

ABSTRACT

The behavior of two different models of gas-surface interactions is studied using the Direct Simulation Monte Carlo (DSMC) method. The DSMC calculations examine differences in predictions of aerodynamic forces and heat transfer between the Maxwell and the Cercignani-Lampis-Lord (CLL) models for flat plate configurations at freestream conditions corresponding to a 140 km orbit around Venus. The size of the flat plate represents one of the solar panels on the Magellan spacecraft, and the freestream conditions correspond to those experienced during aerobraking maneuvers. Results are presented for both a single flat plate and a two-plate configuration as a function of angle of attack and gas-surface accommodation coefficients. The two-plate system is not representative of the Magellan geometry but is studied to explore possible experiments that might be used to differentiate between the two gas-surface interaction models. The Maxwell and CLL models produce qualitatively similar results for the aerodynamic forces and heat transfer on a single flat plate. However, the flowfields produced with the two models are qualitatively different for both the single-plate and two-plate calculations. These differences in the flowfield lead to predictions of the angle of attack for maximum heat transfer in a two-plate configuration that are distinctly different for the two gas-surface interaction models.

Nomenclature

A	area of plate
Ar	argon
C_D	drag coefficient, $2D/\rho_\infty V_\infty^2 A$
C_H	heat-transfer coefficient, $2q/\rho_\infty V_\infty^3$
C_L	lift coefficient, $2L/\rho_\infty V_\infty^2 A$
CLL	Cercignani-Lampis-Lord model
CO	carbon monoxide
CO ₂	carbon dioxide
D	drag
E	energy per molecule
k	Boltzmann's constant
L	lift
m	molecular mass
N ₂	molecular nitrogen
p	normal momentum
q	heat flux
S	speed ratio, $V_\infty/(m/2kT_\infty)^{1/2}$
T _∞	freestream temperature
V _∞	freestream velocity
x, y	coordinates in plane of flat plate
z	coordinate normal to flat plate
α	thermal energy accommodation coefficient

ε	fraction of diffuse scattering in Maxwell model
ρ_∞	freestream density
σ	momentum accommodation coefficient
θ_i	angle of attack
θ_r	angle of reflection
Θ_r	mean angle of reflection in CLL model
τ	tangential momentum

Subscripts

i	incident
n	normal
r	reflected
t	tangential
w	wall

INTRODUCTION

In hypersonic flight at very high altitudes, gas-surface interactions are the dominant physical process governing aerodynamic forces and heat transfer. Our present understanding of these interactions is severely limited, especially for the highly energetic gas-surface collisions that occur during orbital or high-altitude aerobraking and entry conditions. Predictions of aerothermodynamic behavior are subject to the same uncertainties as those in the gas-surface interaction model itself (Ref. 1). Therefore, the models used for such predictions play an integral role both in mission analysis and in the extraction of scientific data from vehicles such as the Magellan spacecraft used for aerobraking experiments in the Venusian atmosphere (Refs. 2-4).

The Direct Simulation Monte Carlo (DSMC) method of Bird (Ref. 5) is commonly used to simulate rarefied flow problems, and the accuracy of the method depends directly on the accuracy of the gas-surface interaction model. The Maxwell model is the most widely used and is based on classical thermodynamics in which it is assumed that molecules will either reflect diffusely from a surface with complete energy accommodation or will reflect specularly with no change in energy. (See Fig. 1) An accommodation coefficient, ε , is defined which specifies the fraction of molecules that will be scattered diffusely, with $\varepsilon = 0$ giving complete specular reflection, and $\varepsilon = 1$ giving complete diffuse reflection.

While the Maxwell model is useful for describing the overall classical thermodynamic behavior of gas-surface interactions, it does not accurately describe the detailed molecular behavior observed under certain conditions in fundamental gas-surface scattering experiments. For moderate to high energy scattering from engineering surfaces, the flux distribution of scattered molecules frequently has a lobular shape that is centered about an angle, Θ_r , which tends to approach the specular angle for very high energies and/or low angles of attack. The Cercignani-Lampis-Lord model (CLL) (Ref. 6) is one of several models developed to handle such behavior. (See Fig. 2) In the CLL model, the transformations of the normal and tangential components of velocity are assumed to be mutually

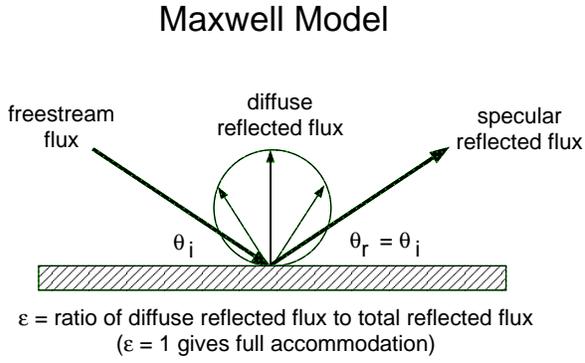


Fig. 1 - Schematic of Maxwell reflection model.

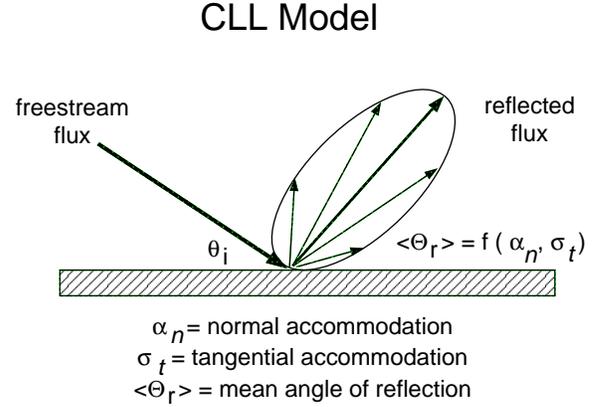


Fig. 2 - Schematic of CLL reflection model.

independent. Analysis of the flux distribution of scattered molecules shows it to be centered around an average scattering angle, $\langle \Theta_r \rangle$, which is a function of normal and tangential accommodation coefficients, α_n and σ_t .

$$\langle \Theta_r \rangle = f(\alpha_n, \sigma_t)$$

The mean energy of the reflected molecules is also a function of these normal and tangential accommodation coefficients,

$$\langle E_r \rangle = F(\alpha_n, \sigma_t)$$

The purpose of this paper is to examine the differences in aerothermodynamic quantities (forces and heat transfer) predicted with these two gas-surface interaction models. The Maxwell and CLL models are incorporated into a DSMC code, and calculations are performed for hypersonic, rarefied flow about flat plates. The conditions selected are the same as those used in a study by Rault (Ref. 7) of the Magellan spacecraft orbiting Venus. Calculations are performed for a single flat plate having dimensions the same as one of the solar panels of the Magellan spacecraft. Calculations are also performed for a two-plate configuration to explore possible experiments that might be used to differentiate between the two gas-surface interaction models.

ACCOMMODATION COEFFICIENTS AND GAS-SURFACE INTERACTION MODELS

A variety of definitions for accommodation coefficients exists in the literature. The traditional definition of "thermal accommodation" is usually expressed as (Ref. 8)

$$= \frac{E_i - E_r}{E_i - E_w}$$

where E_i is the incident energy per molecule, E_r is the reflected energy, and E_w is the energy per molecule corresponding to fully diffuse scattering with full accommodation to the wall temperature. Similar definitions can be defined for other flux quantities to yield normal and tangential momentum

accommodation coefficients, σ_n and σ_t ,

$$\sigma_n = \frac{P_{i,i} - P_{r,i}}{P_{i,i} - P_w}, \quad \sigma_t = \frac{i_i - r_i}{i_i}$$

and a general definition of accommodation coefficient is given in Ref. 9. These various definitions have been defined partly for convenience in relating experimentally observed behavior to various empirical gas-surface models.

In the Maxwell model, the fraction of diffusely-scattered molecules, ϵ , is equivalent to the thermal accommodation coefficient defined above. Traditionally, the model is considered to have only this single adjustable parameter, and the momentum accommodation coefficients also follow once ϵ is specified, i.e., σ_n and σ_t are also determined by ϵ . However, σ_n and σ_t are sometimes viewed as being independent of the energy accommodation. In the traditional implementation of the Maxwell model in DSMC calculations, it has usually been assumed that the energy and momentum accommodation are not independent, and that assumption is used in the present implementation for the Maxwell model.

The CLL model is derived assuming that there is no coupling between the normal and tangential momentum components, and treats the normal component of translational energy, α_n , and the tangential component of momentum, σ_t , as two independent, disposable parameters. However, in the implementation of the CLL model in DSMC, Bird (Ref. 5) has shown that it is equivalent to specify the normal and tangential components of translational energy since α_t can be considered equivalent to $\sigma_t(2-\sigma_t)$. In presenting the results with the CLL model, we will use the quantities α_n and σ_t as the two disposable parameters.

In addition, the present simulations will also consider the accommodation of internal energy, α_i , the implementation of which is described below.

DSMC METHOD

The DSMC method is widely used for simulating rarefied flows and is described in detail in Ref. 5. The method consists of tracking the motion of representative molecules as they move in physical space while undergoing collisions with other molecules and with physical boundaries within or surrounding the computational volume. The volume is discretized into cells within which samples of density, momentum, and energy are stored for computing macroscopic properties of the flow. Surfaces within the computational volume are also discretized, and samples of momentum and energy transfer to elements of the surface are stored for computing forces and heat transfer. In the present study, gas collisions are treated with the variable hard sphere (VHS) model with internal energy exchange allowed only for rotational degrees of freedom.

The DSMC computer code used in the present study is a three-dimensional code described in Ref. 5 which uses uniform Cartesian cells. The original code included the Maxwell gas-surface interaction model and was modified to include the CLL model as an option. In the implementation of the Maxwell model, accommodation of internal energy is set equal to the parameter ϵ . Those molecules which scatter diffusely have their internal energies adjusted by sampling from an equilibrium distribution corresponding to the surface temperature, while molecules which scatter specularly retain their incident internal energy.

In the CLL model, accommodation of internal energy is allowed to be independent of the

translational accommodation. However, for all calculations presented here, the internal energy accommodation is kept equal to one or both of the translational accommodation coefficients, α_n or σ_t . For each molecule scattered by the surface in the CLL implementation, an energy state is sampled from an equilibrium distribution corresponding to the surface temperature, and the reflected internal energy is given by

$$E_r^i = \alpha_i E_i^i + (1 - \alpha_i) E_w^i$$

where E^i denotes the internal energy of the molecule.

GEOMETRY AND FLOW CONDITIONS

The hypersonic flow over a flat plate lends itself well to experimentation because its simple geometry makes it an ideal situation in which to compare theory and experiment (Refs. 10-11). Because the Magellan spacecraft has been used as a test for gas-surface interactions (Refs. 3-4), flat plates with the dimensions of one of the solar panels from the Magellan spacecraft (Fig. 3) were used for the DSMC calculations. The dimensions of the solar panel are shown in Fig. 4. Calculations with

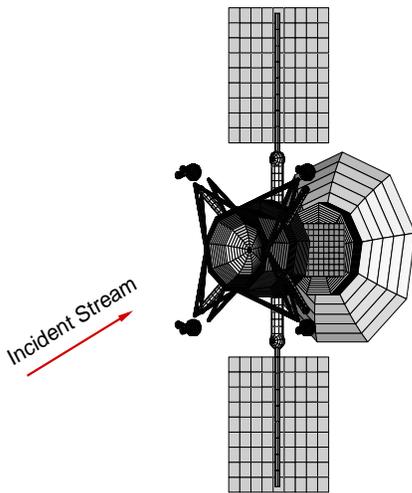


Fig. 3 - Sketch of Magellan spacecraft.

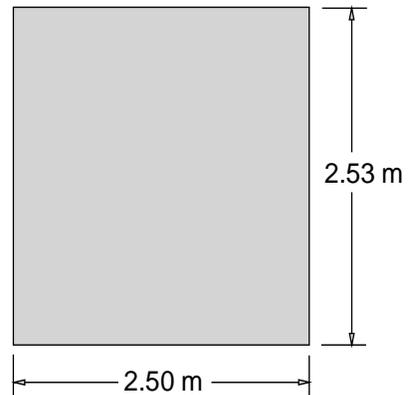


Fig. 4 - Dimensions of Magellan solar panel.

both gas-surface interaction models were made for a range of angles of attack and accommodation coefficients. Calculations were made for a single plate and for a two-plate configuration in which the two plates were displaced by 2.5 m in the directions both normal and parallel to the plane of the plates.

The plates were placed in an environment consistent with Venus' atmosphere at an altitude of 140 km. Freestream conditions taken from Ref. 7 are:

$$\text{Density} = 9.5 \times 10^{16} \text{ molecules/m}^3$$

$$\text{Temperature} = 225 \text{ K}$$

$$\text{Molar Composition: } 75.7\% \text{ CO}_2, 9.6\% \text{ CO, } 8.9\% \text{ Ar, } 5.8\% \text{ N}_2$$

$$\text{Velocity} = 8600 \text{ m/s}$$

$$\text{Speed Ratio (s)} = 28.5$$

The Knudsen number based on the hard sphere diameter for CO₂ is 0.053, and the surface temperature of the plates is assumed to be 300 K.

RESULTS

Results are presented in terms of lift, drag, and heat transfer coefficients using a reference area equal to that of a single plate (solar panel). Results are first presented for a single plate to show the basic comparisons between the two models and with analytical predictions based on the analysis given in Ref. 9. Results for the two-plate system are then presented to demonstrate certain unique flow aspects of this configuration.

Single Flat Plate

DSMC calculations were first performed with gas collisions disallowed in order to compare with free-molecule analytical predictions for both the Maxwell (Fig. 5) and the CLL (Fig. 6) models. Analytical solutions for the Maxwell model are taken from Ref. 5 while analytical solutions for the CLL model are taken from Ref. 9. The collisionless DSMC calculations agree with the analytical solutions within the statistical error in the DSMC sample. Also, for $\epsilon = 1$ in the Maxwell model and $\alpha_n = \sigma_t = 1$ in the CLL model, the two models give precisely the same results as expected.

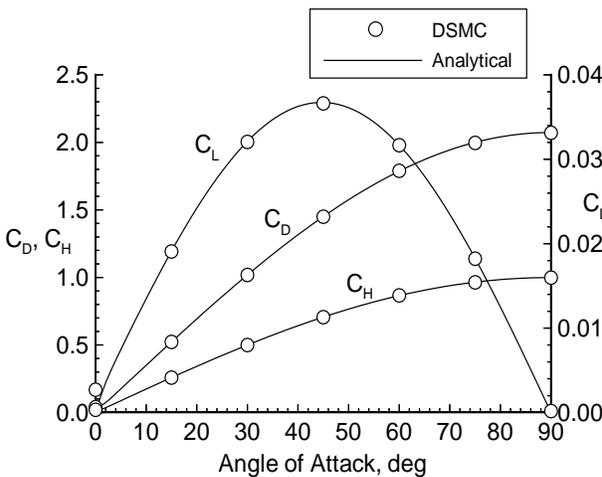


Fig. 5 - Comparison of DSMC collisionless and analytical free-molecule predictions using Maxwell model. $\epsilon = 1$.

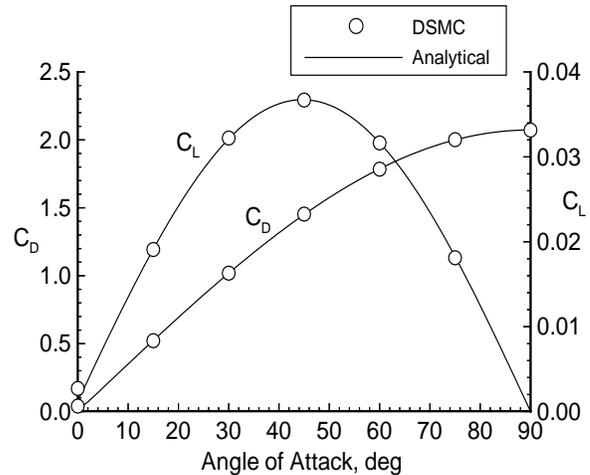
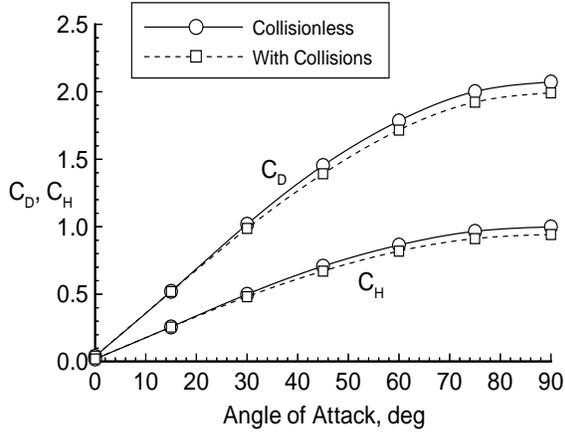
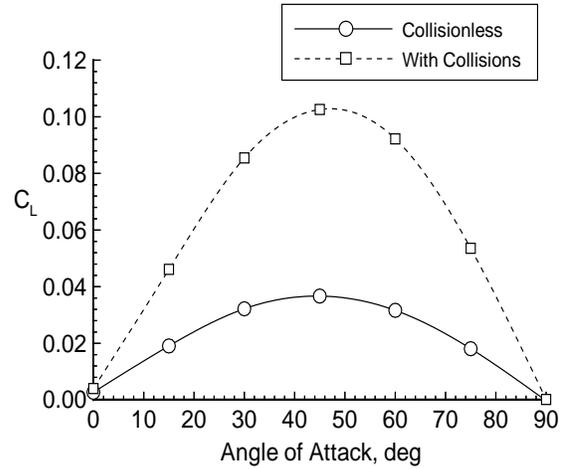


Fig. 6 - Comparison of DSMC collisionless and analytical free-molecule predictions using CLL model. $\alpha_n = \sigma_t = 1$. (Note: Analytical model not available for heat transfer.)

DSMC simulations were then performed with collisions allowed. Again, for $\epsilon = 1$ in the Maxwell model and $\alpha_n = \sigma_t = 1$ in the CLL model, the two models give precisely the same results. However, the effect of including gas-gas collisions is to decrease both the drag and heat transfer slightly while increasing the lift significantly. (See Fig. 7) The two models were then compared at an angle of attack of 45 degrees with varying accommodation coefficients. (See Fig. 8) For the CLL model, α_n was kept equal to σ_t . The CLL model and Maxwell models predict the same lift, drag and heat transfer when the accommodation coefficients are equal to zero or one. For accommodation



(a) Drag and heat transfer coefficients.



(b) Lift coefficient.

Fig. 7 - Effect of gas-gas collisions on DSMC predictions of lift, drag, and heat transfer. CLL model with $\alpha_n = \sigma_t = 1.0$.

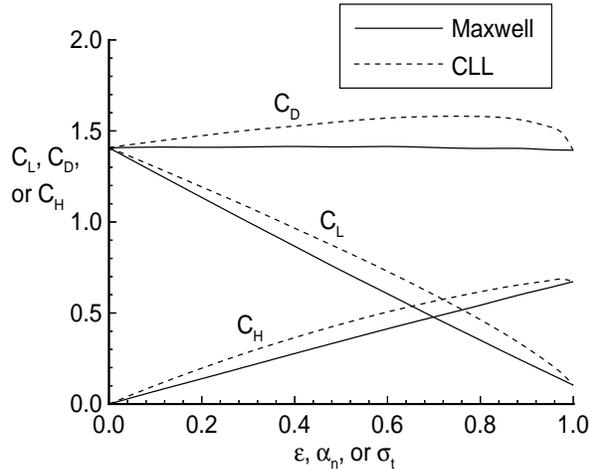


Fig. 8 - Comparison of Maxwell and CLL DSMC predictions. Angle of Attack = 45 deg.

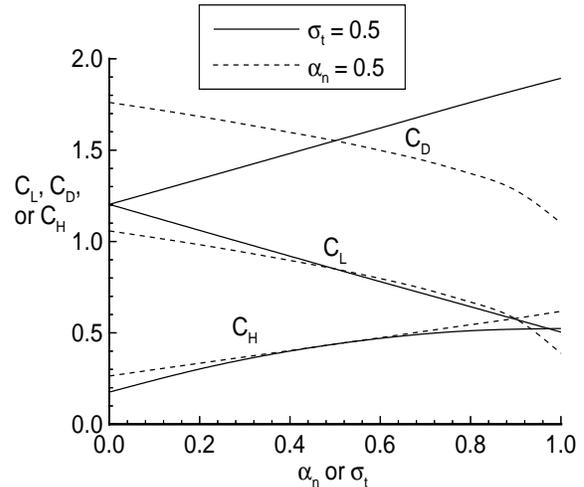


Fig. 9 - Effect of varying α_n and σ_t independently on CLL DSMC predictions. Angle of Attack = 45 deg.

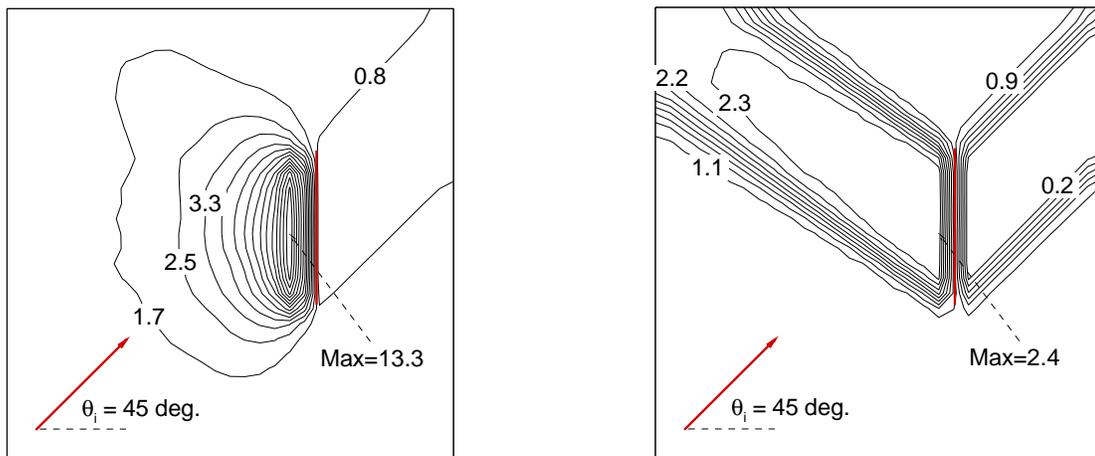
coefficients not equal to zero or one, the CLL model gives higher aerodynamic forces and heat transfer than the Maxwell model for the same value of their respective accommodation coefficients. The differences are greatest for lift and drag when $\varepsilon = \alpha_n = \sigma_t = 0.8$ where the CLL model gives a drag coefficient of 1.58 and a lift coefficient of 0.46 compared to values of 1.40 and 0.35 for the respective coefficients with the Maxwell model. The heat transfer coefficient, on the other hand, has its greatest difference when $\varepsilon = \alpha_n = \sigma_t = 0.5$. Here, simulations with the CLL model produce a heat-transfer coefficient of 0.44 compared to 0.35 predicted with the Maxwell model.

The effects of changing the tangential and normal accommodation coefficients independently in the CLL model are shown in Fig 9. For the solid curves, the tangential accommodation coefficient is held constant (along with internal energy) at 0.5, while the normal accommodation coefficient is varied from 0.0 to 1.0. For the dashed curves, the normal accommodation coefficient is held constant (along with internal energy) at 0.5, while the tangential accommodation is varied from 0.0 to 1.0. Variations in α_n or σ_t seem to have approximately the same effect on both lift and heat transfer, i.e., as the coefficients vary from 0.0 to 1.0 the heat transfer increases and the lift coefficient decreases.

Varying α_n , however, has the opposite effect on drag than that caused by varying σ_t . When α_n is increased from 0.0 to 1.0 the drag coefficient decreased at approximately the same rate as the lift. When σ_t is increased from 0.0 to 1.0, however, the drag coefficient increases at approximately the same rate as the lift coefficient decreases. Therefore, changing α_n has little effect on the lift-to-drag ratio; it remains nearly constant at a value of 0.6. Changing σ_t , however, has a profound effect on the lift-to-drag ratio. As σ_t increases from 0.0 to 1.0, the lift-to-drag ratio decreases from 1.0 to 0.3.

The simulations were repeated with each coefficient held constant at 0.8 (along with the internal energy) while the other coefficient was varied from 0.0 to 1.0. These simulations produced results similar to those where the constant coefficients were held equal to 0.5. When σ_t is held constant at 0.8, and α_n varies from 0.0 to 1.0, the lift-to-drag ratio remains constant at approximately 0.48. When σ_t is increased from 0.0 to 1.0, the lift-to-drag ratio decreases from 1.0 to 0.18.

One way to visualize the manner in which the two models produce these differing behaviors is to examine the density contours around the plate. When $\epsilon = 0.5$, the Maxwell model predicts that most molecules will be generally distributed symmetrically along the windward side of the plate with only a slight bias in density toward the specular direction (Fig. 10(a)). When $\alpha_n = \sigma_t = 0.5$, however, the CLL model predicts that the distribution of molecules is strongly biased toward the specular direction (Fig. 10(b)). This behavior is caused by differences in the velocity distributions of the scattered molecules. With the Maxwell model, scattered molecules consist of a combination of specularly reflected molecules which have the same velocity distribution as the incoming molecules except that their velocity component normal to the surface is reversed and diffusely reflected molecules which have a Maxwellian velocity distribution characteristic of the surface temperature. For a "cold" plate, the diffusely reflected molecules remain in the vicinity of the surface longer and result in a density buildup near the plate. On the other hand, the CLL model provides a much more complex description of the velocity distribution of scattered molecules in which the overall mean velocity, temperature, and mean scattering angle are complex functions of the incoming velocity, the surface temperature, and the normal and tangential accommodation coefficients. For accommodation coefficients less than one but greater than zero, the CLL model gives a somewhat higher average velocity of scattered molecules and a more continuous distribution of molecules scattered near the specular angle. The result is that molecules do not remain near the surface as long as with the Maxwell model, and lower densities occur near the plate. This behavior leads to further speculation about possible differences one might



(a) Maxwell model, $\epsilon = 0.5$.

(b) CLL model, $\alpha_n = \sigma_t = 0.5$.

Fig. 10 - Number density (normalized to freestream) contours about flat plate. Angle of Attack = 45 deg. x-z plane.

encounter if other surfaces were present near the plate and is the motivation for the two plate calculations presented in the next section.

Two-Plate System

The two-plate system incorporates a second identical flat plate which is displaced 2.5 meters in the x and z directions from the original plate, placing it 2.5 meters in front of and above the original plate. This geometry gives an angular displacement of the center of each plate that is 45 degrees from the normal to the other plate and was selected because it was felt that it might maximize the interaction between the plates. Density contours shown in Fig. 11 illustrate the new geometry and the differences between the Maxwell and CLL model results.

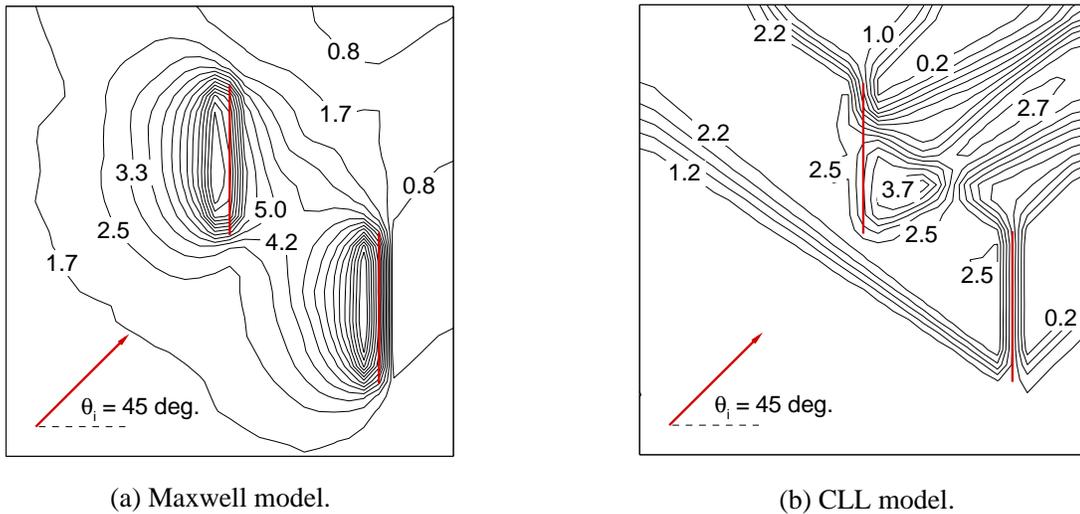


Fig. 11 - Number density (normalized to freestream) contours about two-plate configuration. Angle of Attack = 45 deg. x-z plane.

DSMC calculations were performed at a constant angle of attack of 45 degrees while the accommodation coefficients for both the Maxwell and CLL models were once again varied from 0.0 to 1.0, and lift, drag and heat-transfer coefficients for the combined two-plate system are shown in Fig. 12. The CLL and Maxwell models again give identical results when the accommodation coefficients are equal to 0.0 or 1.0 just as for a single plate. Other features of the comparison are similar to those with a single plate, i.e., the CLL model predicts higher values for lift, drag, and heat transfer when the accommodation coefficients are not equal to zero or one, and the maximum differences between the two models occur in lift and drag when the accommodation coefficients are equal to 0.8 and in the heat transfer when the accommodation coefficients are equal to 0.5.

Because the aerodynamic coefficients shown in Fig. 12 are based on the reference area for a single plate, one might expect the coefficients for the two-plate system to be twice as large as for the single plate. However, the lift coefficient is only slightly larger than the single plate results, while the drag coefficient is slightly larger at $\epsilon = \alpha_n = \sigma_t = 0$ but increases to almost twice the single-plate value at $\epsilon = \alpha_n = \sigma_t = 1.0$. This behavior is caused by the interference between the two plates resulting when molecules that are reflected from the windward side of the rear plate hit the leeward side of the front plate. The forces caused by these secondary reflections essentially cancel the lift of one plate (i.e., the forces in the lift direction due to these secondary reflections are negative) and are only a weak function of the accommodation coefficients. A similar phenomena occurs for the drag force except that the

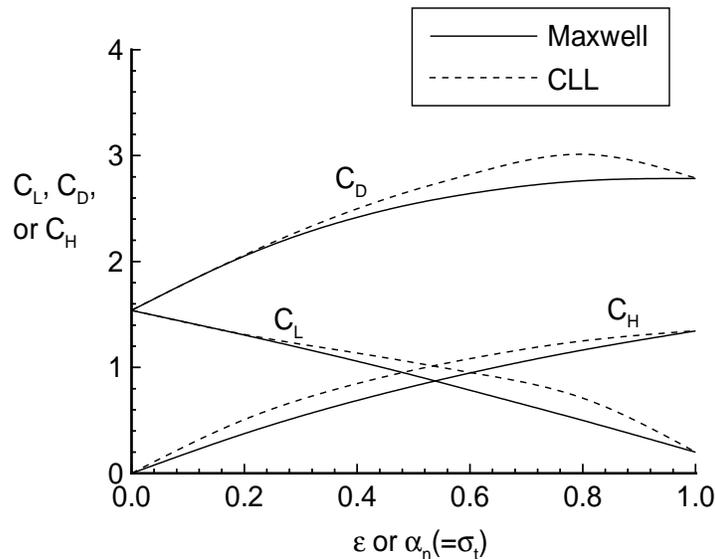


Fig. 12 - DSMC predictions of lift, drag, and heat transfer for two-plate configuration as a function of accommodation coefficient. Angle of Attack = 45 deg. (Lift, drag, and heat-transfer coefficients are based on reference area for a single plate.)

cancelling force is more strongly dependent on the accommodation coefficients. Therefore, the drag increases significantly as the accommodation coefficients are increased rather than remaining relatively constant as it does for a single plate.

Fig. 13 shows the effect of angle of attack for the two-plate system. In the Maxwell DSMC calculations, ϵ was held constant at 0.5, while in the CLL DSMC simulations, α_n and σ_t were held constant to 0.5. The behavior of the drag coefficient is somewhat similar to that for the single plate simulations (see Fig. 7), although the rate of increase with angle of attack is lower at smaller angles. However, the lift coefficient for the two-plate system shows a maximum at an angle of attack of 60 degrees rather than at 45 degrees as with the single plate, and a second local maxima occurs at 30 degrees with the Maxwell model. The presence of the second plate also causes the heat transfer coefficient to reach a maximum at an angle of attack other than 90 degrees as it does with the single plate. Furthermore, the CLL model and Maxwell models give different predictions for this angle, a

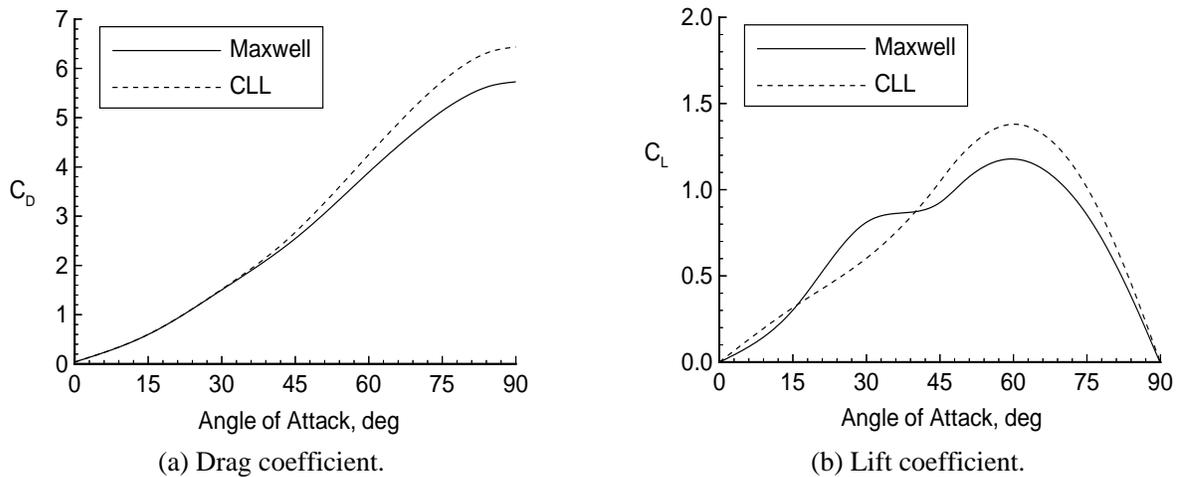
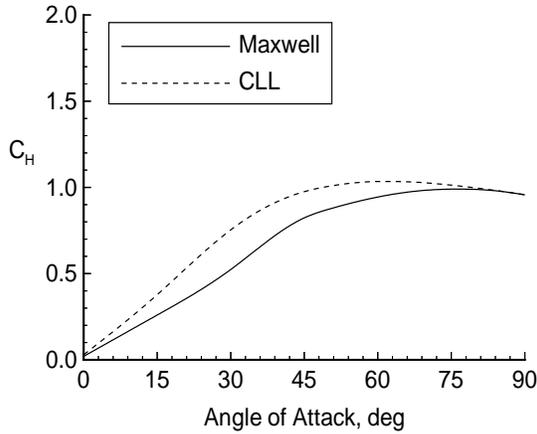


Fig. 13 - DSMC predictions of lift, drag, and heat transfer for two-plate configuration as a function of angle of attack. $\epsilon = \alpha_n = \sigma_t = 0.5$. (Lift, drag, and heat-transfer coefficients are based on reference area for a single plate.)



(c) Heat-transfer coefficient.
Fig. 13 - Concluded.

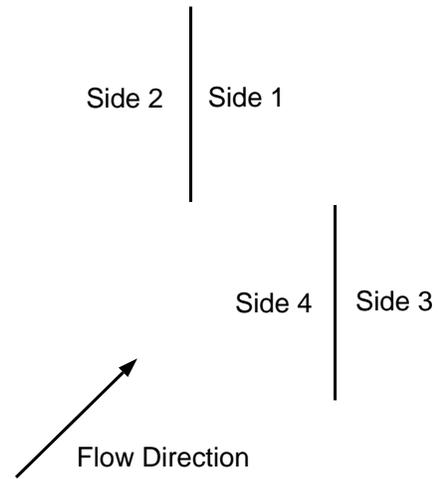
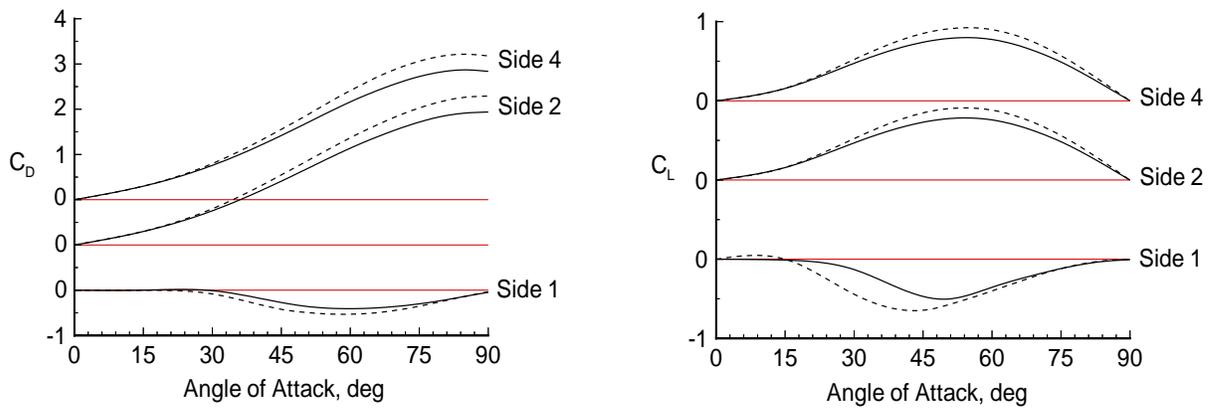


Fig. 14 - Numbering convention for sides of two-plate configuration.

fact that will be discussed in more detail.

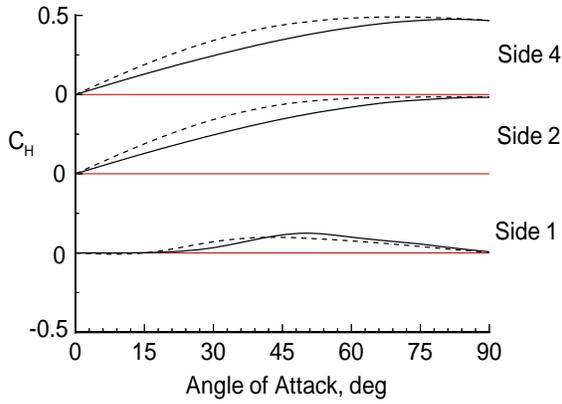
To further examine the detailed behavior of the two-plate system, surface forces and heat transfer were extracted separately for each side of each plate. These sides are numbered as follows: Side 1 is the leeward side of the front plate, Side 2 is the windward side of the front plate, Side 3 is the leeward side of the back plate, and Side 4 is the windward side of the back plate. (See Fig. 14) For the present DSMC simulations, there were insufficient molecules striking the leeward side of the back plate (Side 3) to gather meaningful statistics on the surface forces and heat transfer. A comparison of the aerodynamic forces and heat transfer obtained with each gas-surface interaction model for sides 1, 2, and 4 is shown in Fig. 15 for $\epsilon = \alpha_n = \sigma_t = 0.5$. Sides 2 and 4 dominate the contributions to the total forces and heat transfer and show essentially the same qualitative behavior as that shown in Fig. 13 for the complete system. Side 1 shows some interesting qualitative variations with angle of attack but no distinct differences between the Maxwell and CLL model results.

Further calculations were performed for other values of the accommodation coefficients. These results (Fig. 16) showed that Side 4 was the only side which exhibited a distinct difference in qualitative behavior between the Maxwell and CLL models. The Maxwell model predicts the heat



(a) Drag coefficient. (b) Lift coefficient.

Fig. 15 - DSMC predictions of lift, drag, and heat transfer for two-plate configuration as a function of angle of attack. $\epsilon = \alpha_n = \sigma_t = 0.5$. (Lift, drag, and heat-transfer coefficients are based on reference area for a single plate.)



(c) Heat-transfer coefficient.
Fig. 15 - Concluded.

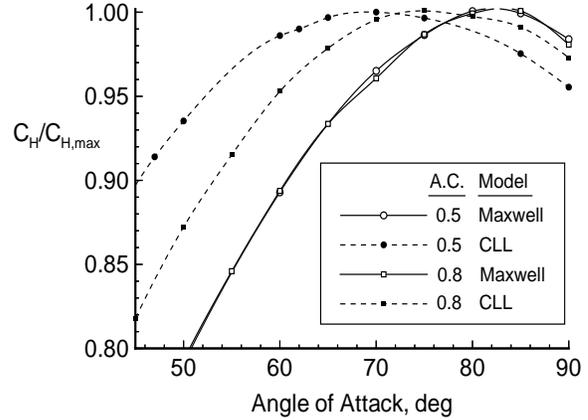


Fig. 16 - Variation of heat-transfer coefficient with angle-of-attack for various accommodation coefficients.

transfer is maximized at an angle of attack which is independent of the accommodation coefficient, while the CLL model predicts the angle of attack at which the heat transfer is maximized is a strong function of the accommodation coefficients. DSMC simulations were run for several other accommodation coefficients, and the results show that the angle of attack for maximum heat transfer for Side 4 always occurs at about 83 degrees with the Maxwell model while varying from about 55 degrees for $\alpha_n = \sigma_t = 0.1$ to about 83 degrees for $\alpha_n = \sigma_t = 1.0$ with the CLL model. (See Fig. 17) The behavior with the CLL model is attributed to the lobular nature of the scattered molecules which are then backscattered from Side 1 (front plate) and return to Side 4 (back plate). Since the densities are relatively low for the current simulations, gas-gas collisions are not that important. Therefore, it is likely that a free-molecular analysis could be performed using the CLL model to provide a full analytical description of this behavior.

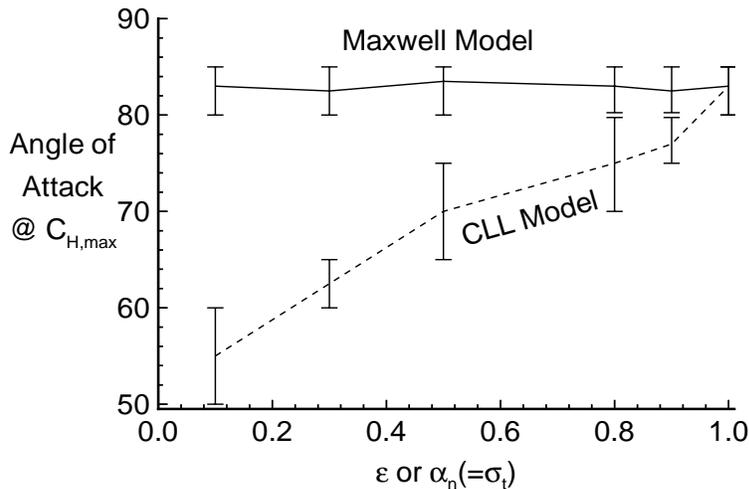


Fig. 17 - Variation of angle of attack for maximum heat-transfer as a function of accommodation coefficient. Results for windward side of rear plate (Side 4). Error bars are estimated uncertainties in determining the maximum angle from DSMC results.

DISCUSSION

The relative insensitivity of the aerothermodynamic coefficients to the gas-surface interaction model for a single flat plate is not too surprising. Both the Maxwell and CLL models are constructed to give the same behavior in the limits where the gas and surface are in thermal equilibrium. In fact, under more continuum-like conditions, the two models give essentially identical results (Ref. 5). For the Venus aerobraking conditions used in the present study, the flow is highly rarefied, and gas-surface interactions dominate the overall aerothermodynamic behavior (i.e., gas-gas collisions have only a small effect). Although there are quantitative differences, they are generally small (order of 10-20%), and the qualitative behavior as a function of angle of attack and overall accommodation is essentially the same for the two models. However, the details of the flowfield are quite different for the two models. The superposition of diffusely and specularly scattered molecules characteristic of the Maxwell model and the more continuous molecular flux distribution with its lobular shape given by the CLL model result in a radically different density field around the plate.

The differences in flowfield structure observed for the two models were explored for a two-plate system to obtain additional information on possible qualitative differences that might occur in one or more aerothermodynamic quantities. It was hypothesized that such differences might be exploited experimentally as a means of determining which model gives a better representation of the gas-surface behavior for high-velocity aerobraking and orbital flight conditions. It was expected that by placing a second plate in the near vicinity of the first, there might be some sensitivity to the lobular nature of the scattering with the CLL model. In effect, the second plate might act as a "detector" for molecules scattered from the first plate. In fact, such a sensitivity was found, although the manner in which it was manifested was somewhat unexpected. The results show a qualitative difference in the angle of attack at which the maximum heat transfer occurs with the CLL model, showing it to be strongly dependent on the accommodation coefficients, while the Maxwell model gives results that are independent of the accommodation coefficient. The surprising feature is that this qualitative difference appears to be the result of secondary backscatter from the rear side of the front plate to the front side of the rear plate. Thus it is a second-order effect, and even though the variations in the angle of attack for maximum heat transfer are quite large, the actual variations in heat transfer coefficient are quite small. This makes it more difficult to determine the location of the maxima and would require very precise heat-transfer measurements in order to exploit this phenomena experimentally.

The calculations presented in this report have only covered a limited number of parametric variations. Further calculations with additional combinations of normal and tangential accommodation coefficients or where the internal energy accommodation is varied independently might provide more insight into the sensitivity of the aerothermodynamic quantities to gas-surface model. Other multiplate configurations and/or other geometries might also be worth investigating in order to identify conditions where experimental measurements might be more feasible. However, the significant differences observed in overall flowfield behavior between the Maxwell and CLL models even for these simple shapes suggest that it may be important to determine which gas-surface interaction model best represents the physical behavior expected for complex aerobraking configurations.

CONCLUDING REMARKS

Direct Simulation Monte Carlo calculations have been made to examine differences in predictions of aerodynamic forces and heat transfer between the Maxwell and the Cercignani-Lampis-Lord (CLL) gas-surface interaction models for flat plate configurations at freestream conditions

corresponding to a 140 km orbit around Venus. The size of the flat plate is that of one of the solar panels on the Magellan spacecraft, and the freestream conditions are one of those experienced during aerobraking maneuvers.

Results were calculated for both a single flat plate and a two-plate configuration as a function of angle of attack and gas-surface accommodation coefficients. The two-plate system is not representative of the Magellan geometry but is studied to explore possible experiments that might be used to differentiate between the two gas-surface interaction models.

Although the Maxwell model and the CLL model have fundamental differences, they give similar predictions of aerodynamic forces and heat transfer on a single flat plate. The two models, however, differ in their predictions of the flowfield around the plate. These differences in the flowfield lead to predictions of the angle of attack for maximum heat transfer in a two plate configuration that are distinctly different. The angle of attack at which maximum heat transfer occurs with the CLL model is a function of accommodation coefficient, while the angle of attack for maximum heat transfer for the Maxwell model is constant. Further investigation into this behavior is required to provide better understanding of the effects of gas-surface models in DSMC calculations and ultimately a better understanding of the accommodation coefficients of materials and gases for orbital and aerobraking conditions.

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