with physical time in the real flow and all calculations are unsteady, although steady flow is obtained as the large-time state of the unsteady flow. A computational cell network is employed in real space for the selection of collision pairs and the sampling of flow properties. The intermolecular collisions are dealt with on a probabilistic rather than a deterministic basis. The stability problems are completely absent in this method.

The computational requirements would be very large if multidimensional calculations were employed in the continuum regime. Therefore, a one-dimensional version of the DSMC method is used to efficiently simulate the flow along the stagnation streamline. The stagnation streamline is modeled as a constant area flow with undisturbed freestream molecules entering at one end and a solid surface at the other end (Fig. 1). Initially, the flow is undisturbed freestream, and then an unsteady shock wave propagates from the surface as the freestream molecules are introduced. At some stage, molecules are removed from the sides of a downstream section of the flow (the section between the solid surface and the specified center of the shock wave) such that the exit number flux equals the inlet flux. The flow then settles down to a steady state, and all the conservation equations of the flow are satisfied as long as the section over which the molecules are removed corresponds to the region between the shock and the surface. This is the simulation of the steady flow along the stagnation streamline of the blunt body. The appropriate set of molecules for removal is achieved by removing them with the probability proportional to the square of the velocity component normal to the freestream.[2]

The region over which the molecules are removed must be specified. Molecule removal starts at the point within the shock wave where the density is equal to the mean density across the shock wave. For the present calculations, the mean density is assumed to be six times the freestream density. The molecular distribution is assumed to be equilibrium upstream of the specified shock location for the theory to be valid.

Results

The freestream conditions and the wall temperature are those experienced by the nose region of the Shuttle Orbiter during re-entry.[3] In addition, the wall is assumed to be diffuse, with full thermal accommodation, and finite catalytic in nature.

Figure 2 shows the density profiles along the stagnation streamline at an altitude of 74.98 km for different shock locations, where ρ is the density, η is the coordinate along the stagnation streamline, and η_s is the shock standoff distance. It can be seen from these density profiles that the shock wave merges with the viscous layer when the shock wave is very close to the stagnation point. The same merging behavior occurs for the larger shock standoff cases, as the altitude is increased.[3] A large increase in density occurs near the wall that is characteristic of the cold wall re-entry conditions. Thermodynamic nonequilibrium is evident in Fig. 3, where the shock wave and the outer part of the shock layer cannot be characterized with a single temperature. The translational temperature rise is quite rapid and always precedes the density rise. This initial rise in the translational temperature is due to the bimodal velocity distribution: the molecular sample consisting of mostly undisturbed freestream molecules, with just a few molecules that have been affected by the shock. The large velocity separation between these two classes of molecules gives rise to the early translational temperature. The extent of thermodynamic nonequilibrium increases with rarefaction, i.e., the collision rate decreases with increasing altitude.

The shock wave region is a region of very high chemical activity. Also, a significant amount of dissociation occurs upstream of the peak temperature. For a given shock location, the amount of dissociation decreases with increasing altitude and the flow eventually approaches a chemically frozen state with increasing altitude.

The stagnation point convective heat transfer rate q, as a function of shock location η_s, is shown in Fig. 4 for the various altitudes. It can be seen from this figure that the heat

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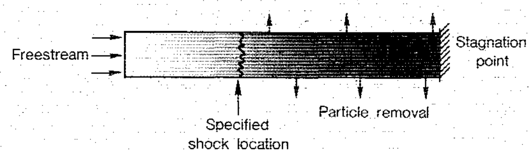

Fig. 1 Stagnation streamline representation for DSMC simulations.

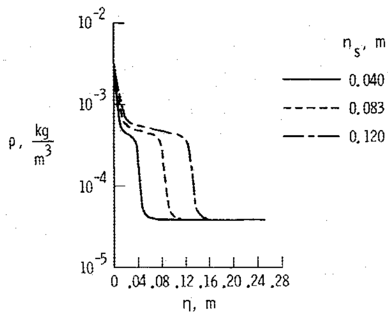

Fig. 2 Density profiles along the stagnation streamline (Alt = 74.98 km).

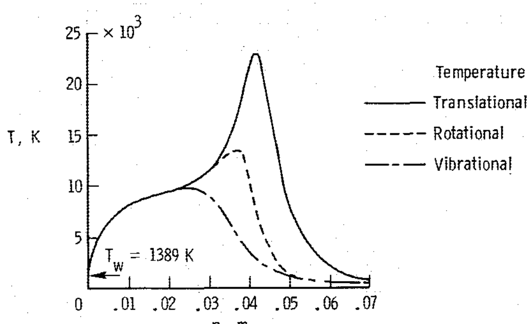

Fig. 3 Extent of thermodynamic nonequilibrium ($\eta_s = 0.04$ m).

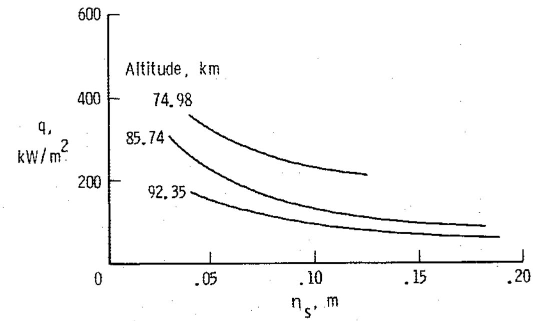

Fig. 4 Stagnation point heat transfer vs shock location.

transfer rate increases as the specified shock standoff distance is reduced for a given altitude. This is due to the increase in the temperature gradients near the surface as the shock standoff distance decreases. Also, the heat transfer rate for a given shock standoff distance decreases with increasing altitude because of the decrease in the density.

These results illustrate that even in what is normally considered continuum flow, the shock wave region can have a significant amount of rarefaction effects in terms of thermal and chemical nonequilibrium. A major advantage of the one-dimensional DSMC method is that it reduces the computational task considerably and still provides important information concerning the flow, even when the flowfield is predominantly continuum.

References

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