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RAREFIED FLOW PAST A FLAT PLATE AT INCIDENCE

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Abstract

Results of a numerical study using the direct simulation Monte Carlo (DSMC) method are presented for the transitional flow about a flat plate at 40 degree incidence. The plate has zero thickness and a length of 1.0 m. The flow conditions simulated are those experienced by the Shuttle Orbiter during reentry at 7.5 km/s. The range of freestream conditions are such that the freestream Knudsen number values are between 0.02 and 8.4, that is, conditions that encompass most of the transitional flow regime. The DSMC simulations show that transitional effects are evident when compared with free molecule results for all cases considered. The calculated results demonstrate clearly the necessity of having a means of identifying the effects of transitional flow when making aerodynamic flight measurements as are currently being made with the Space Shuttle Orbiter vehicles. Previous flight data analyses have relied exclusively on adjustments in the gas-surface interaction models without accounting for the transitional effect which can be comparable in magnitude. The present calculations show that the transitional effect at 175 km would increase the Space Shuttle Orbiter lift-drag ratio by 90 percent over the free molecular value.

Nomenclature

C_D	drag coefficient, $2D/\rho_\infty U_\infty^2 \ell$
C_F	skin-friction coefficient, $2F/\rho_\infty U_\infty^2 \ell$
C_H	heat-transfer coefficient, $2q/\rho_\infty U_\infty^3$
C_L	lift coefficient, $2L/\rho_\infty U_\infty^2 \ell$
C_p	pressure coefficient, $2p/\rho_\infty U_\infty^2$
D	drag force
F	skin friction
K_{N_∞}	freestream Knudsen number, λ_∞/ℓ
L	lift force
ℓ	length of the flat plate
$\overline{M}$	molecular weight of air
p	pressure
q	heat flux
R	universal gas constant, R = 8.3143 J/mol.K
S_∞	freestream speed ratio, $U_\infty \sqrt{\overline{M}}/2RT_\infty$
T	thermodynamic temperature
T_∞	freestream temperature
Tw	surface temperature
U_∞	freestream velocity
u	velocity component tangent to the plate surface
v	velocity component normal to the plate surface
x	coordinate measured along the plate surface
y	coordinate measured normal to the plate surface
α	angle of incidence
ε	fraction of specular reflection
λ_∞	freestream free path

ρ_∞ freestream density

ρ density

Introduction

The development and application of future hypersonic space vehicles require accurate predictions of aerothermal loads during reentry. A portion of the reentry for these vehicles will take place in the transitional flow regime where nonequilibrium effects become important in establishing the thermal and aerodynamic response of these vehicles. In order to simplify the computational requirements, the lift-drag characteristics for vehicles such as the Space Shuttle Orbiter are often approximated[1-2] with a flat plate at incidence for the free molecular regime. For the transitional flow regime, empirical approximations are normally used to predict the aerodynamic forces for such vehicles. Examples of such applications are given in Refs. 1, 2, and 3 for the Space Shuttle Orbiter. Therefore, numerical studies on basic configurations such as a plate at incidence can provide useful information and physical insight concerning the nature of transitional flows.

A flat plate as a basic aerodynamic surface has remained the focus of the transitional flow research by several authors [Refs. 4-8]. But most of these investigations are for zero incidence and do not cover the range of flow parameters of interest. There are very few experimental and theoretical investigations of the flat plate at incidence [Refs. 9 and 10]. Even these do not cover the large incidence and high speed ratio characteristics of hypersonic flight. Furthermore, they are limited to the continuum flow regime.

In the present paper the direct simulation Monte Carlo (DSMC) method of Bird,[10-11] with the variable hard sphere (VHS) molecular model, is used to simulate the transitional flow past a flat plate at 40 degree incidence. The flow conditions and incidence angle simulated are those which the Space Shuttle Orbiter experiences during reentry. The DSMC is the only suitable numerical technique to simulate the transitional flow regime accurately because it allows the direct implementation of nonequilibrium flow models. The various nonequilibrium phenomena are the main characteristics of the transitional flow regime, and the DSMC method simulates the flow physics adequately. The present calculations show that the transitional effect for a diffuse surface would increase the Space Shuttle lift-drag ratio by 90 percent over the free molecular value at approximately 175 km altitude.

Computational Approach

The DSMC method[11-12] 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 concurrently 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. When the boundary conditions are such that the flow is steady, then the solution is the asymptotic limit of unsteady flow. The computation is always started from an initial state that permits an exact specification such as a vacuum or uniform equilibrium flow. Consequently, the method does not require an initial approximation to the flowfield and does not involve any iterative procedures. A computational cell network is required in physical space only, and then only to facilitate the choice of potential collision pairs and the sampling of the macroscopic flow properties. Furthermore, advantage may be taken of flow symmetries to reduce the dimensions of the cell network and the number of position coordinates that need to be stored for each molecule, but the collisions are always treated as three-dimensional phenomena. The boundary conditions are specified in terms of the behavior of the individual molecules rather than the distribution functions. All procedures may be specified in such a manner that the computational time is directly proportional to the number of simulated molecules.

Conditions for Calculations

The freestream conditions considered in the present study are for an altitude range of 90 to 130 km. For the 1.0-m flat plate with zero thickness, the corresponding freestream Knudsen numbers are 0.023 to 8.439. During the Shuttle's reentry trajectory, the same freestream Knudsen numbers based on the mean aerodynamic chord of 12 m correspond approximately to an altitude range of 100 to 175 km. The freestream velocity, incidence angle, and wall temperature are assumed constant at 7.5 km/s, 40 deg, and 1000 K, respectively, that is, conditions experienced by the Space Shuttle Orbiter during reentry. These conditions are summarized in Table 1, where the freestream values are those given by Jacchia[13] for an exospheric temperature of 1200 K.

The surface of the plate is assumed to be diffused with full thermal accommodation and to promote recombination of the oxygen and nitrogen atoms. Recombination probabilities appropriate for the Shuttle thermal protection tiles are imposed. The oxygen and nitrogen recombination probabilities are 0.0049 and 0.0077, respectively.

Since the computational requirements increase significantly with increasing freestream density, computations are performed only in the transitional flow regime.

Results and Discussion

Since the flat plate at incidence is a basic element of lifting surfaces, it is often used for numerical and experimental studies in hypersonic flow research. Furthermore, the configuration is also helpful in understanding the reentry of space vehicles such as the Space Shuttle Orbiter. Therefore, attention is focused on the flow structure, surface quantities, and aerodynamic characteristics resulting from low-density flow about a flat plate at 40 degree angle of attack (Fig. 1).

Flowfield Structure

Figures 2 to 7 present calculated flowfield quantities on the compression side (lower surface) of a flat plate at two freestream Knudsen numbers (0.023 and 8.439). Results at three different locations along the surface are presented. Two regions of interest are those near the plate surface and the shock wave. Near the surface, a large increase in density occurs which is characteristic of a high-velocity flow about a cold wall. These results also clearly demonstrate that the shock wave is fully merged with the viscous layer for Knudsen number values of 0.023 and 8.439. The density and velocity profiles for a Knudsen number value of 0.023 (Figs. 2 and 3) show that the shock wave thickness increases gradually along the surface of the plate. However, for a freestream Knudsen number of 8.439 (Figs. 5 and 6), the extent of the flowfield disturbances remains almost constant along the surface because of the large degree of rarefaction at this Knudsen number.

The overall nondimensional kinetic temperature, T/T_∞, shown in Figs. 4 and 7 for the freestream Knudsen number values of 0.023 and 8.439, respectively, is defined for a nonequilibrium gas as the weighted mean of the translational and internal temperatures. These figures show that the overall kinetic temperature rise in the shock wave precedes the density rise. The initial rise in temperature is due to the bimodal velocity distribution: the molecular sample consists 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 results in the early temperature increase.

The temperature rise in the shock wave is comparatively large near the leading edge and then gradually decreases toward the trailing edge (Figs. 4 and 7). This obviously shows that the strength of the shock wave decreases along the surface of the flat plate. The difference in peak shock-wave temperatures at different locations is less for the higher Knudsen number condition. The shock wave is very diffuse for the higher Knudsen number condition because of the large freestream mean free path. The temperature and velocity profiles also show a significant temperature jump and velocity slip at the surface for both values of Knudsen number. Consequently, the flowfield exhibits the effects of rarefaction for all the cases considered.

Surface Quantities

The surface pressure, skin friction, and heat transfer coefficients are presented in Figs. 8, 9, and 10, respectively, for the lower surface of the flat plate at 40-deg incidence. The effects of rarefaction are shown by comparing the results for different freestream Knudsen numbers. The variation of the pressure coefficient with rarefaction is moderate provided the gas-surface interaction is diffuse, as assumed in the present calculations. The calculated pressure coefficient is greater than the free molecular value for large freestream Knudsen numbers. In contrast, the skin friction and heat transfer coefficients (Figs. 9 and 10) are very sensitive to rarefaction effects and approach the free molecule value with increasing rarefaction.

Aerodynamic Characteristics

Figures 11 and 12 present the drag and lift coefficients as a function of freestream Knudsen number for the flat plate at 40-deg incidence. These results show the expected variation in the transitional flow regime. The drag coefficient increases and the lift coefficient decreases substantially with increasing rarefaction, and both approach the free molecule limit. The change in the drag and lift coefficients is due primarily to an increase in the skin friction rather than to a change in the pressure coefficient. Figure 13 presents the the lift-drag ratio as a function of freestream Knudsen number where the trend is the same as the lift coefficient data, which experience a significant decrease with increasing rarefaction.

The effect of angle of incidence variation on the aerodynamic coefficients is demonstrated in Figs. 14 to 16 for the 8.4 Knudsen number case. The DSMC results are compared with those obtained using free molecule expressions for lift and drag coefficients and lift-drag ratio. Figure 14 shows that the lift coefficient increases with angle of attack, reaches a maximum value at 45 deg, then decreases with further increase in angle of attack. The DSMC values are considerably higher than the free molecule values, indicating that transitional effects are evident even at this highly rarefied condition. Figure 15 shows that the drag coefficient agrees well with the free molecule calculations for small incidence. However, at higher incidence the DSMC values are slightly lower than free molecule values because of the over prediction of skin friction by the free molecule method. Figure 16 presents the corresponding lift-drag ratio comparison and shows the same trend of the transitional effects as in the lift coefficient data.

These results have important implications for the interpretation of flight measurements used to deduce aerodynamic coefficients under rarefied conditions. As early as 1985, it was recognized (Ref. 14) that transitional effects rather than specular reflection might be influencing the interpretation of the flight measurements; however, no calculations were available to establish the fact. At altitudes of 160 km and above, the conventional procedure[1-3] has been to interpret the flight measurements using the free molecule flow calculations. Such procedures are used to establish what fraction of the gas-surface interaction is specular. But it can be seen from the present calculations that the transitional effects persist even at very high altitudes (160 km and above). This is clearly demonstrated in Fig. 16 where the transitional effect increases the lift-drag ratio by 90 percent for a flat plate at 40-deg incidence. The freestream Knudsen number for this condition is 8.4 which corresponds to Shuttle conditions at approximately 175 km. This transitional effect is quite large, and if not properly interpreted could be mistaken for a contribution due to the specular reflection. For example, the free molecule results for lift-drag ratio as a function of angle of incidence for different fractions of specular reflection are shown in Fig. 17. As the fraction of specular reflection increases, the lift-drag ràtio also increases for a given incidence angle. Since these two separate effects both produce increased lift-drag ratio, interpretation of flight measurements must account for the transitional effects.

Conclusions

Results obtained with the direct simulation Monte Carlo (DSMC) method for hypersonic flow past a flat plate at incidence show the effects of the transitional flow regime on the aerodynamic characteristics. These effects are significant even for large freestream Knudsen numbers. Thus, the interpretation of aerodynamic flight data for space vehicles such as the Space Shuttle Orbiter must be done in concert with calculations that describe the transitional effects. Failure to account for this effect could significantly distort the interpretation of the gas-surface interactions under highly rarefied conditions.

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Table 1. Freestream Conditions

[Length of the flat plate, ℓ, = 1 m, and angle of incidence, α, = 40 deg.]

Altitude, km	$\mathcal{M}$, g/mol	K_{N_∞}	U_∞, km/sec	ρ_∞ kg/m^3	T_∞, K	S_∞
90	28.810	0.023	7.5	3.418×10^{-6}	188	23.1
100	28.257	0.137	7.5	5.640×10^{-7}	194.3	21.6
120	26.159	3.146	7.5	2.269×10^{-8}	367.8	15.7
130	25.441	8.439	7.5	8.220×10^{-9}	499.7	13.3

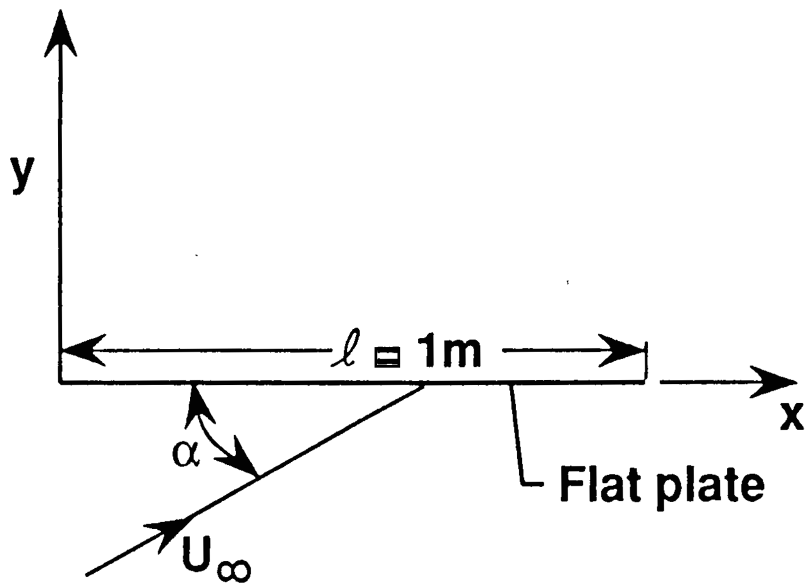

Figure 1. Flat plate configuration at incidence.

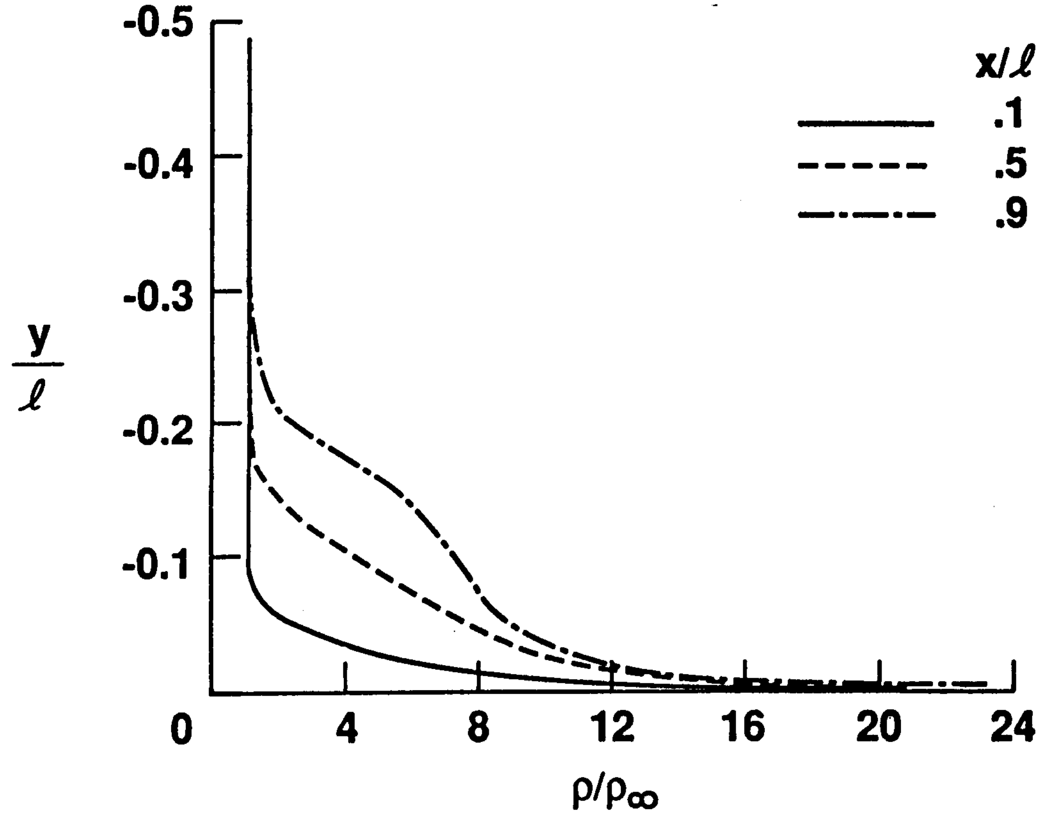

Figure 2. Density profiles normal to the plate surface. (K_{N_∞} = 0.023, and α = 40 deg.)

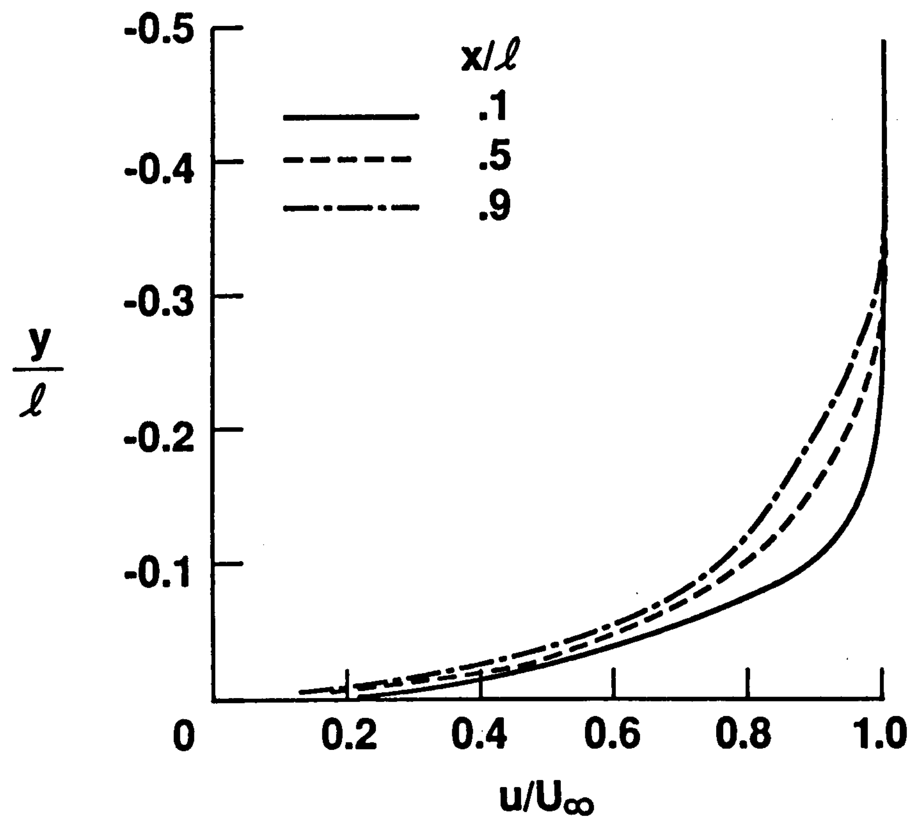

Figure 3. Tangential velocity profiles normal to the plate surface. (K_{N_∞} = 0.023, and α = 40 deg.)

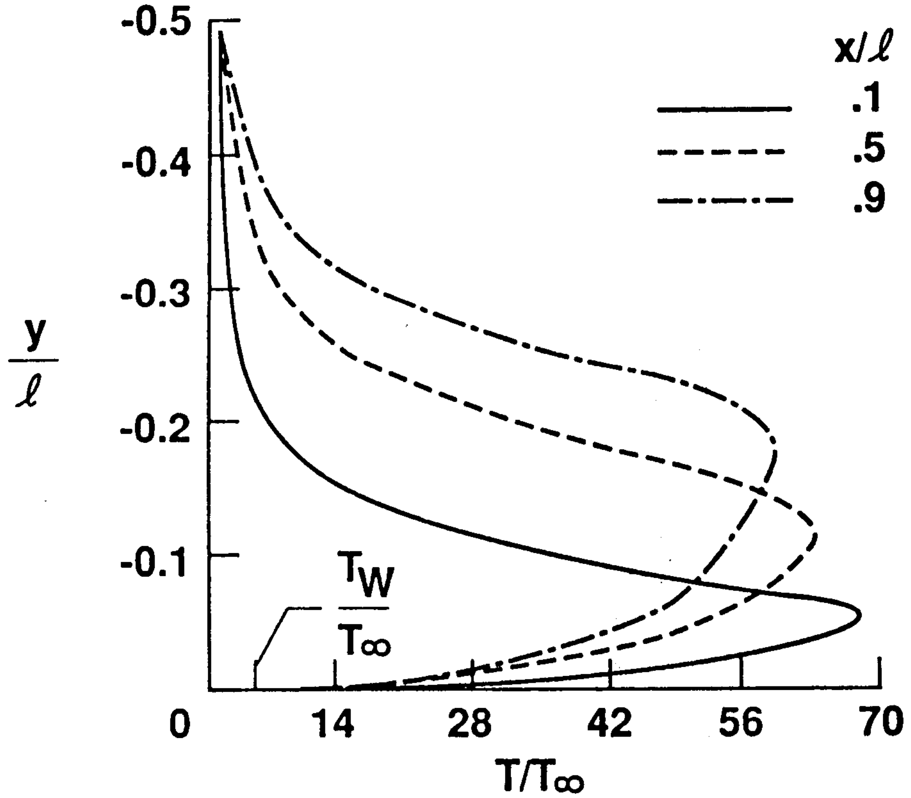

Figure 4. Temperature profiles normal to the plate surface.
(K_{N_∞} = 0.023, and α = 40 deg.)

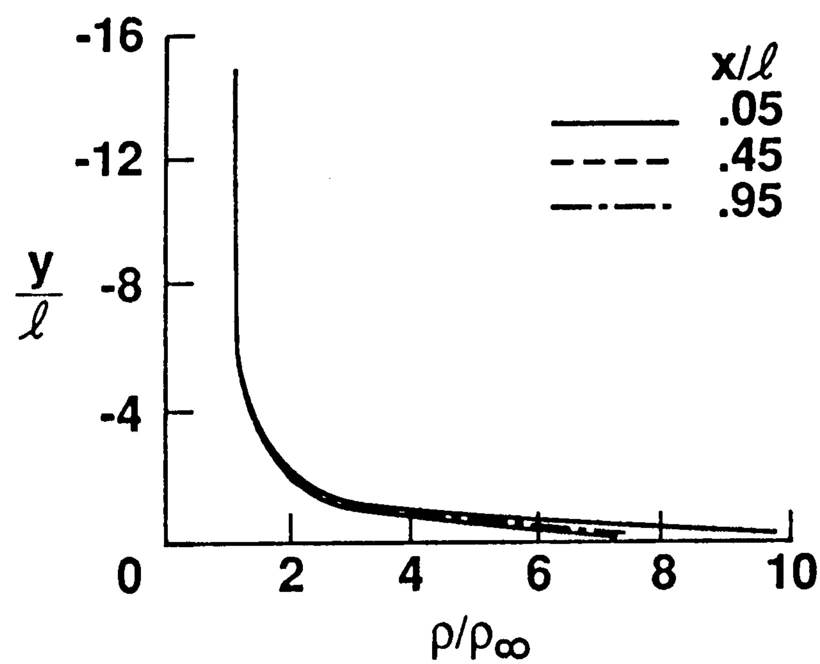

Figure 5. Density profiles normal to the plate surface. (K_{N_∞} = 8.439, and α = 40 deg.)

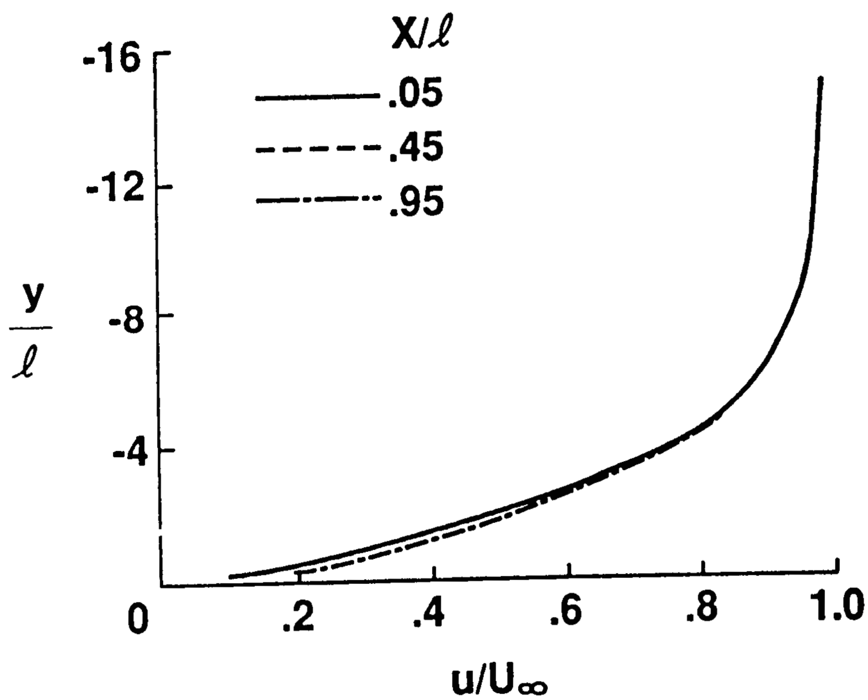

Figure 6. Tangential velocity profiles normal to the plate surface. (K_{N_∞} = 8.439, and α = 40 deg.)

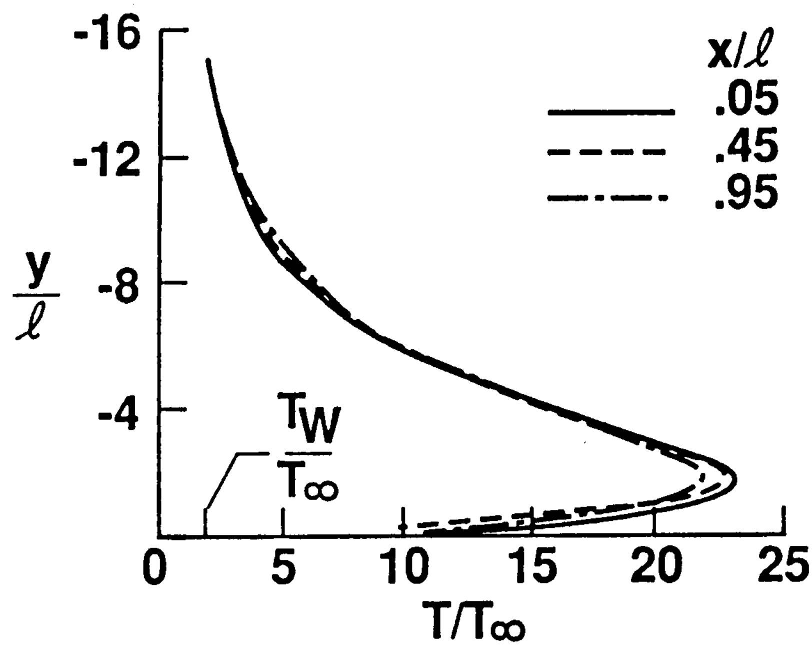

Figure 7. Temperature profiles normal to the plate surface.
(K_{N_∞} = 8.439, and α = 40 deg.)

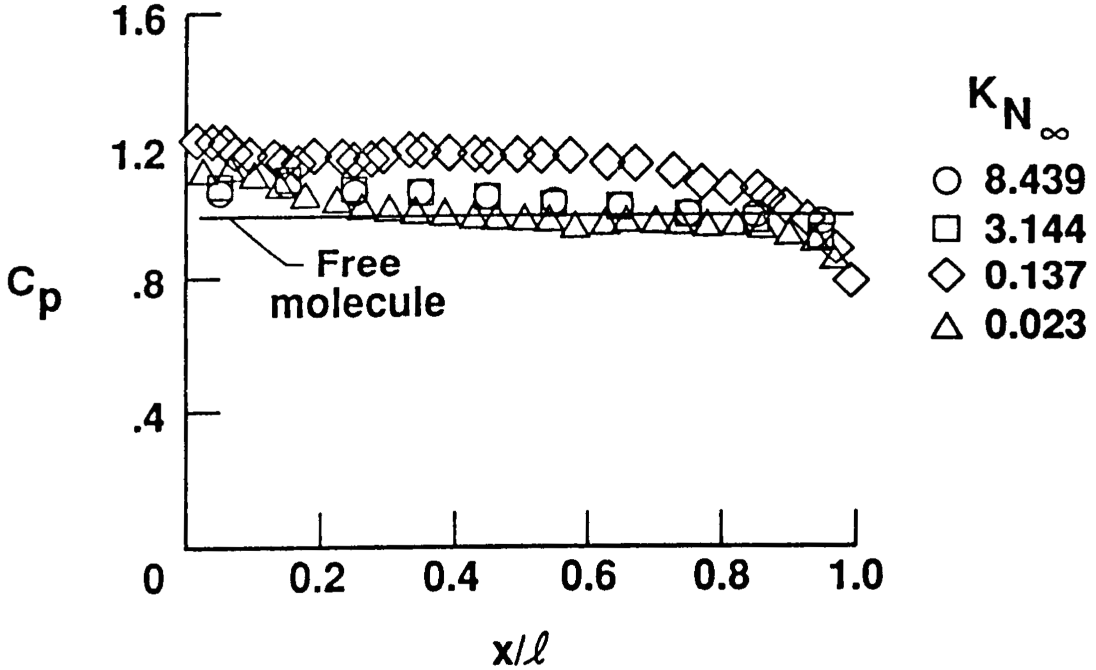

Figure 8. Effect of rarefaction on the compression side surface pressure coefficient. (α = 40 deg.)

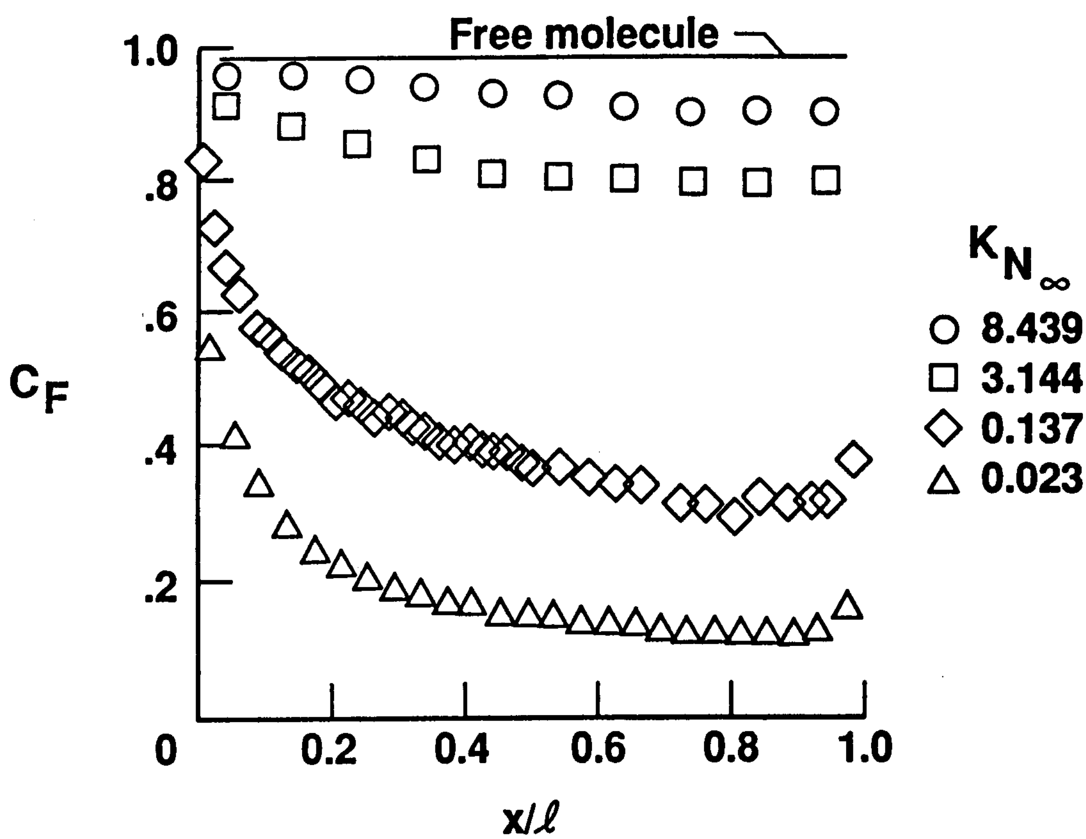

Figure 9. Effect of rarefaction on the compression side surface skin-friction coefficient. (α = 40 deg.)

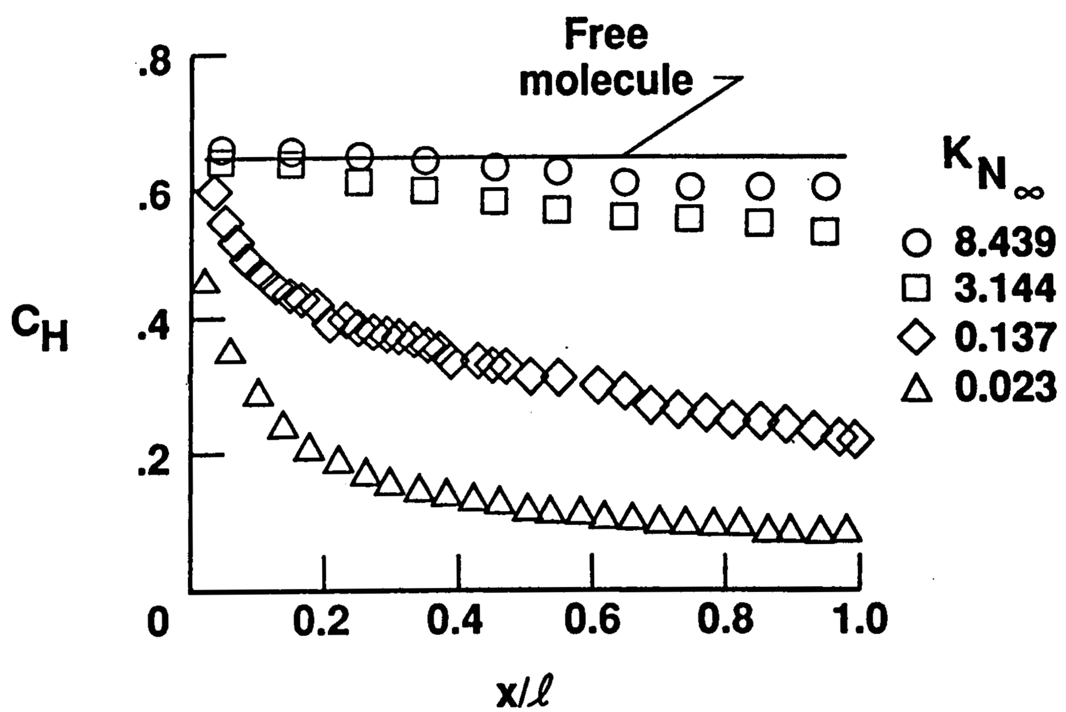

Figure 10. Effect of rarefaction on the compression side surface heat transfer coefficient.
(α = 40 deg.)

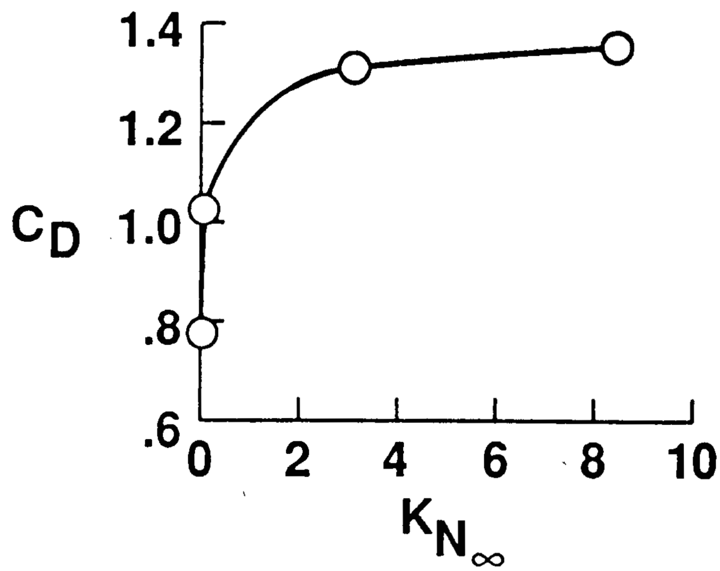

Figure 11. Drag coefficient versus Knudsen number.
(α = 40 deg.)

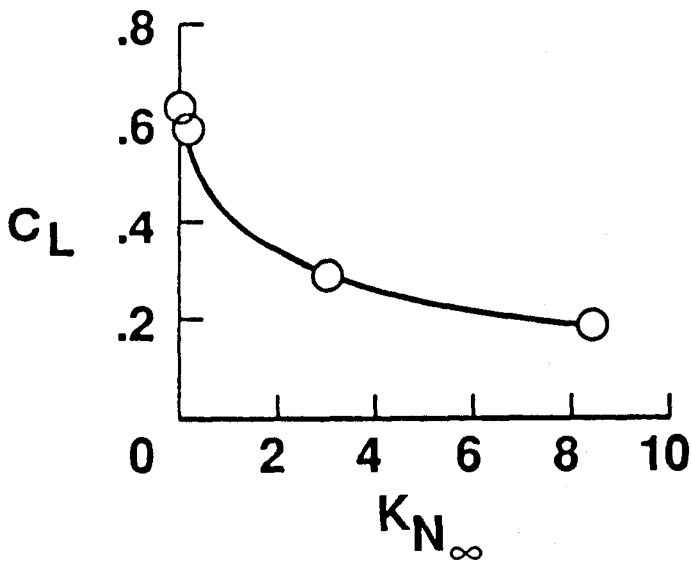

Figure 12. Lift coefficient versus Knudsen number.
(α = 40 deg.)

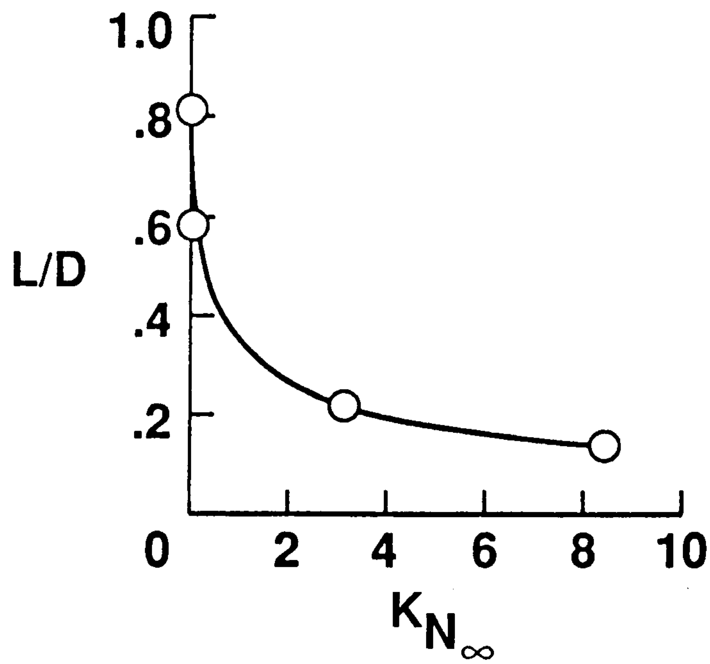

Figure 13. Lift-drag ratio versus Knudsen number.
(α = 40 deg.)

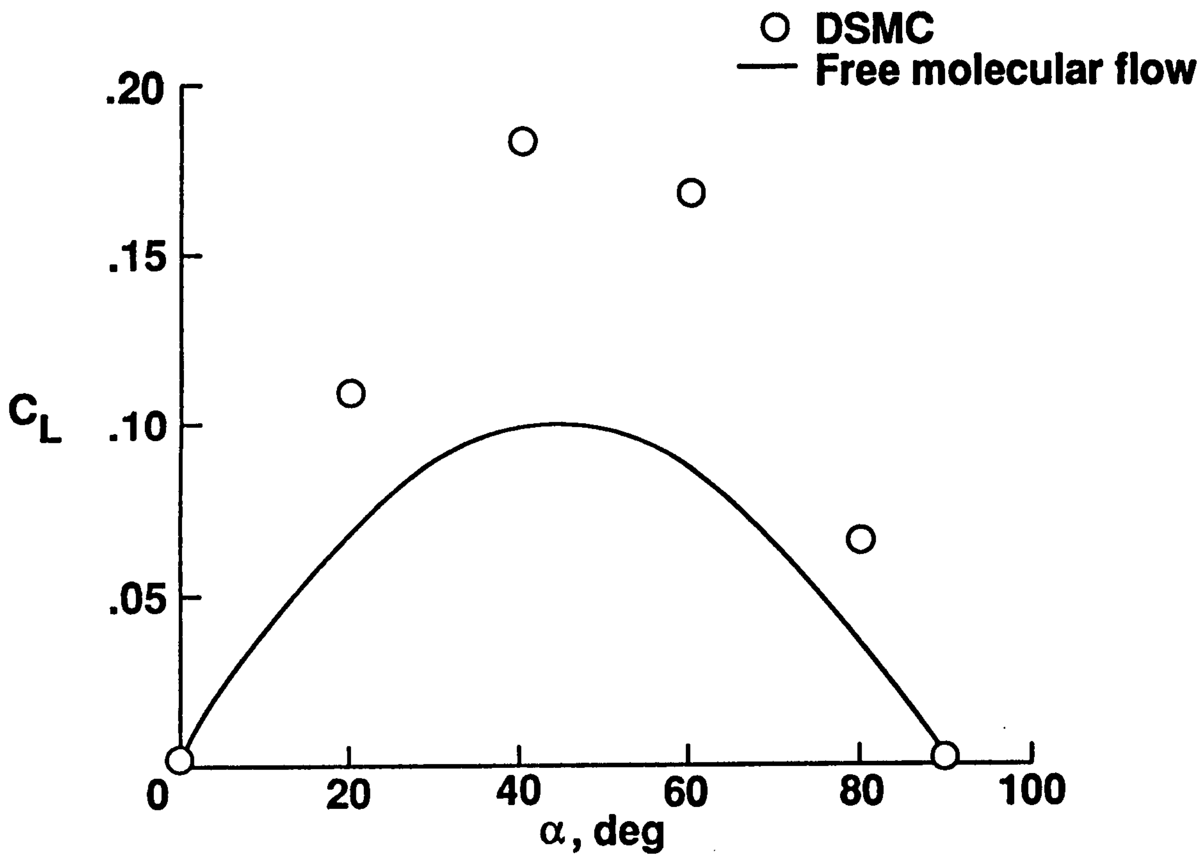

Figure 14. Lift coefficient versus incidence angle for $K_{N_\infty} = 8.439$.

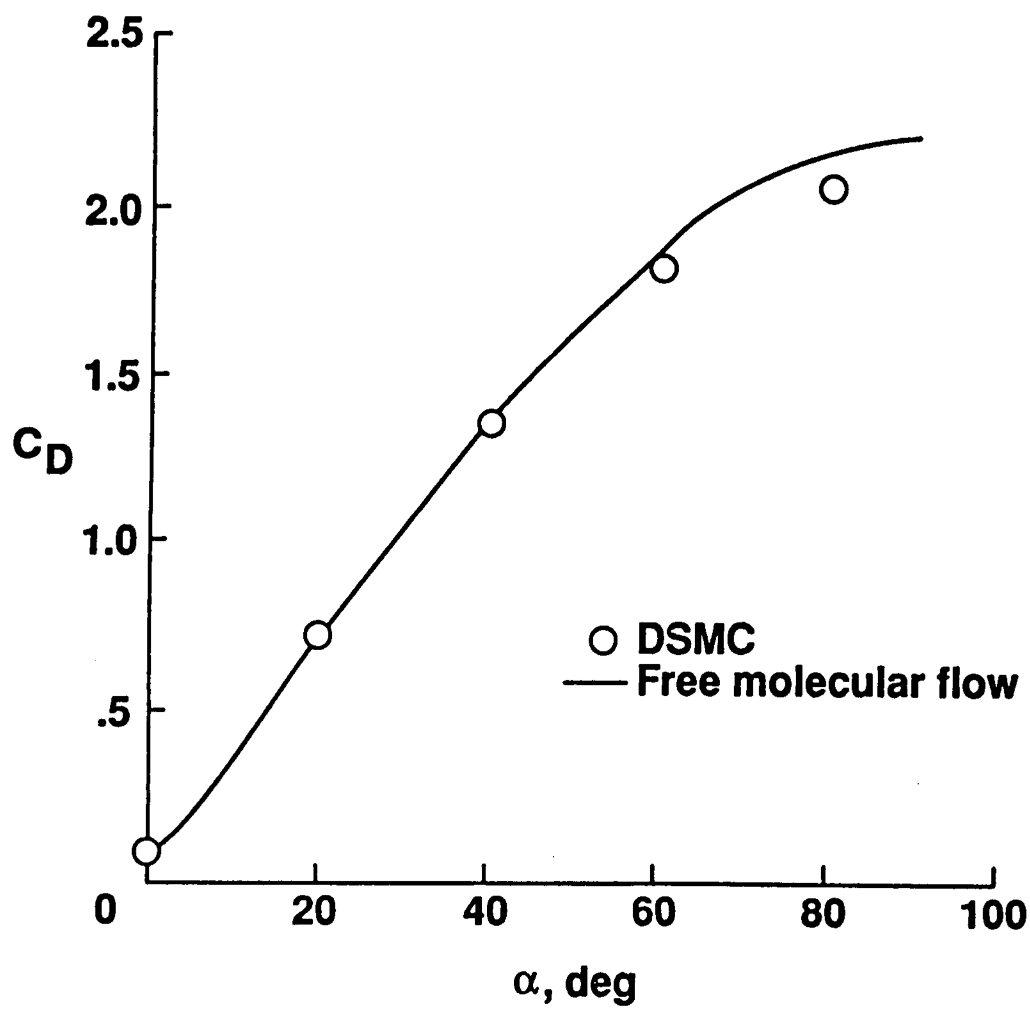

Figure 15. Drag coefficient versus incidence angle for $K_{N_\infty} = 8.439$.

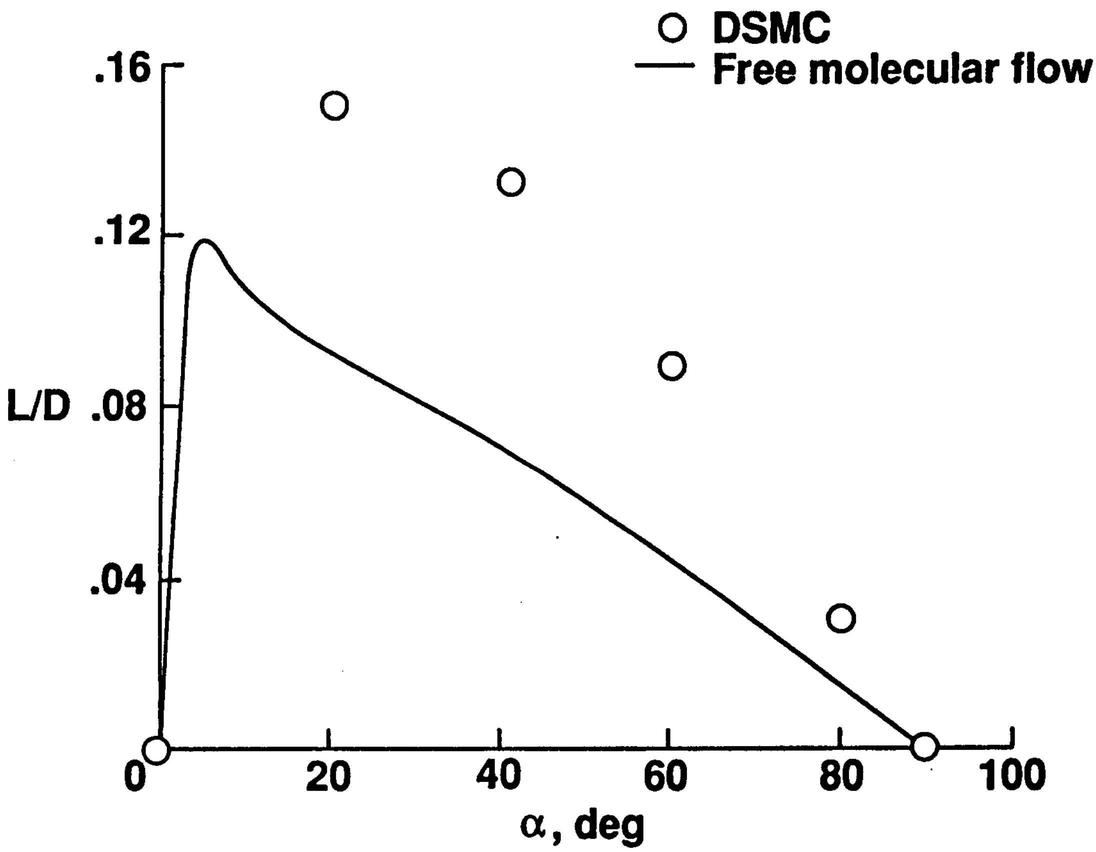

Figure 16. Lift-drag ratio versus incidence angle for $K_{N_\infty} = 8.439$.

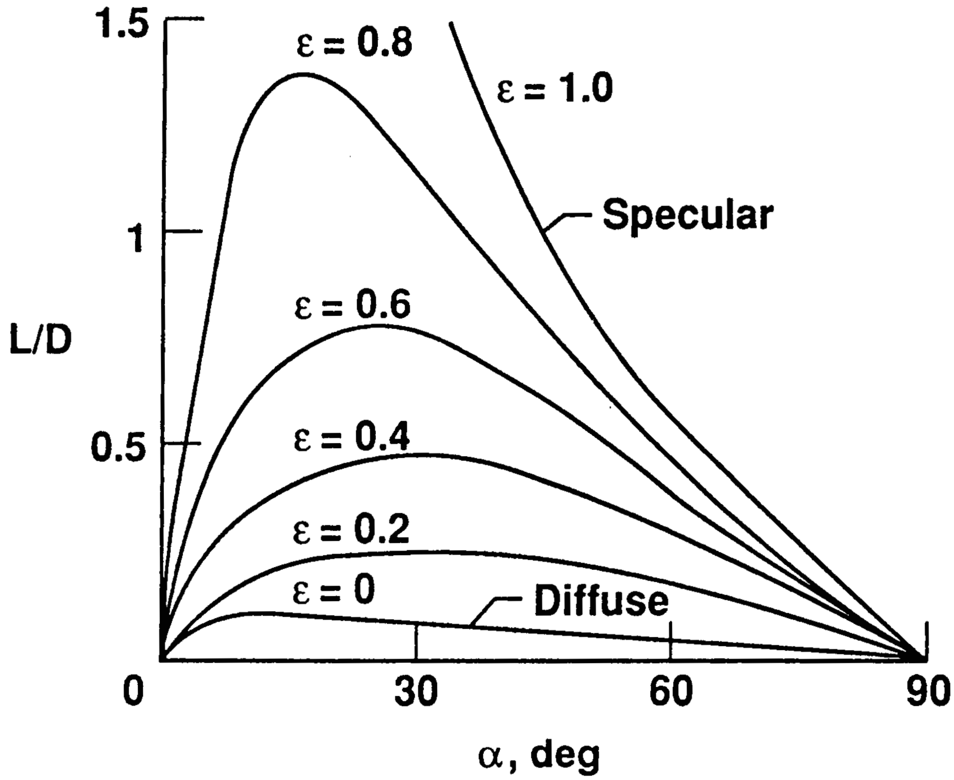

Figure 17. Flat plate free molecule lift-drag ratio versus incidence angle.
(S_∞ = 13.1 and T_w / T_∞ = 2.0)

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16. Abstract

Results of a numerical study using the direct simulation Monte Carlo (DSMC) method are presented for the transitional flow about a flat plate at 40 degree incidence. The plate has zero thickness and a length of 1.0 m. The flow conditions simulated are those experienced by the Shuttle Orbiter during reentry at 7.5 km/s. The range of freestream conditions are such that the freestream Knudsen number values are between 0.02 and 8.4, that is, conditions that encompass most of the transitional flow regime. The DSMC simulations show that transitional effects are evident when compared with free molecule results for all cases considered. The calculated results demonstrate clearly the necessity of having a means of identifying the effects of transitional flow when making aerodynamic flight measurements as are currently being made with the Space Shuttle Orbiter vehicles. Previous flight data analyses have relied exclusively on adjustments in the gas-surface interaction models without accounting for the transitional effect which can be comparable in magnitude. The present calculations show that the transitional effect at 175 km would increase the Space Shuttle Orbiter lift-drag ratio by 90 percent over the free molecular value.

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